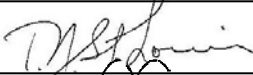
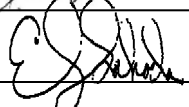
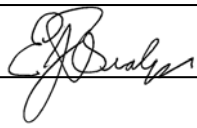


NGNP Hydrogen Plant Alternatives Study

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LIST OF ACRONYMS

BUN	Bunsen Reaction
CDA	Clean Dry Air
CSTR	Continually Stirred Tank Reactor
CTF	Component Test Facility
DDN	Design Data Needs
DOE	Department of Energy
DRL	Design Readiness Level
EDI	Electro-Deionization
FUS	Feed and Utility Systems
HAD	Hydroiodic Acid Decomposition
HHV	High Heating Value
HPAS	Hydrogen Plant Alternatives Study
HPS	Hydrogen Production System
HTGR	High Temperature Gas Reactor
HTSE	High Temperature Steam Electrolysis
HYS	Hybrid Sulfur
INL	Idaho National Laboratory
LHV	Low Heating Value
LWR	Light Water Reactor
MT	Metric Tonne
NGNP	Next Generation Nuclear Plant
NHI	National Hydrogen Initiative
NHSS	Nuclear Heat Supply System
PCHX	Process Coupling Heat Exchanger
PEM	Proton Exchange Membrane
PFDs	Process Flow Diagrams
PPU	Product Purification System
PTFE or Teflon	Polytetrafluoroethylene
ROT	Reactor Outlet Temperature
SCFD	Standard Cubic Feet per Day
SDD	System Design Description
SDE	Sulfur Dioxide Depolarized Electrolyzer
SI	Sulfur Iodine
SIC	Silicon Carbide
SMR	Steam Methane Reforming
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory
SSCS	Structures Systems and Components
TRL	Technology Readiness Level

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EXECUTIVE SUMMARY

PURPOSE AND OBJECTIVES

The purpose of this study is to compare three hydrogen production technologies and processes on consistent technical and economic bases. The technologies and associated process systems are the leading candidates for deployment with a High Temperature Gas Cooled Reactor (HTGR). These processes are the Sulfur Iodine (SI), High Temperature Steam Electrolysis (HTSE), and Hybrid Sulfur (HyS) water splitting technologies. Additionally, the study provides the cost and technology readiness basis for further development, testing, and demonstration of each technology.

The economic viability of each technology is assessed based on capital costs, operating costs, technical risk, safety, and operability. Standard industry practice with respect to process engineering and cost estimating were used to assess the economic viability of each technology for commercial implementation. Only limited credit was given for cost improvements from technology breakthroughs. Operating costs were based on first-of-a-kind process availability. All of these technologies are at an early stage of development, and the individual operability and safety concerns were identified and evaluated to further define risks to commercialization. To that end, an analysis was performed that evaluated the sensitivity of hydrogen cost, per kilogram of hydrogen produced, against variations in the range of the HTGR outlet temperature (i.e., from 950°C to 700°C).

Although there are many potential configurations for hydrogen production processes coupled to HTGRs, a single scenario was developed for this study to make the comparison consistent and easy to understand. This scenario sizes each hydrogen process to approximately the same production rate as a large commercial hydrogen facility in operation today. Three flowsheets with consistent assumptions, and using commercially available equipment where possible, were developed based on that production rate. The flowsheets were used to rate the process maturity and identify technology development and design needs for major equipment and subsystems. It was assumed that design, development, and construction would be completed in a ten year period. Estimated costs are based on industry databases for materials and labor, and on the estimates of technical experts from associated research and development programs. This comparison process is consistent with industry practices used to assess the commercial potential of new technologies and chemical processes.

Besides economic viability, the commercial potential of a technology depends upon its industrial safety and operability. Although all of these technologies are at an early stage of development, attributes of each that raise operability or safety concerns are identified and evaluated.

SUMMARY OF THE STUDY PROCESS

Both the study process and the evaluation criteria are depicted in Figure ES-1.

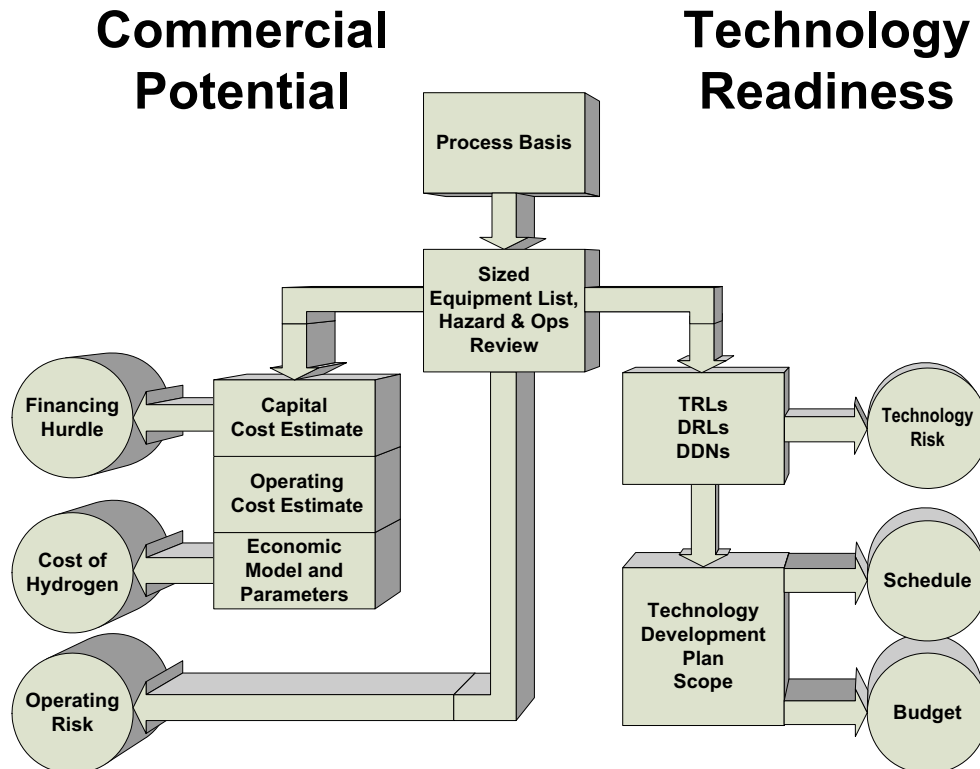


Figure ES-1: Hydrogen Plant Alternatives Study Work Flow

Commercial potential is judged by the cost of production of hydrogen, the operating risks, and the capital cost of the plant. Any one of these may present a hurdle to financing. Technology readiness is measured by Technology Readiness Levels (TRLs) and by the projected schedule and budget to reach commercial readiness. Also important is the technology risk or the likelihood of reaching a commercial process within the projected schedule and budget. The process basis for each process technology consists of a process flow scheme, a mass and energy balance and process flow diagrams. From the process basis, a sized equipment list and a hazard and operability review were developed. These formed the basis for capital and operating cost estimates, Technology Readiness Levels, Design Readiness Levels (DRLs), and Design Data Needs (DDNs). The latter three items were further developed into a technology maturation plan including estimates of cost and schedule.

MAJOR FINDINGS

The major metrics by which the three water-splitting technologies were compared are shown in Table ES-1. These metrics represent the two major criteria: commercial potential and technology readiness. The number of HTGRs required, power conversion system cost, imported electricity, and cost of production shown for each case correspond to a plant producing the

capacity shown in the first row of the table. The plant capacity is intended to match the capacity of a large commercial hydrogen plant by current standards. Capacities are not equal in all cases because of adjustments made to better optimize the cost of production in each case.

Table ES-1: Technology Comparison Matrix

Commercial Potential	SI	HyS	HTSE
Plant Capacity, Million Standard Cubic Feet per Day (MMSCFD)	157	142	142
Hydrogen Production Process Capital Cost (no contingency) ⁽¹⁾ , \$ million	2,672 ⁽²⁾	916	506
Number of HTGRs required	3	2	1
Power Conversion System Capital Cost, \$ million	N/A ⁽³⁾	178	217
Nuclear Heat Supply, \$/MW _{th}	25 to 35		
Imported Electricity, MW _e hr/hr	226	100	327
Cost of Production, \$/kg	10.71	6.83	6.04
Operating Risk, Low (L)/ Medium (M)/ High (H)	H	M-H	M-H
Technology Readiness			
TRL ⁽⁴⁾	2	2	3
Number of Technology Challenges (Refer to Tables ES-3 to ES-5)	9	8	6
Risk – Low (L)/ Medium (M)/ High (H)	H	M-H	H
R&D Schedule to Reach Commercial Status, years	10	10	10
R &D Budget to Deploy Commercial-Scale Demonstration, \$ million	178	194	130

(1) Capital cost does not include the cost of the HTGR(s). Cost of nuclear heat is assessed as \$/MW_{th} assuming that the nuclear heat required by the respective process is purchased “over the fence.” This cost factor reflects the capital cost of the HTGR(s).

(2) This capital cost estimate is imprecise due to the large amount of exotic materials of construction (tantalum, tantalum alloys, and tantalum lined steel) for which reliable costs for large quantities are not available. To establish a lower limit to the capital cost, the estimate was also executed using carbon steel as the material of construction. This estimate resulted in a capital cost of \$1,201 million.

(3) PCS cost is associated with the electrolyzers, which is not present in the SI technology.

(4) Technology Readiness Levels (TRLs) are rated from 1 to 10, with 1 corresponding to observed phenomena in the laboratory without any defined application and 10 corresponding to one that is ready for commercial-scale demonstration. A TRL of 2 corresponds to there being the formulation of a technology concept and application. A TRL of 3 corresponds to there being a proof of concept through laboratory scale testing and experimentation.

Major findings of this study are presented below and support for these findings is presented in the following section.

Competitiveness

- The best of the HTGR-based water-splitting processes is not projected to be competitive with Steam Methane Reforming (SMR) until the price of natural gas exceeds about \$15/MMBtu plus a real escalation rate of 2%/yr and/or there is an equivalent cost or tax associated with carbon collection and sequestration.
- Operating risks of these technologies are very high in comparison with current hydrogen production plants. Of the three hydrogen production technologies, the SI process has the highest risk because of the complex chemical process and the large inventory of hazardous chemicals.
- The HyS and HTSE processes should be competitive with ambient temperature alkaline or PEM electrolysis, even when considering the future cost goals associated with those technologies.

Capital Cost

- Costs of electrolytic cells dominate the capital cost of both the HTSE and HyS technologies. Available cost estimates are indicative at best. The authors utilized the best estimates available from the technology developers for capital costs associated with key components of these developing technologies. Otherwise, costs not provided by the technology developers are consistent in source and accuracy. SI iodine inventory costs are about the same as the cost of the electrolytic cells.

Technology Limitations and Challenges

- All three water-splitting technologies have irreducible costs and complexity due to fundamental thermodynamic limitations. Alleviation by additional research or engineering is considered limited.
- For HTSE, thermodynamic limitations indicate that this process may be better suited to a combined process heat application in which HTSE uses process heat above 700°C and the other applications, such as cogeneration, uses the lower portion. Even this arrangement faces serious challenges. Alternately, HTSE could be coupled to a conventional light water reactor with heat recuperation integrated into the electrolysis module, if dedicated hydrogen production is the goal.

Technology Development

- Insufficient design has been carried out on the major components of these technologies to have assurance either that all the major component engineering and design issues have been discovered or that some of the major issues identified here can be resolved.
- Materials of construction, including auxiliary materials such as seals, gaskets, and linings, will be a major development issue. Development of these items is not included in the R&D program, yet they may be a limiting factor associated with cost and schedule.

- Current plans for technology development are for demonstrations larger than is typically required by industry. In part because each technology will operate in a modular fashion or with multiple process trains, smaller demonstrations may be sufficient to demonstrate viability. Additionally, viability of the processes may be demonstrated with a non-nuclear heat source.

NGNP Application

- For HTSE, there is a distinct disproportion between the amount of nuclear heat supplied by the HTGR and the amount of process heat used by the technology. There is significantly more heat produced by the HTGR than required by the process. Scaling up a HTSE process to match the nuclear heat output would result in an unrealistically large hydrogen production rate. Coupling HTSE with a HTGR also presents formidable challenges with thermal expansion of the process piping and thermal insulation within vessels and the electrolysis modules. From a commercial perspective, there is little incentive to incur the significant development costs and risks in developing HTSE for a HTGR when there are other more attractive alternatives for HTSE (e.g., an LWR).
- A key step in the SI process, HI reactive distillation, has not yet been proven in principle and operating risks and costs are likely to be very high. It too is an unlikely candidate for NGNP application.
- Although it also faces several challenges, the HyS process is the most likely candidate, at this time, for the earliest commercial-scale demonstration with NGNP or to replace an industrial-scale SMR process.
- The risk is high that none of these technologies can reach commercial-scale demonstration readiness in time to support a demonstration immediately following NGNP's initial start-up.

SUMMARY OF REASONS FOR THE MAJOR CONCLUSIONS AND RECOMMENDATIONS

Capital Cost

The capital cost of all three of these technologies is high in comparison to steam methane reforming plants. Current estimates for a ~150 million SCFD steam methane-based hydrogen plant range around \$300 million.

The estimated cost of the hydrogen production plants developed for this study, excluding nuclear reactors, range from about three to ten times the cost of a comparably sized steam methane reforming plant. This is not surprising given the complexity of these plants, costly materials of construction, and the high cost components such as electrolytic cells.

Total capital required to develop the respective hydrogen production facilities is summarized in Table ES-2. Costs are developed for facilities with about 142 MMSCFD hydrogen output, including costs associated the nuclear heat supply and an allocation for new nuclear power plants to provide the imported electricity.

Table ES-2: Technology Capital Requirements

Capital Requirements (\$M)	SI	HyS	HTSE
Capital Cost of Hydrogen Plant	3,061	1,326	903
Capital Cost of Nuclear Heat Plant(s)	2,912	2,192	1,349
Total Capital Required for Hydrogen Production Facility	5,973	3,518	2,252
Capital Required for New Nuclear Generation Plants (Imported Electrical Power)	813	410	1,177
Total Capital Required for Hydrogen Production Plant Development	6,786	3,928	3,429

It can be seen from Table ES-2 that the direct capital required for the development of a hydrogen production facility is the lowest for the HTSE process with the HyS process requiring about 50% more capital and the SI process requires about 2.6 times more capital than the HTSE Process. As mentioned previously, the above costs are based on the best estimates available from the technology developers for capital costs associated with key components of these developing technologies. Otherwise, costs not provided by the technology developers are consistent in source and accuracy. Additionally, it should be noted that the above costs are based on the design bases and assumptions detailed within this study. The authors caution that care should be taken when comparing these numbers against others based on different reference conditions and assumptions.

The HyS and the HTSE process have about the same financing hurdle when considering the capital required to construct new nuclear generating capacity to supply the imported power required for hydrogen production. The SI process has the highest financial hurdle when considering both process plant capital costs and new nuclear generating capacity.

Cost of Production

Cost of production of hydrogen from these plants is largely dependent upon the capital charges and the cost of the nuclear heat. However imported electric power is a significant cost contributor for the SI and HTSE processes. Cost of hydrogen is estimated to be \$10.71/kg H₂ for the SI process, \$6.83/kg H₂ for the HyS process, and \$6.04/kg H₂ for the HTSE process.

The economic analysis assumes that all utilities, including the nuclear process heat, are purchased “over-the-fence.”

Generally, the SI process was the most sensitive to variations in the value of the economic assumptions used to estimate the cost of hydrogen. The HyS and HTSE processes were less sensitive to variations in the value of the economic assumptions used to estimate the cost of hydrogen.

Reductions in capital cost, and the IRR, would provide the greatest opportunity for reducing the cost of hydrogen in the SI process. The capital cost for the SI process is dominated by the cost of the exotic materials of construction. Identification of alternate less costly materials would result in the greatest reduction in the cost of hydrogen produced by the SI process.

Reduction in capital cost would also result in lower hydrogen costs for the HyS and HTSE processes

The SI and HyS hydrogen production costs were most sensitive to IRR, nuclear heat costs, capacity factor, and electricity costs – in that order – while HTSE hydrogen production costs were sensitive to electricity costs, nuclear heat costs, and IRR.

The above mentioned costs of production for the three production technologies were then compared on an equivalent basis to the prices for hydrogen from alternate baseline technologies. The baselines chosen are natural gas steam methane reforming and alkaline water electrolysis. Based on the analyses performed in the study, the hydrogen costs varied between \$2 to \$3/kg H₂ for steam methane reforming and varied between \$4 to \$6/kg H₂ for alkaline water electrolysis.

Hydrogen Selling Price

As part of the study, a sensitivity analysis of the hydrogen selling price versus various Reactor Outlet Temperatures (ROT) was conducted for each of the technologies. Intuitively, the lowering of the ROT would have an effect of increasing the contribution of the HPS cost to the hydrogen selling price and reducing the contribution of the NHSS cost to the price. The selling price of hydrogen as a function of the ROT is shown in Figure ES-2.

It can be seen in Figure ES-2 that HTSE has not only the lowest calculated hydrogen selling price, but also the least sensitivity to NHSS reactor outlet temperature. The magnitude of sensitivity can be explained by the HTSE process cycle using the least amount of high-temperature heat among the three processes. At a 950°C reactor outlet temperature, the reference HTSE HPS uses a small fraction of the heat from one reactor unit. As reactor outlet temperature declines, the fraction from the HTGR is less, and to provide the required heat for the electrolysis process greater amounts of ohmic heating are utilized. Thus, as the temperature of the heat from the NHSS decreases, the amount of heat per unit output of the HTSE process is even less. However, since the fraction of high-temperature heat in the reference 950°C case is so small, the influence on hydrogen selling price is slight. At or below a NHSS outlet temperature of about 850°C, the energy budget is such that no process heat is required.

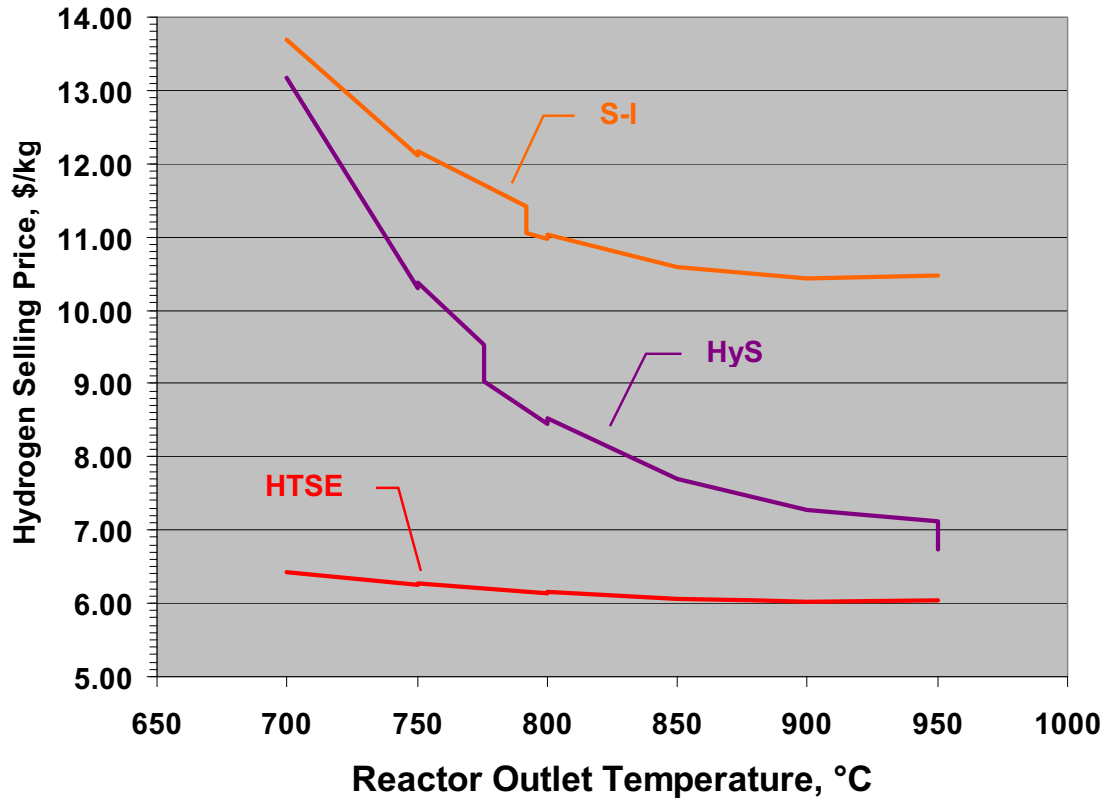


Figure ES-2: Hydrogen Selling Price as a Function of Reactor Outlet Temperature

Both Hybrid Sulfur and Sulfur Iodine cycles have rapid capital cost increase and increasing power consumption as the conversion in the Sulfuric Acid Decomposer per pass declines with lower maximum process temperature. This is because the Sulfuric Acid Decomposition section flows need to be greater, pumping power is higher, and energy for acid concentration is greater.

Hybrid Sulfur has the most sensitivity to NHSS reactor outlet temperature at the 750°C end of the range calculated. This is a phenomenon of the limit on usable heat set by the pinch point in the Sulfuric Acid Decomposer. All heat below approximately 500°C can only be used for electric generation.

The same sensitivity is not shown by the Sulfur Iodine cycle because the NHSS heat goes to both the Sulfuric Acid Decomposition section and to the HI section. Therefore, less heat is committed to the Acid Decomposer and consequently limited by the pinch.

A notable result is that, based on the mathematical model and assumptions of this evaluation, the hydrogen price with all factors considered is relatively flat as a function of reactor outlet temperature down to about 800-850°C for SI and HTSE. This trend would suggest that HTSE is a better match for an HTGR at lower temperatures than the other two technologies.

However, this trend is misleading. Rather, the relatively modest increase in selling price is due to the fact that HTSE is increasingly importing inexpensive electricity for process use and is relying less and less on nuclear heat from the HTGR for process heat. In other words, HTSE technology is more appealing at lower temperatures because its process heat demands are being provided through other more economical energy sources than a HTGR.

Operating Risk

The operating risk for all of these technologies is high. Operating risk includes such aspects as the potential for operating failure, loss of investment, and down-time. For HTSE, there is a serious potential for hot hydrogen and/or hot oxygen leakage. This would result in a hydrogen flame with resulting loss of investment or operator injury, depending upon the design of the cell stacks. There are roughly 1500 km of seal length in the cell modules in the current design, all of which are operating at temperatures at or above 800°C, but at a relatively low differential pressure. The operating temperature is above the auto-ignition temperature for hydrogen guaranteeing a flame rather than an explosion.

Both Hybrid Sulfur and Sulfur Iodine plants handle large amounts of sulfuric acid as well as mixtures of hot steam, sulfur trioxide, sulfur dioxide, and oxygen. The potential for corrosion from these materials increases the risk of leakage. Economical materials currently available for this service consist of polymer lined steel. Mechanical damage to the linings can cause very rapid corrosion of the pressure boundary and catastrophic failure. Increased maintenance can alleviate this problem, but detection of lining failure is difficult and uncertain.

In addition, the Sulfur Iodine process requires circulation of very large amounts of iodine and hydroiodic acid. The estimated inventory of the base case plant is 7500 tonnes of iodine. The stoichiometric circulation rate of iodine is 2 kmols/s in each of the three trains, which equals 508 kilograms per second or about ½ ton per second. The circulation rate is actually higher because iodine as well as HI is circulated to the HI decomposition section. The corrosive nature of these materials enhances the potential for leaks, spills, and increased maintenance costs.

Technology Readiness Level (TRL)

The technology readiness level for each of these technologies is currently low. This is the case because although some critical systems, structures, and components (SSCs) of each technology have advanced beyond the early stages of development, others have not. For sulfuric acid decomposition, used in both HyS and SI, the functionality of the bayonet tube has been tested at bench scale. A catalyst with a reasonable commercial life, however, has not. The technology as a whole therefore cannot advance beyond the level of the least developed component.

Risk

Risk as used here means the likelihood of not achieving a commercial, economically viable process design, including all critical components, in a ten year period. Risk is therefore

relative to process economics and schedule. Given a higher value product or a more leisurely schedule, the risk of failure to achieve these goals is reduced. The standard by which risk is judged here is the standard set by this study. The risk we are judging is the likelihood of missing the economic and schedule parameters set forth in this study by a significant margin due to technology development challenges.

By a careful analysis of the challenges faced by each technology, the risks fall into five major categories:

- **Fundamental (F)** limitations: These are clear limits set by the laws of physics, chemistry, and thermodynamics. It is evident that no amount of research or engineering will overcome these.
- **Possible (P)** fundamental limitations: These are limits that may be fundamental, but that could be circumvented by an alternative design.
- **Obscure (O)** path to success: These are issues for which little consideration has yet been given.
- **Difficult (D)** but relatively clear path forward: Some consideration has been given to these issues and the path forward is reasonably clear, but could still raise challenges to schedule and cost.
- **Straightforward (S)** path to success. These issues are treated in the body of the report, but are not dealt with here.

Some engineering judgment is involved in these rankings and some disagreement between honest judges is to be expected. Table ES-3 through Table ES-5 list the major technical issues of each technology and categorize them according to the above scheme of five major categories (F, P, O, D or S). The initial letter of each category is used as a designator in the tables.

Table ES-3: Major HTSE Technology Challenges

A. Uses proportionately little high temperature process heat	F
B. High temperature heat added between cell stack and heat recuperation	F
C. Thermal expansion in the delivery piping and pipe insulation	P
D. Thermal insulation of electrolyzer modules	P
E. Reliably sealing the cells from hydrogen, steam, air, and oxygen leaks	P→O
F. Rapid deactivation of the cells	O→D
G. Cell scale-up	P

- A. Very little of the energy required to electrolyze steam into oxygen and hydrogen can be supplied as process heat using the HTSE technology. At best only 15% of the total energy to split water would be added as process heat. The rest is added as electrical energy. Considering the process heat as a fraction of the total heat used for both process heat and electrical generation, the fraction is only about 7%. This means that if a 550 MW_{th} HTGR were used exclusively for process heat, the plant capacity would be about 900 MMSCFD of hydrogen and the amount of

imported electricity would be 3,000 MW_e·hr/hr. The bench scale laboratory work that has been carried out thus far has been using the thermal neutral point as the benchmark case. Consequently, process heat is required only to compensate for thermal losses. The thermal requirement of the process is generated by ohmic losses in the cells.

- B. Process heat must be added between the cell stack and the recuperation equipment. This results in several very challenging engineering problems including distributing very hot steam and air to many cell stacks, limiting heat losses from the pipe and stacks, designing for thermal expansion of the distribution piping, designing for thermal expansion of the stacks and of tension bars meant to maintain pressure on the inter-cell seals, penetrating a pressure boundary at very high temperatures and pressures with large electrical cables, and maintaining the integrity of electrical connections in a very hot and possibly oxidizing environment. Recognizing these issues, the technology development team has developed a recuperator integrated into the cell stack. Combined with operation at the thermal neutral point, this is an elegant approach. However, it practically precludes using any appreciable amount of nuclear process heat from a HTGR.
- C. Thermal expansion of the delivery pipe is a more difficult issue than it at first appears. The fact that the piping must operate at very high temperatures and possibly pressures will require that it be very heavy wall pipe. This will reduce its flexibility considerably thereby increasing the stress on critical fittings (e.g., elbows) during expansion of the piping. Expansion loops will be required to compensate for about two meters of expansion. The length of these loops will add appreciably to the length, pressure drop, and heat losses from the piping. From discussions with piping experts, it is not clear that a feasible solution is available. It is unclear at this time how this expanding piping will be insulated such that the insulation will accommodate or expand with the piping.
- D. Per the study's design, the operating temperature and pressure of the electrolyzer modules are 870°C and 56 bar, respectively. For the modules, the insulating properties of any internal insulation will be an order of magnitude lower than we expected due to the high operating pressure. Up to about 40 bar, the thermal conductivity of gases are affected only very slightly by pressure. As pressure rises above this level, however, the thermal conductivity increases very rapidly. The thermal conductivity of the insulation is entirely dependent upon the conductivity of the gas in the insulation. For internal insulation, this will be air and oxygen. For air and oxygen above 40 bar, the dependence of thermal conductivity on pressure changes dramatically and becomes quite strong. Although the effect on the Prandtl number is negligible, the effect on conductivity, and therefore presumably also on viscosity, is large. For gas trapped in the insulation, conductivity and not Prandtl number is important: heat

transmission is mostly by conduction, not convection. The net effect is that the insulation becomes largely ineffective.

- E. The sealing issues inherent in the current design are described above. A cell stack design that does not require enclosure by a pressure vessel may mitigate some of the problems, but it raises additional issues. Such a stack design would be able to operate only at low pressure. This would require much larger equipment as well as expensive compression of low pressure hydrogen to pipeline pressures.
- F. Current active cell life is extremely short by commercial standards. The causes of de-activation are as yet unknown. This may be a problem related to dissolved ions in the feed water or may be inherent to the cell design itself. This is discussed in further detail in the HyS section below. If the current Ceramtec cell design is indeed inherently life limiting, alternative cell designs such as the all ceramic NASA cells may need to be considered. It should be noted, however, that the NASA cells are at a much earlier stage of development. Therefore, if the Ceramtec design is deemed not to be viable because of cell longevity, there is the implication that the technology readiness will need to be downgraded further.
- G. Cell scale-up is an issue for both HTSE and HyS. In the case of SO₂ electrolysis cells, there are similar commercial cells operating in chlor-alkali and in water electrolysis service. There is a reasonable chance, therefore, that this electrolysis technology can be successfully scaled to commercial size. For HTSE cells, on the other hand, operating conditions are far more demanding. Although solid oxide fuel cells have been developed and tested at a reasonable scale, there are significant differences between fuel cells and electrolysis cells that call into question the possibility of developing electrolysis cells at a scale large enough to make a nuclear heated installation practical. Differential thermal expansion at high temperatures may establish a physical limit to the cell size.

The cell deactivation and scale-up challenges may be resolved in a timely fashion for the NGNP project. The disproportionate process heat requirement and the difficulty of applying process heat to this technology, or the need to operate at low pressures and compress the products, reduce the incentive for using this as an NGNP application. The risk of reaching commercial status in time for commercial deployment with NGNP is high due to several key technical challenges: the thermal expansion issues associated with the electrolyzer modules' structure, distribution piping, and cell stacks; the thermal insulation of the electrolyzer modules; and the sealing of the cells.

Table ES-4: Major HyS Technology Challenges

A.	Only 65% of the NHSS can be used for sulfuric acid decomposition.	F
B.	Decomposer tolerance to contaminants	P→O
C.	Metal to ceramic transition in the sulfuric acid decomposer	D→S
D.	Decomposition catalyst	D
E.	Thermal and hydraulic design of the decomposer	D→S
F.	Sulfur leakage through cell membranes	D
G.	Cell tolerance to contaminants	O
H.	Shunt currents	O

- A. Thermal analysis of the sulfuric acid decomposition shows that there is a heat recovery limitation associated with the bayonet reactor and the shape of the enthalpy versus temperature curve. In essence, the minimum process temperature at which heat can be used is 500°C. This means that the minimum temperature of helium leaving the sulfuric acid decomposer must be about 520 to 550°C. The remainder of the nuclear heat must be used in processes that use lower temperature heat. If the nuclear reactor return temperature is around 350°C, a significant portion of the nuclear heat cannot therefore be used in the process. Steam can be raised and power generated with this heat, but this would be high-cost power because of the scale of the reactor and generation plant.
- B. All of these technologies use liquid water as a feedstock. No matter how well the water is purified, there will be dissolved ions in it. The products are all gaseous and therefore these ions will be left in the system. After extended operation these will have an effect on the cells and decomposer. Those effects have not been identified or quantified.
- C. The sulfuric acid decomposer will most likely use silicon carbide heat transfer surfaces because of its resistance to both corrosion and loss of strength at high temperatures. The pressure boundary will, however, be metallic. At some point, regardless of the design, there must be a transition between silicon carbide and metal. This will be in the form of a seal or some kind of brazing or welding. Potential solutions for this are available, but further investigation is required.
- D. Decomposition catalyst now being used is costly and has a limited lifetime. A commercially viable catalyst must be developed. Although catalyst development is never straightforward, several avenues of approach have been suggested and the experts are hopeful that a catalyst can be developed in a timely fashion.
- E. Initial studies have been made of the thermal and hydraulic characteristics of the decomposer under ideal conditions. These must be extended to include reaction kinetics and realistic estimates of heat transfer rates, pressure drops, and the like.

- F. Current SO₂ electrolysis cell operation shows a significant amount of sulfur formation on the hydrogen side of the proton exchange membrane (PEM). This indicates that one or more sulfur species are migrating through the membrane. Until now the approach has been to try different membrane materials to reduce this effect. Recent progress at SRNL has demonstrated cell operation for relatively short durations (i.e., 50 hours) without sulfur build-up or noticeable cell degradation, and longer term testing is planned. This may ultimately be successful, but it may be fruitful to work at better understanding the fundamentals of the problem.
- G. See paragraph “B” above.
- H. Distributing electrolyte flow to many cells in parallel while they are connected in series electrically presents the opportunity for current to flow through the electrolyte and short circuit the cells. This shunt current can become a serious problem with large cell stacks.

The use of only a portion of the nuclear energy as process heat is a handicap for this technology, but it does not appear to render it economically uncompetitive with the other technologies. Lack of tolerance to contaminants and shunt currents may be potential roadblocks to this technology, but insufficient knowledge is available to make that judgment now. The risk of HyS reaching commercial status in time for NNGP is now high. If the contaminant and shunt current issues can be laid to rest promptly, the risk is deemed to be moderate.

Table ES-5: Major SI Technology Challenges

A. Decomposer tolerance to contaminants	P→O
B. Process tolerance to contaminants	O
C. Metal to ceramic transition in the sulfuric acid decomposer	D→S
D. Decomposition catalyst	D
E. Thermal and hydraulic design of the decomposer	D→S
F. Large inventory of iodine and hydroiodic acid (7500 tonnes @ \$20,000 per tonne)	F
G. Large circulation rate of iodine and hydroiodic acid	F
H. Hydroiodic acid decomposition	O
I. Materials of construction (Tantalum raw material costs \$40+ per pound)	D

- A. See item “B” under the HyS Challenges.
- B. See item “B” under the HyS Challenges.
- C. See item “C” under the HyS Challenges.
- D. See item “D” under the HyS Challenges.

- E. See item “E” under the HyS Challenges.
- F. The iodine inventory necessary to produce commercial quantities of hydrogen is large and costly. This is also a theoretical limit. It cannot be substantially reduced by further investigation. The inventory for one plant represents about 30% of the current worldwide annual production. It would cost \$150 million at today’s prices.
- G. The iodine circulation rate between the Bunsen reaction section and HI decomposition is about 3 tons or 1 cubic meter per second. This makes any intermediate storage between the units impractical. Operating upsets in one unit will be immediately propagated to the others rendering operations difficult.
- H. Most work to date on hydroiodic acid decomposition in the Nuclear Hydrogen Initiative has focused on an extractive distillation method. This method has been judged to be technically and economically infeasible. The alternative technology, reactive distillation has not been proven in principal. Moreover, design of the reactive distillation column will involve incorporating a catalytic section and handling two liquid phases. These are complex process engineering techniques that are difficult to reduce to practice. No effort has as yet been applied to design this on an industrial scale.
- I. For the most part, materials of construction for the SI process can be carbon steel lined with polytetrafluoroethylene (PTFE or Teflon®). Surfaces used for heat transfer cannot use this material because of its insulating qualities. Surfaces subject to erosion or with penetrations such as distillation tray or packing supports may not use this material due to the possibility of lining failure and catastrophic corrosion. The only identified substitutes are tantalum or tantalum alloys. The cost of these materials will increase the capital cost of this plant unacceptably. Moreover, it is uncertain whether tantalum is available or can be fabricated in the quantities and forms required. Developing alternative materials is a time-consuming process and almost certainly cannot be accomplished in the required time frame.

The combination of the effects of large iodine inventory and circulation rates, the contaminant tolerance issue, and the lack of economical materials of construction make the risk of reaching commercial status for NNGP high.

Schedule

The development schedules presented by the technology developers all indicated that the required work could be completed within about 10 years. These estimates are based upon the assumption that the work will proceed in an orderly fashion without major roadblocks. This

analysis shows, however, that there is a significant likelihood of major delays and detours in the development path for all of these technologies.

Budget

The research and development budgets presented are those proposed by the technology developers researched for this study. Like the schedules, they are based upon an orderly progression of work following the current view of the remaining technology issues. If a development issue arises that clearly will have significant cost implications, such as the need to develop new materials, a decision will have to be made to continue with a larger budget or abandon the effort. With the current state of knowledge, the budgets are the best that can be produced. What is not included is the engineering effort recommended by this study to accompany the development effort. A first estimate for the engineering effort is that it can be covered by increasing each of the R&D budgets by 10%.

CONCLUSION

There is significant risk that none of the technologies can demonstrate commercial viability within ten years. Schedule risk can be reduced by focusing on a single technology on which to concentrate resources. Further, initiating design will identify development needs earlier, allowing more time to investigate other options and still meet project deadlines. Of the three technologies, the HyS process poses the least risk of achieving commercial status as a HTGR application.

TRLs, sensitivity analysis, and the estimation of \$/kg H₂ costs are important only if a technology is fundamentally viable. All of these metrics assume a timely solution to the engineering problems. The overriding consideration in selecting a candidate technology should be the risk posed by unknowns and unresolved issues. Both HTSE and SI at this point pose risks that are significantly greater than those presented by HyS. If a single technology path is chosen for coupling with a HTGR, HyS is the most suitable candidate based on this study's findings.

The SI process was eliminated due to cost; a need for large quantities of exotic materials (i.e., tantalum and iodine), complexity, and technical risk due to lack of fundamental data and adequate design concepts.

HTSE was eliminated primarily due to the lack of proportion between the nuclear heat supply source and the need for process heat. However, HTSE also has serious technical challenges with regard to thermal expansion and thermal insulation. In contrast with both the SI and HyS processes, the HTSE technology using HTGR process heat requires extraordinary amounts of both equipment and piping that operate at both extremely high temperature and very high pressure. These problems are amenable for very short piping runs and for equipment where the pressure envelope can be maintained at a low temperature, but this is not the case for HTSE. In the author's view, HTSE technology and HTGR technology, as they have been developed to date, are not a good match. From a commercial perspective, there would be little point in facing the enormous development costs and risks identified herein by developing a large centralized

HTSE system for the sake of supplying only a small portion of the energy required for splitting water as heat. This is especially so since a much less challenging, and perhaps even less costly, solution is available by using electricity alone. All these issues are extraneous to two basic issues having to do with the cell itself: the brief useful life of cells tested thus far and the scaling up of cells to a reasonable size. These challenges also pose significant technical risks.

Commercial enterprises would typically have made a selection by this stage of development, although they typically would not assume the financial risk associated with the identified technology challenges. Further, they commonly prove viability with smaller demonstrations. Demonstrating the hydrogen process at a smaller scale and with a non-nuclear heat source is judged to be as viable as a large demonstration coupled to the NGNP. A benefit of this approach is the ability to test severe transients for the hydrogen process independent of operating limits of a prototype reactor.

RECOMMENDATIONS

- Work should be carried out with electrolytic cell and fuel cell manufacturers to overcome the most serious technical challenges associated HyS cells and stacks (i.e., sulfur deposition and shunt currents).
- Serious design efforts developing alternatives should be started as soon as possible on major components such as helium control valves, SOEC stacks and enclosures, HyS electrolytic cells and enclosures, sulfuric acid decomposers, and Bunsen reactors and hydroiodic acid decomposition reactors.
- Added attention should be given to the interface components between the NHSS and the process plant. This includes not only the IHX but also high-temperature gas circulators, helium flow control valves, insulation, and features to accommodate thermal expansion.
- Consideration should be given to demonstrating the hydrogen process with a smaller, non-nuclear heat source to allow acceleration of testing, provide cost savings, and improve test flexibility.

INTRODUCTION

PURPOSE AND OBJECTIVES

The purpose of this study is to compare three hydrogen production technologies and processes on consistent technical and economic bases. The technologies and associated process systems are the leading candidates for deployment with a High Temperature Gas Cooled Reactor (HTGR). These processes are the Sulfur Iodine (SI), High Temperature Steam Electrolysis (HTSE), and Hybrid-Sulfur (HyS) water splitting technologies. Additionally, the study provides the cost and technology readiness basis for further development, testing, and demonstration of each.

The economic viability of each technology is assessed based on capital costs, operating costs, technical risk, safety, and operability. Standard industry practice with respect to process engineering and cost estimating were used to assess the economic viability of each technology for commercial implementation. Only limited credit was given for cost improvements from technology breakthroughs. Operating costs were based on first-of-a-kind process availability. All of these technologies are at an early stage of development and the individual operability and safety concerns were identified and evaluated to further define risks to commercialization. To that end, an analysis was performed that evaluated the sensitivity of hydrogen cost, per kilogram of hydrogen produced, against variations in the HTGR outlet temperature (i.e., from 950°C to 700°C).

Although there are many potential configurations for hydrogen production processes that could be coupled to any of one of multiple process applications, a single scenario was developed to make the comparison consistent and easy to understand. This scenario sizes each hydrogen process to approximately the same production rate as any large commercial hydrogen facility in operation today. Three flowsheets with consistent assumptions, using commercially available equipment where possible, were developed based on that production rate. The flowsheets were used to rate the process maturity and identify technology development and design needs for major equipment and subsystems. It was assumed that design, development, and construction would be completed in a 10 year period. Estimated costs are based on industry databases for materials and labor, and on the estimates of technical experts from associated research and development programs. This comparison process is consistent with industry practices used to assess commercial potential of new technologies and chemical processes.

Besides economic viability, the commercial potential of a technology depends upon its safety and operability. Although all of these technologies are at an early stage of development, attributes of each that raise operability or safety concerns are identified and evaluated.

A life cycle cost assessment is developed for each hydrogen production technology. The life cycle cost assessment includes:

- Estimated capital costs with consistent component sizing, material selections, and installation estimates;
- A qualitative estimate of plant reliability and availability;

- Raw material costs;
- Routine and corrective maintenance costs including replacement costs;
- Waste type and disposal costs;
- Management, technical, and operating staff costs; and
- Electrical and thermal power costs.

This study also assesses the technical risks based on the Technology Readiness Levels associated with each of the hydrogen production technologies. A technology development plan is generated for each candidate. Special attention is given to issues that, if remaining unresolved, will prevent scale-up and eventual commercial implementation.

One intended purpose of this study was to provide an estimate of the duration required for each process to be ready for demonstration in the Component Test Facility (CTF) and the schedule for subsequent demonstration in the CTF. A similar estimate was planned for HTGR demonstration of these same technologies that would confirm they were ready for commercial deployment. Duration of basic technology development tasks were estimated, but too many uncertainties remain to be able to make reasonable estimates of demonstration dates for any of the technologies. Development costs have been estimated, but are similarly uncertain.

Reactor outlet temperature (ROT) may have a significant effect on the efficiency of the water splitting processes, and the hydrogen production rate from a 550 MW_{th} HTGR nuclear reactor, depending upon the water-splitting process. The ROT will influence the cost of hydrogen, cost of equipment, reliability, and the technology and design readiness level for each process. A preliminary assessment of the sensitivity of each of these to the ROT is to be made.

DESCRIPTION OF THE PROCESS OF PREPARING INFORMATION

Despite the fact that the three leading water-splitting technologies have been under development for several years, adequate information to make the assessments proposed in this study was not immediately available. Moreover, the information that was available had not been prepared on a consistent basis. This study attempted to place the basis for comparison of each technology on an equal footing and to bring all information to a level adequate for preliminary economic and technical assessment generally accepted in the process industries.

Available simulations were gathered from published reports and the work of the technology developers. Without exception these required reworking. In general, the assumptions made by the technology developers were far too optimistic especially with regard to pressure drop and the capability of industrial heat transfer equipment. The work that had recently been done on the bayonet sulfuric acid decomposition reactor was judged to be superior to that available in the older SI simulations and a new sulfuric acid decomposition simulation was prepared for this technology.

The simulations obtained from the technology developers provide mass and energy balances as well. But these balances had to be made to match with interfacing flowsheets and balances and with the NHSS. At this point, the capacity of the hydrogen production facility was fixed so as to approach the target capacity without unduly penalizing any technology.

Once the revised simulations were completed, process flow diagrams (PFDs) were prepared. These diagrams contain significantly more information than the simulation diagrams. Simulation diagrams indicate the basic functions of a process and the unit operations and stream conditions. PFDs show this data and also show all the major equipment needed to carry out these functions. Final PFDs also show the major control functions as well, but in this study little attention has been paid to these. Materials of construction for the process equipment are also shown on the PFDs.

The PFDs are the departure point for most of the other work in this study. They are used as the basis for the hazard and operability review and for equipment sizing. The PFDs also provide insight into required process steps that have not been included in the simulations. All technologies, for example, will require both feed water treatment and product purification steps that do not appear in the simulations. The requirements for each technology are somewhat different in this regard and therefore have an impact on the cost of production. Preparation of the PFDs also revealed technology development and design issues that were not identified in the basic technology development phases.

Equipment identified during the PFD development was next sized. Flows and heat duties from the properly adjusted mass and energy balances were used for this purpose. This step also revealed additional development needs. The list of sized equipment and the PFDs are the basis for the preliminary equipment layouts and the cost estimates included herein.

The development requirements identified by the technology developers, as well as those identified as part of this study, were listed according to the associated structure, system, or component, and design data needs were identified for each. These were then assigned a Technology Readiness Level (TRL) after discussion with the technology developers and a Design Readiness Level (DRL). Development paths were prepared for the CTF development road mapping task and were adjusted slightly for the needs of this report.

Development tasks, schedules, and budgets were solicited from the technology developers and reviewed by this team.

THE EVALUATION PROCESS

Introduction

This section describes the process used to evaluate hydrogen production technologies for the Hydrogen Production Facilities (HPF) of the U.S. Department of Energy (DOE) NGNP. The purpose of this evaluation is to facilitate identification of an optimum technology among competing alternatives and to support the allocation of funding and scheduling of resources for the future hydrogen technology development efforts sponsored by DOE.

Evaluation Criteria

The candidate technologies are evaluated in two major areas: commercial potential and technology readiness, as shown in Figure 1.

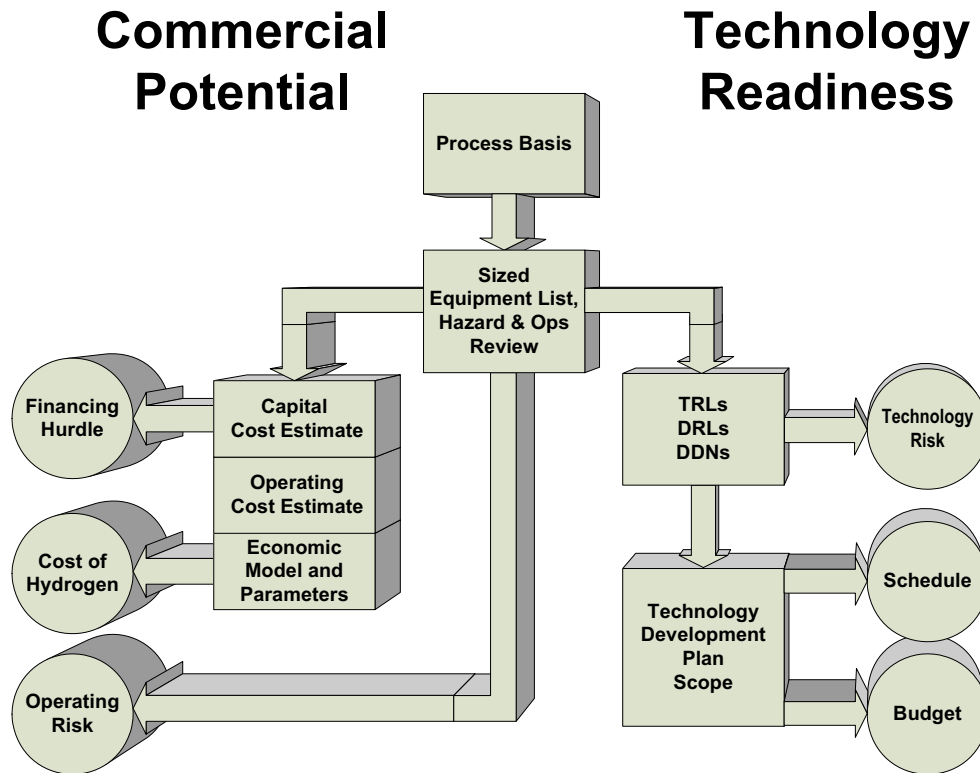


Figure 1: Evaluation Criteria

Commercial potential evaluates the following criteria to assess the potential for successful commercial development:

- The initial capital cost representing a financing hurdle;
- Life-cycle cost of hydrogen, and;
- Operational risks associated with the process technology, including environmental, safety, and health aspects.

The technology readiness evaluates the following criteria to assess the potential for successful development of a HPS based on the following criteria:

- The likelihood of success;
- The time required for development, and;
- The cost of the development program.

Process Evaluation Basis

The following items define the base case for which the life-cycle cost of production of hydrogen and other criteria are evaluated. They are drawn in part from a report titled Summary of Bounding Conditions for Development of the NGNP Project, June 2008, Idaho National Laboratory (INL/EXT-08-14370). Some of the parameters listed here are varied in the sensitivity analyses that are part of this study to determine the effect on both the technology economics and development plan. These sensitivity analyses are listed in Sensitivity Analyses subsection below.

- **Hydrogen Technologies:** Hydrogen production technologies considered in the HPAS are HTSE, HyS, and SI. HyS and SI share the same sulfuric acid decomposition step. The major design and operating parameters of this step are common to both technology process flow schemes.
- **Reactor Technologies:** Reactor technologies are not studied directly, but power, temperature levels, and energy costs used in the study are representative of a Pebble Bed Modular Reactor at 500 MW_{th} or a prismatic core reactor at 565 to 600 MW_{th}. No allowance is made for piping and equipment heat losses or additions due to circulator inefficiency. All configurations use a secondary helium loop to reduce tritium transport and to isolate the process streams from the primary helium loop in the event of a leak in either the Intermediate Heat Exchanger (IHX) or the Process Coupling Heat Exchanger (PCHX). This is reflected in the helium delivery temperatures to the PCHX. It should be noted that the reference HTGR design basis requires that there is little or no pressure differential between the helium-to-helium and helium-to-process sides of the IHX and PCHX, respectively.
- **System Energy Balance:** The HPS is supplied heat from a HTGR in the form of hot helium. The cost of this energy is estimated for the base case and charged to the hydrogen plant. Heat not usable by the process is used to generate electricity and the cost of generating power from this heat is estimated separately. A Rankine cycle is used and generation efficiency is varied depending upon the maximum steam temperature available in each case. In this way, the value of the unused exported heat is estimated. Any electricity deficit or surplus is balanced by imports from or exports to the grid. Cost of imports from the grid in excess of that generated by the unused nuclear heat accounts for a carbon penalty, and the sensitivity analysis is then performed for variations in the carbon penalty/credit as it affects the relative price advantage of nuclear hydrogen.
- **Plant Size:** In industrial practice, a technology provider is required to meet the capacity requirements of the customer. Plant size is therefore set by attempting to match a technology with current large hydrogen plant capacities. A medium plant size is approximately 30 to 50 million Standard Cubic Feet per Day (MMSCFD) and a large-scale plant capacity is about 120 MMSCFD. The latter is used as a target capacity. Adjustments are made to the capacity so as not to unduly penalize a given technology. Consequently, the production capacity used for HTSE and HyS is 142 MMSCFD, and for SI is 157 MMSCFD.

- **Operating Temperatures:** Maximum operating temperature of the PCHX is 870°C on the process side. The inlet process side temperature and therefore the temperature of the return helium is set by process requirements. The maximum return helium temperature is 490°C; the minimum is 350°C.

Commercial Potential

The **Financing Hurdle** consists of the capital cost estimate for a commercial-scale hydrogen plant and includes project overheads, contingency, and owner's costs. The result is reported in \$US.

The **Life Cycle Cost of Hydrogen** is estimated based upon the capital cost estimate, estimated operating costs, and the set of economic parameters listed in Table 1. The result is reported as a \$US/kg of hydrogen product.

Table 1: Economic Parameters

Parameter	Value
Reference Dollar Year	3rd Quarter 2008
Assumed Start-up Year	2030
Plant Maturity Assumption	N th -of-a-Kind plant
Financing	100% Equity
After-Tax Real IRR	10%
Project Overall Capital Cost Contingency	10%
Plant Life	30 years
Lifetime Capacity Factor	8,200 hr/yr (94%)
Construction Period	3 years
Costs in Construction Years	25% / 45% / 30%
Start-up Period	1 year
Income Tax Rate (composite)	38.9%
Property Tax Rate	1% of Overnight Capital Cost
Insurance Rate	1% of Overnight Capital Cost
Working Capital	15% of Incremental Change in Annual Operating Costs

The **Operating Risk** is a qualitative assessment of each process based on the following factors:

- **Hazard Ranking of the chemicals used.** The hazard ranking is based on the NFPA 704, "Standard System for the Identification of the Hazardous Materials for Emergency Response" and the Code of Federal Regulations Title 49, "Subpart B

Table of Hazardous Materials and Special Provisions,” “Part 172.101, Hazardous Material Table.” Increased operating risks are associated with handling of more hazardous chemicals. Table 2 identifies the chemical hazard classification of the chemicals involved in each hydrogen production process.

- **Process complexity.** The number of chemical operations required to obtain the hydrogen product and the number of components, including installed spare capacity, required for the process operations. Increased operating risks are associated with processes that require multiple integrated chemical operations and require a large number of operating equipment.
- **A preliminary hazards assessment.** Identification of inherent environmental, health, and safety hazards associated with each hydrogen production process. Increased operating risks are associated with processes that have more inherent hazard scenarios.

Table 2: Chemical Hazard Classifications

Chemical		NFPA 704				49CFR172.101 Hazard Class	Hazards
		Health (blue)	Flammability (red)	Reactivity (yellow)	Special (white)		
Air	N ₂ /O ₂					-	
Water	H ₂ O					-	
Oxygen, 50%	O ₂ / N ₂	0	0	0	OX	2.2, nonflammable gas, oxidizer	Oxidizer
Oxygen, pure	O ₂	0	0	0	OX	2.2, nonflammable gas, oxidizer	Strong Oxidizer
Hydrogen, pure	H ₂	1	4	0		2.1, flammable gas	Asphyxiate, Explosive
Sulfur Dioxide	SO ₂	2				2.3, poison gas	Toxic, Corrosive
Sulfur Trioxide	SO ₃	3	0	2		8, corrosive, poison	Toxic, Corrosive
Hydroiodic Acid	HI	3	0	1	COR	8, corrosive	Toxic, Corrosive
Iodine	I ₂	3	0	1	OX	8, corrosive solid	Toxic, Corrosive, Strong Oxidizer
Sodium Hydroxide (aq. sol)	NaOH	3	0	1		8, corrosive	Toxic, Corrosive
Sulfuric acid	H ₂ SO ₄	3	0	2	W ⁽¹⁾	8, corrosive	Toxic, Extreme Corrosive

Note (1) : denotes “Avoid Water”

Using this information, a qualitative assessment is developed for each of the hydrogen production processes. The qualitative assessments are ranked as follows:

- Low – Limited hazardous materials, simple chemical process, limited hazards that are easily mitigated, and few operating components.
- Medium Low.
- Medium High.
- High – Large number of hazardous materials required for the process, complex chemical process, increased hazards that are not easily mitigated, and a large number of operating components.

Technology Readiness

The technology readiness assessment is based on data contained in Section 8, which is excerpted from WEC's NGNP Technology Development Road Mapping Report.

- The ***Likelihood of Success*** distinguishes between the difficulties of the development goals, as defined by the TRLs, DRLs, and DDNs for each of the technologies and their components. The difficulty of reaching each goal is assessed and the number of goals for which a clear path is not evident or for which there does not appear to be more than one viable solution is enumerated. Comparative metrics are the number of TRLs, DRLs, and DDNs to bring each technology first to TRL-6, and then to TRL-8.
- The ***Development Schedule*** is the duration of time required for the technology development schedule based on the Technology Maturation Plan. Comparative metrics are durations to bring each technology first to TRL-6, a successful pilot scale demonstration, and then to TRL-8, a demonstrated integrated prototype.
- The ***Development Cost*** is the cost of technology development based on the scope and schedule in Section 8. Comparative metrics are cost to bring each technology first to TRL 6 and then to TRL 8.

Sensitivity Analyses

The following sensitivity analyses are included in this study:

- ***Reactor Outlet Temperature.*** The effect of ROT on both the life-cycle cost of production and the development cost and schedule are studied. ROT is set at 950°C in the base case. An alternative case with a ROT of 750°C is examined and the effects evaluated. Any temperatures between these that represent a step change in hydrogen cost, or development cost and schedule, are identified.
- ***Price of electricity and carbon penalty on imported power.*** For the cases identified above, the effects of the price of electricity and the price of a carbon penalty are evaluated separately.
- ***Cost of converting unused heat to electricity or conversion efficiency.***

- ***Plant size.*** For each technology, the effect of varying plant size and requiring that specific plant hydrogen capacities be met is evaluated against the cost of production of hydrogen.
- ***Capital Costs.*** Capital costs of major components and subsystems.
- ***Reliability.*** Reliability and expected availability of these major components and subsystems as well as of the overall plant.
- ***Maintenance Costs.*** Routine and corrective maintenance including replacement costs.
- ***Staffing.*** Management, technical, and operating staff requirements.

1 TECHNOLOGY DESCRIPTIONS

The following five sections describe the basic concepts of the technologies that make up the core of the three processes being compared in this report. The Hybrid Sulfur process incorporates two central technologies, Sulfuric Acid Decomposition (Oxygen Generation) and Sulfur Dioxide Depolarized Electrolysis (Hydrogen Generation), as shown in Figure 1-1.

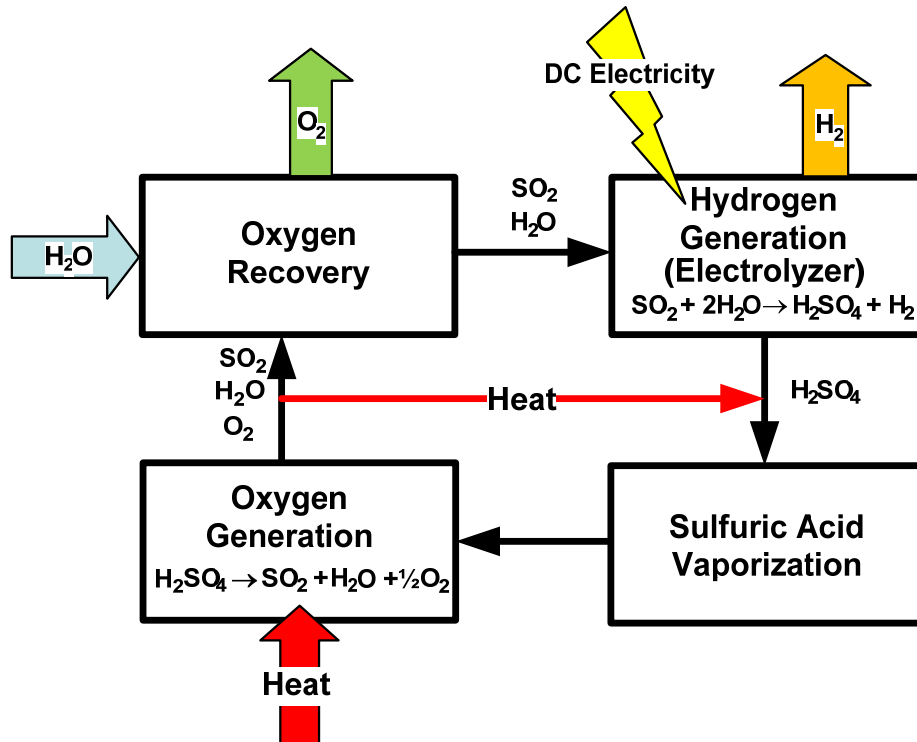


Figure 1-1: The Hybrid Sulfur Process

The Sulfur Iodine process also uses Sulfuric Acid Decomposition technology, but it replaces the electrolysis technology with two chemical technologies, the Bunsen Reaction and Hydroiodic Acid Decomposition, as shown in Figure 1-2. Please note that the Bunsen Reaction is denoted as “Chemical Reactions” in Figure 1-2.

Sulfur-Iodine Cycle

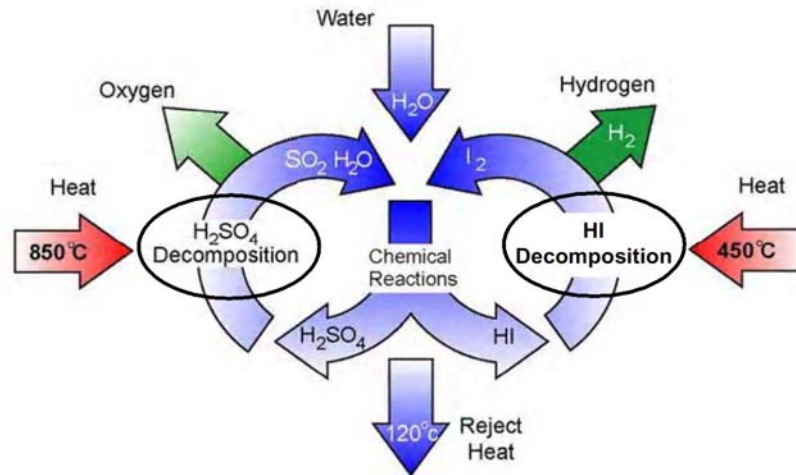


Figure 1-2: The Sulfur Iodine Process

The High Temperature Steam Electrolysis process is simpler than the previous two processes in that it incorporates only one central technology: steam electrolysis by means of Solid Oxide Electrolysis Cells. The HTSE process is shown in Figure 1-3 on the next page.

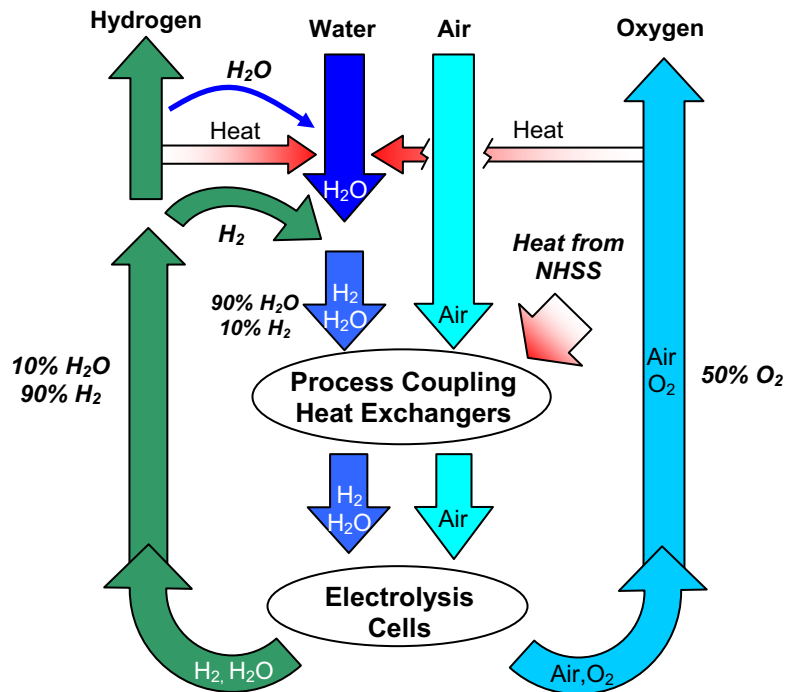
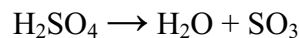


Figure 1-3: The High Temperature Steam Electrolysis Process

In the following sections, the major thermodynamic and kinetic reasons for considering each technology are discussed, as well as their major advantages and limitations. The intent of these sections is to orient the reader. Advantages and limitations will be treated in more detail in the subsequent sections of the report that deal with process and technology development.

1.1 SULFURIC ACID DECOMPOSITION

Although it is embodied slightly differently in each, this technology is common to both the Hybrid Sulfur and the Sulfur Iodine processes. The point of sulfuric acid decomposition is that it replaces a portion of the energy required to split water provided as work in water electrolysis with heat. It therefore virtually eliminates the thermal losses associated with the generation of electricity from thermal energy for this portion of the water splitting energy. The basic chemistry is simple. Sulfuric acid is first decomposed into water and sulfur trioxide.



This occurs quantitatively and uncatalyzed at temperatures well below the maximum at which the reactor operates.

The more difficult reaction is the decomposition of sulfur trioxide:



This step requires a catalyst and estimated conversions at expected operating temperatures (i.e., $\sim 870^{\circ}\text{C}$) are about 50%. These reactions are favored as pressure is lowered and temperature is raised. The decomposition reactor should therefore be designed to operate at the highest temperature that can practically be achieved. Although a lower pressure favors the chemical equilibrium, mechanical considerations in the reactor design make operating significantly below the helium heat transfer medium pressure, that is ~ 90 bar, difficult.

One of the most difficult challenges in decomposing sulfuric acid at high temperatures (i.e., $>800^{\circ}\text{C}$, 1073°K) and pressures (i.e., up to 90 bar) is finding a material that can contain the process at the required conditions without significantly corroding or deteriorating, while also providing adequate heat transfer characteristics. Silicon carbide (SiC) is the one commercially available substance that meets these requirements. Since SiC is ceramic, it cannot be shaped as easily as metal. This greatly complicates the design and fabrication of process vessels and piping. A particular concern is making and maintaining sealed joints between individual SiC and SiC-metal components that operate at high temperature and pressure.

Responsibility for developing this reaction process for the NHI program belongs to Sandia National Laboratories (SNL). SNL has devised an innovative solution that makes use of readily available SiC shapes and does not have any high-temperature connections^[Ref. 1]. Their bayonet decomposition reactor features internal recuperation and allows all of the connections to be made at relatively low temperatures, where polytetrafluoroethylene (PTFE) and similar materials can be used for seals. The essential elements of SNL's bayonet decomposition reactor are shown in Figure 1-4.

In its simplest form, the reactor consists of one closed ended SiC tube co-axially aligned with an open ended SiC tube to form two concentric flow paths. A baffle tube may be included to enhance heat transfer. High-temperature heat is applied externally, except near the open end. Concentrated liquid H_2SO_4 is fed at the open end to the annulus, where it is vaporized before passing through an annular catalyst bed. The decomposition reaction takes place in the catalyst bed, using heat provided by the external heat source. SO_2 , O_2 , and H_2O vapor product returns through the center and loses its heat to the feed through recuperation. Cooled and partially condensed product exits out the open end into a metal base or manifold at a temperature low enough (i.e., $\leq \sim 250^{\circ}\text{C}$, or 523°K) to allow the use of PTFE seals. Imbedding the open ends of the SiC tubes in a metallic manifold facilitates the transition to metal pipe.

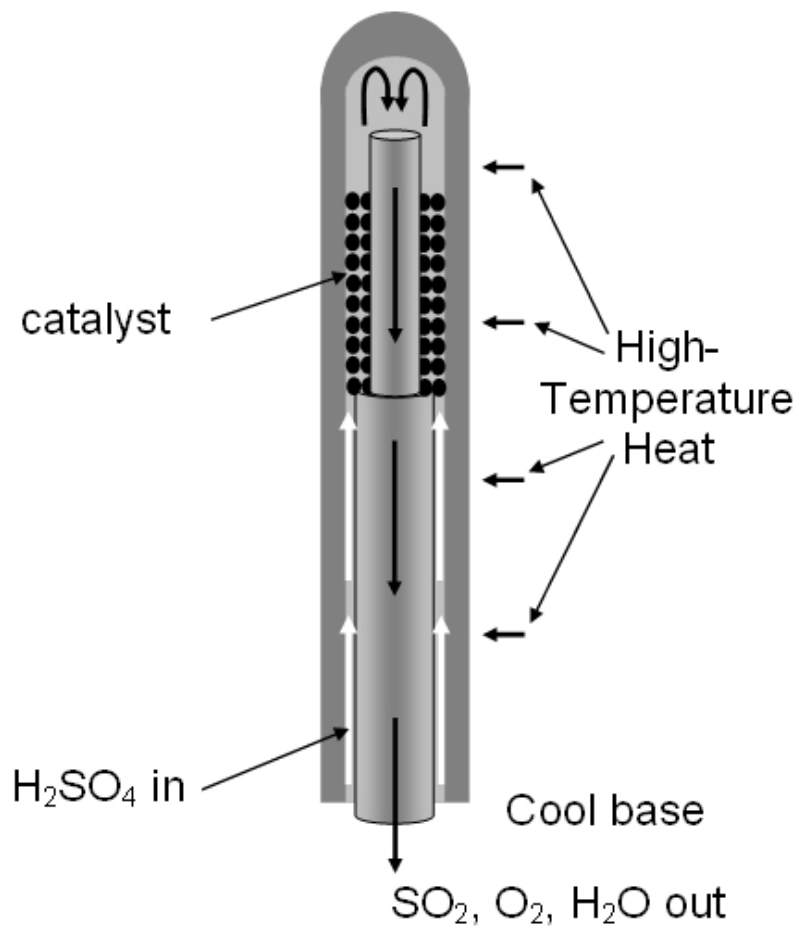


Figure 1-4: Schematic Diagram of the SNL Bayonet Decomposition Reactor

The catalyst for this reactor is being developed by Idaho National Laboratory (INL) as part of the NHI Program.

Heat transfer limitations will impose a high surface-to-volume ratio limit, thereby keeping diameters small. Therefore, it should be obvious that a single bayonet will not have sufficient capacity for a full-scale reactor. However, it is easy to envision an arrangement in which many bayonets are attached in parallel to a manifolded base plate to achieve the necessary production rate. This would be at least somewhat analogous to the common practice with commercial fixed bed catalytic reactors, in which an endothermic reaction is carried out in parallel in multiple narrow tubes held between two tubesheets, with the heat source on the shell side. Advantages of the bayonet design include internal heat recuperation, the need for low-temperature connections only, corrosion resistance, and low fabrication cost. In fact, SiC bayonets are an off-the-shelf item, since they are used commercially for thermowells^[Ref. 2].

Process economics favors using as much high temperature process heat for decomposition of sulfuric acid as possible. The amount of heat available for decomposition is

determined by the concentration of acid in the feed to the decomposer. Higher acid concentration results in more heat available for decomposition. This is due to two major effects. As the water content of the feed is reduced, the amount of water that must be heated to the decomposition temperature is also reduced. Although most of this heat can be recovered, it must be recovered at a lower temperature, thus reducing the energy availability for decomposition. Moreover, the pinch point between the feed and effluent acid gases will change also affecting the quantity of recoverable heat.

At a given helium circulation rate and decomposer inlet temperature, the slope of the helium cooling curve – that is stream enthalpy vs. temperature – is fixed. As more water is added to the process stream, the slope of the process heating curve is reduced. With a pinch point at the cold end of the curve, the total acid flow must be reduced to maintain the same outlet temperature or the outlet temperature must be reduced while maintaining the acid flow. Refer to Figure 1-5 and Figure 1-6. In either case, the amount of acid that is decomposed drops off rapidly with increasing water content in the feed. A concentration of 75% acid has been selected for this study to represent a reasonably high concentration that is achievable in the acid concentration steps. Because of the high affinity of sulfuric acid for water, concentrations above about 75% cannot be practically attained by flashing or vacuum distillation at temperatures below about 250°C.

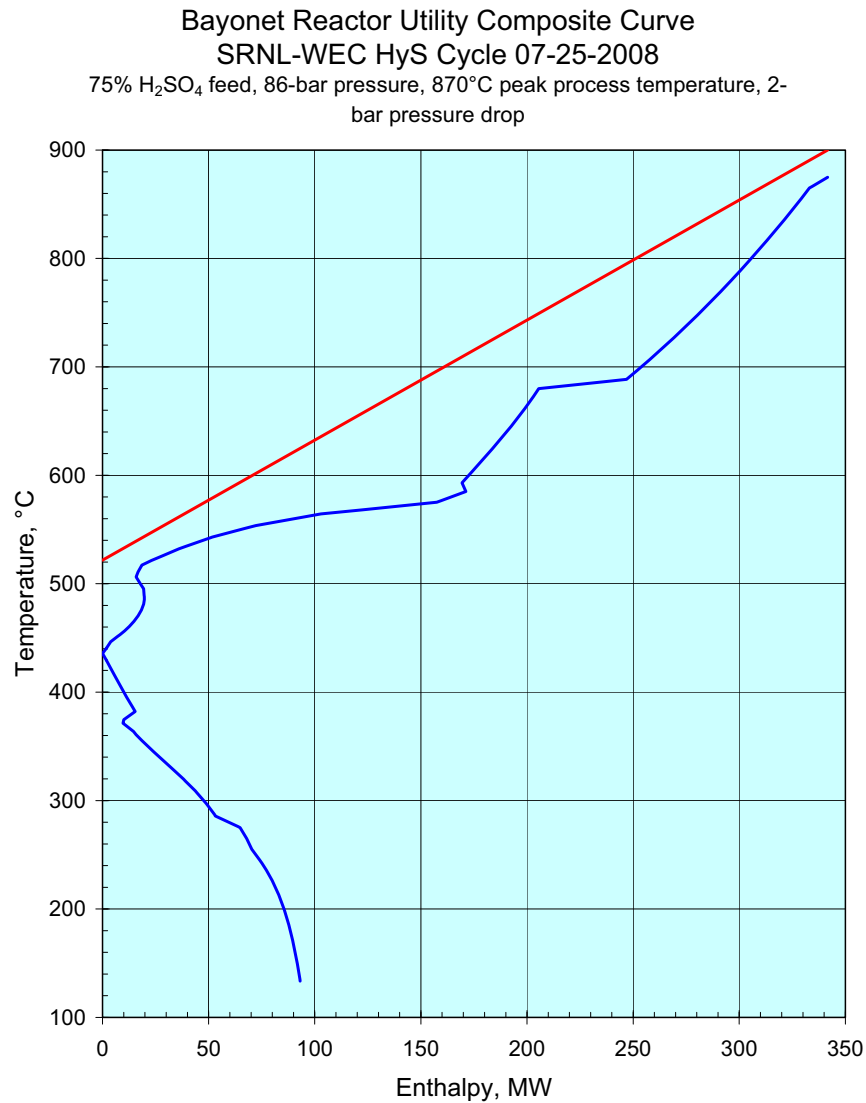


Figure 1-5: Sulfuric Acid Decomposition Bayonet Reactor Helium Cooling and Process Stream Heating Curves

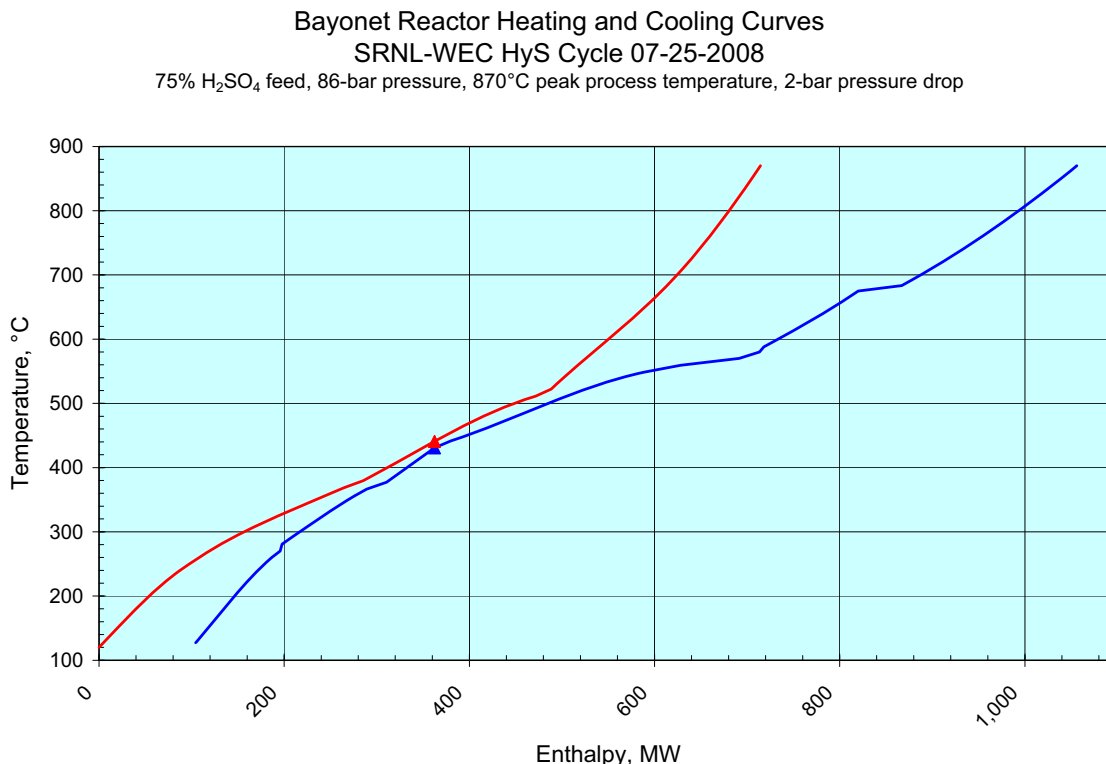


Figure 1-6: Sulfuric Acid Decomposition Bayonet Reactor Process Stream Heating and Cooling Curves

1.2 SULFUR DIOXIDE DEPOLARIZED ELECTROLYSIS TECHNOLOGY

The Hybrid Sulfur process uses a low-temperature, liquid phase electrolysis similar to existing electrolytic processes to generate hydrogen from water. The HyS cycle is attractive because the standard cell potential for SO₂-depolarized electrolysis is -0.158 V at 25°C (298°K) in water. The reversible potential increases to -0.243 V if SO₂ is dissolved to saturation at 1 bar total pressure in a 50-wt% H₂SO₄-H₂O solution, the most likely anolyte. This means that the Sulfur Dioxide Depolarized Electrolyzer (SDE) will consume much less electricity per mole of hydrogen product than water electrolysis, which has a reversible cell potential of -1.229 V at 25°C (298°K)^[Ref. 3]. The energy difference has been supplied as heat for the process of decomposing sulfuric acid.

The catholyte is water and the anolyte is a solution of sulfuric acid, water, and dissolved sulfur dioxide. Sulfur dioxide is oxidized at the anode to produce sulfuric acid and hydronium ions (i.e., protons). The outlet anolyte stream therefore has a higher concentration of sulfuric acid than the inlet anolyte stream. The protons produced at the anode transport as hydronium

ions across the cation-exchange membrane into the catholyte and are reduced at the cathode to produce hydrogen gas. The reactions that constitute this process are as follows:

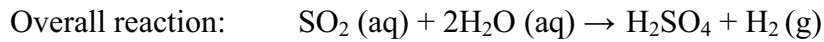
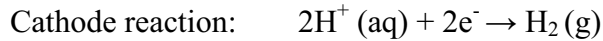
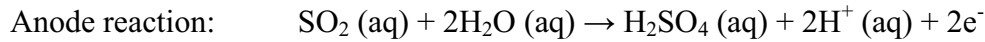


Figure 1-7 depicts a parallel plate single cell electrochemical reactor and the reaction chemistry that occurs at each electrode.

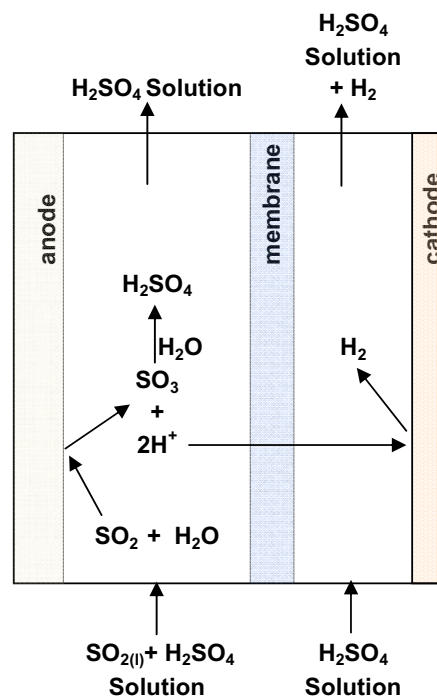
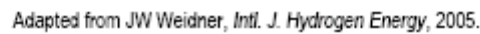


Figure 1-7: Schematic of HyS Electrolysis Reaction

Experimental work is currently being carried out by the Savannah River National Laboratory (SRNL)^[Ref. 4] where they are using a test cell similar to the one shown in Figure 1-8.



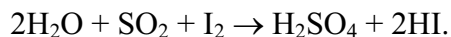
A major challenge for the HyS Process is the development of an efficient, cost-effective electrochemical reactor or SDE. The SRNL is leading efforts supported by the NHI Program to develop such a reactor based on the use of PEM technology. PEM technology is also being developed for water electrolyzers and automotive fuel cells and some of this work may be of use in the development of an SDE. This technology offers high electrochemical efficiency, a small footprint, and the potential of a competitive capital cost.

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1.3 THE BUNSEN REACTION

As described in Section 1, the Sulfur Iodine cycle consists of three coupled chemical reactions: (1) the Bunsen Reaction, (2) Sulfuric Acid Decomposition, and (3) Hydroiodic Acid (HI) Decomposition. The overall process conveniently divides into distinct process sections, as shown in Figure 1-2. The thermodynamic advantage of the Sulfur Iodine cycle is that the energy required to split water can theoretically be supplied entirely as heat rather than as work or electricity as in other water-splitting processes considered here. In reality, as we shall see, this process also requires a considerable input of work.

The Bunsen Reaction may be considered the first step of the cycle, where water, sulfur dioxide, and iodine chemically react to form sulfuric acid and hydrogen iodide as follows:



The sulfuric acid and hydrogen iodide reaction products are then chemically broken down in subsequent decomposition reactions to produce oxygen and hydrogen gas respectively. Other decomposition reaction products, such as sulfur dioxide, water, and iodine, are recycled back from the associated decomposition reactions to the Bunsen Reaction.

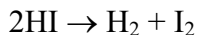
As can be seen in Figure 1-2, the Bunsen reaction is exothermic and the two decomposition reactions are endothermic. Unfortunately, the endothermic reactions require heat at much higher temperatures than could be recovered from the Bunsen Reaction. Therefore, in practical terms, the heat from the Bunsen Reaction is best sent to cooling water and lost.

The Bunsen reaction takes place at the interface between two immiscible liquid phases: (1) an iodine-rich phase, which contains the hydroiodic acid product, and (2) a sulfur dioxide-rich phase, which contains the sulfuric acid product. These phases must be well-mixed in the reactor while the exotherm is being removed and then separated quickly to prevent the formation of elemental sulfur. Separation of light and heavy phases is readily achievable through gravity separation. The ratio of the densities of two phases is on the order of 2:1. A large excess of liquid iodine must be maintained in the system in order to effect good separation between the hydroiodic acid and the sulfuric acid. This has serious implications for process design and economics.

An oxidizing atmosphere is required for the reaction to proceed and product oxygen is usually circulated through the Bunsen reactor to assist in removing sulfur dioxide and to provide this atmosphere. Maintaining adequate concentrations of the reactants in the two liquid phases in the reactor is of prime importance. The phase equilibria, especially of the $\text{HI}/\text{I}_2/\text{H}_2\text{O}$ system, as well as the chemical equilibria, must be well understood to provide an adequate basis for process design. The data currently available is limited and not adequate for a robust process design. Reactor design for equipment larger than bench scale has not progressed further than preliminary concepts.

1.4 HYDROIODIC ACID DECOMPOSITION

Hydroiodic acid decomposition provides the remaining enthalpy required for the water splitting reaction subsequent to sulfuric acid decomposition and the Bunsen Reaction. In this step, elemental hydrogen and iodine are produced by the simple reaction



The reaction is not spontaneous and requires a catalyst. Moreover, the chemical equilibrium is not strongly favorable to the decomposition and product iodine must be removed continuously from the reaction zone in order to keep the hydroiodic acid concentration high enough for the reaction to proceed and to produce reasonable yields. As a result, the reaction must be combined with a separation step. Two strategies have been proposed: (1) extractive distillation with phosphoric acid as a solvent and (2) reactive distillation. Most of the investigative work until now has focused on the former strategy. Difficulties and potential costs presented by the introduction of another very aggressive corrosive chemical, especially in an industrial environment, have caused recent attention to shift towards reactive distillation. Unfortunately, the phase equilibrium data for this system is incomplete and process models based on the available data are not reliable. The feasibility of reactive distillation has yet to be established and equipment design for this step has not begun.

Perhaps the most serious limitation to this technology lies in the disparity between the atomic weights of iodine and hydrogen. Iodine has an atomic weight of approximately 127 while the atomic weight of hydrogen is about 1. That means for every kilogram of hydrogen produced at least 127 kilograms of iodine must be circulated back and forth between the HI decomposition step and the Bunsen reaction. However, the HI decomposition is not complete and a large quantity of elemental iodine is needed for the separation of the acids in the Bunsen step. The iodine circulation rate is therefore much larger than the stoichiometric minimum.

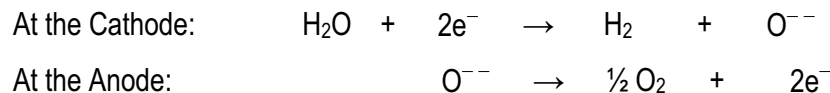
1.5 HIGH TEMPERATURE STEAM ELECTROLYSIS

For large scale hydrogen production, interest in HTSE derives from its prospects for higher overall energy efficiency and reduced electrical energy demand, when compared to conventional water electrolysis. These prospects derive from the following theoretical considerations:

- ***Liquid-to-vapor phase transition using thermal energy, as opposed to electrical energy.*** In conventional electrolysis, electricity provides the energy both to vaporize the water and to split the water into its constituent parts. The relatively low thermal efficiency associated with electricity production increases the total energy requirements. With HTSE, thermal energy (i.e. – process heat) is used to provide the energy for the phase change, thus avoiding electricity production losses for that component of energy.

- **Thermodynamic requirements for heat and work.** In theory, as the temperature of the electrolysis process is increased, the amount of energy that must be input as work (i.e., electricity) decreases.
- **Reduced overvoltage.** In an electrolysis process, the voltage required to drive the process is a direct indicator of electrical energy demand. The principal advantage of HTSE derives from its reduced over-voltage characteristics, relative to low-temperature processes.

In conventional electrolysis, hydrogen and oxygen are generated by passing an electric current through a solution of water and an electrolyte. Hydrogen gas is generated at the cathode and oxygen gas is generated at the anode. The basic reactions that take place at the cathode and anode are shown below.



The transformation of water into hydrogen and oxygen gas is endothermic. Energy must be added to the reaction from the environment. At standard conditions, the amount of energy required to transform one mole of water to one mole of hydrogen gas and one-half mole oxygen gas is 285.83 kJ.

In general, thermodynamic potential of the system may be described by the system's internal energy that is defined using the following equation.

$$\Delta U = \Delta H - p\Delta V = \Delta G + T\Delta S - p\Delta V$$

For a reaction at a given temperature and pressure, ΔH is the enthalpy of reaction, ΔG is the change in free energy, and ΔS is the entropy of reaction. The $p\Delta V$ term is the work associated with the expansion of the gases. Using the above equation, the enthalpy of reaction may be expressed in terms of the change in free energy and entropy:

$$\Delta H = \Delta G + T\Delta S$$

For the electrolysis of water into hydrogen and oxygen, ΔG is work added to the system in the form of electricity while $T\Delta S$ is in the form of heat added by the environment. As temperature of the system increases, ΔH and ΔS of the system do not significantly change. Therefore, as the portion of the work provided through heat increases, the portion provided in the form of electricity will decrease accordingly.

Figure 1-9 illustrates the thermodynamic potentials for the electrolysis of water for a temperature range between 25°C to 1000°C and a system pressure of 1 bar. As can be seen in the figure, there is a significant reduction in the amount of electrical work that needs to be

provided with increasing temperature. At 850°C, this reduction is approximately 25%. Note that the total enthalpy of reaction remains relatively constant with temperature, except at the boiling point, where ΔH drops. This drop, the latent heat of vaporization, is the difference between the high heating value (HHV) and the low heating value (LHV). At higher pressures, there will be an increase in the total energy demand, albeit not significant. At a pressure of 80 bar, it is estimated that there will be an approximate 2% increase in the total energy demand.

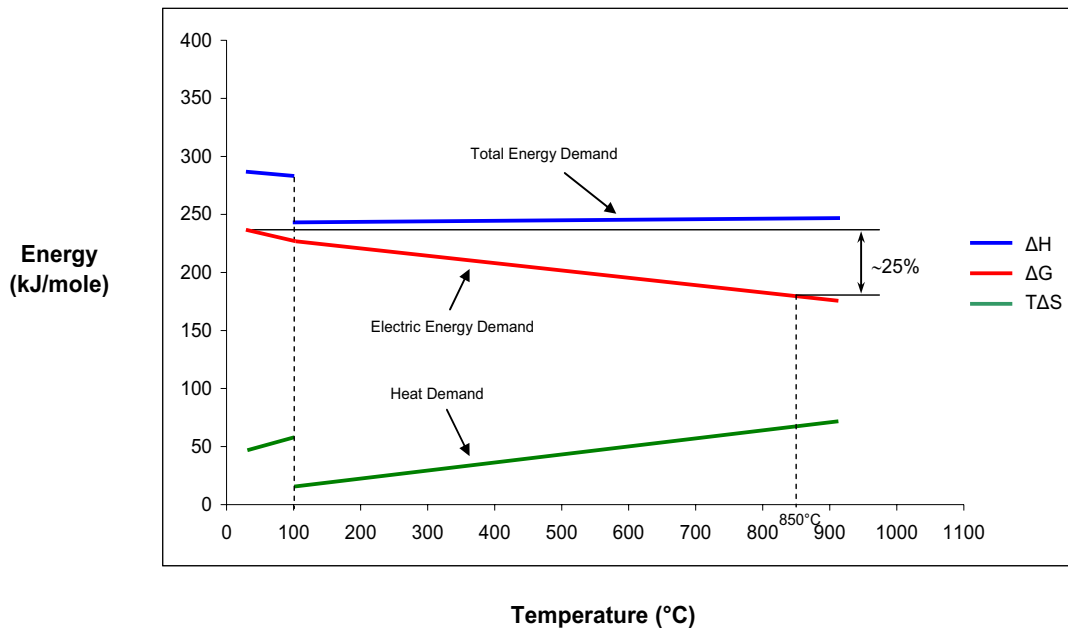


Figure 1-9: Thermodynamic Potential of HTSE

Please note that the Figure 1-9 is illustrative of the thermodynamic potential of HTSE and is for discussion purposes only. The mass and energy balances, electrical consumption estimate, and costs estimates developed for this study are based on the Aspen Plus[®] simulation model for HTSE, which was run at a pressure of 56 bar in the electrolyzers.

An additional advantage is gained with respect to electrolysis cells' electrochemical properties (i.e., overvoltage). Overtoltage is the difference between the cell potential with current flowing and the open cell potential, and is the result of internal resistive losses within the cell. Cell potential (E), or the voltage being applied to a cell, can be described quantitatively by the following expression:

$$E = \frac{\Delta G}{2F} + \frac{RT}{2F} \ln \left[\frac{(N_{H_2} \times N_{O_2^{1/2}})}{N_{H_2O}} \sqrt{\frac{p^\circ}{p}} \right] + IR_{RES} + IR_{PO}$$

The open cell potential is defined by the term $\Delta G/2F$, where F is Faraday's constant and the scalar factor of two corresponding to the number of electrons involved in the reaction per mole of H_2 produced. The second term is a factor to account for non-ideal constituent concentrations and pressure. In this term, R is the universal gas constant, N corresponds to the molar concentrations of the product(s) and reactant(s), as applicable, and p is the pressure at which the reaction takes place. The combination of the first two terms is the actual open cell potential or Nernst potential. The last two terms in the expression correspond to voltage losses due to the resistance of the cell components (e.g., electrodes and electrolyte) and the effect of electric charge polarization between cell electrodes, respectively.

For SOECs, the R_{RES} term is an Arrhenius function of temperature ($e^{\frac{B}{T}}$). The R_{PO} term is a function of current density and an Arrhenius term. Expanding the expression for the cell potential to reflect these functions, considering that A , B , C & D are constants, the equation for cell potential becomes:

$$E = \frac{\Delta G}{2F} + \frac{RT}{2F} \ln \left[\frac{(N_{H_2} \times N_{O_2^{1/2}})}{N_{H_2O}} \sqrt{\frac{p^\circ}{p}} \right] + I A e^{\frac{B}{T}} + I^2 C e^{\frac{D}{T}}$$

The significance of this equation is that the potential decreases with higher pressure and that resistive losses decrease with increasing temperature. Also, by Faraday's Laws there is a direct linear correlation between the applied current and the hydrogen production rate. Electrolysis thermal efficiency therefore decreases monotonically with increasing stack operating voltage at a given temperature, pressure, and cell resistance. In other words, the thermal efficiency is inversely proportional to the stack operating voltage. Thermal efficiency quantifies the heating value of the hydrogen produced per unit of electrical energy consumed.

Moreover, thermal efficiency is inversely proportional to cell resistance and as efficiency decreases ohmic heating of the cell increases and the opportunity for adding heat from a source other than electrical work decreases.

Figure 1-10 shows typical energy budgets for a solid oxide cell operating in either fuel cell or electrolysis cell mode. In the electrolysis mode, the thermal neutral voltage defines the operating point at which the ohmic heating in the cell just matches the reaction heat requirement. The opportunity for adding process heat to the system lies only between the zero current or open cell point and the thermal neutral point. At operating points to the right of the thermal neutral point and to the left of the zero current point, heat must be removed from the cell. As cell resistance increases, the ohmic heating curve gets steeper and the thermal neutral point shifts towards the left.

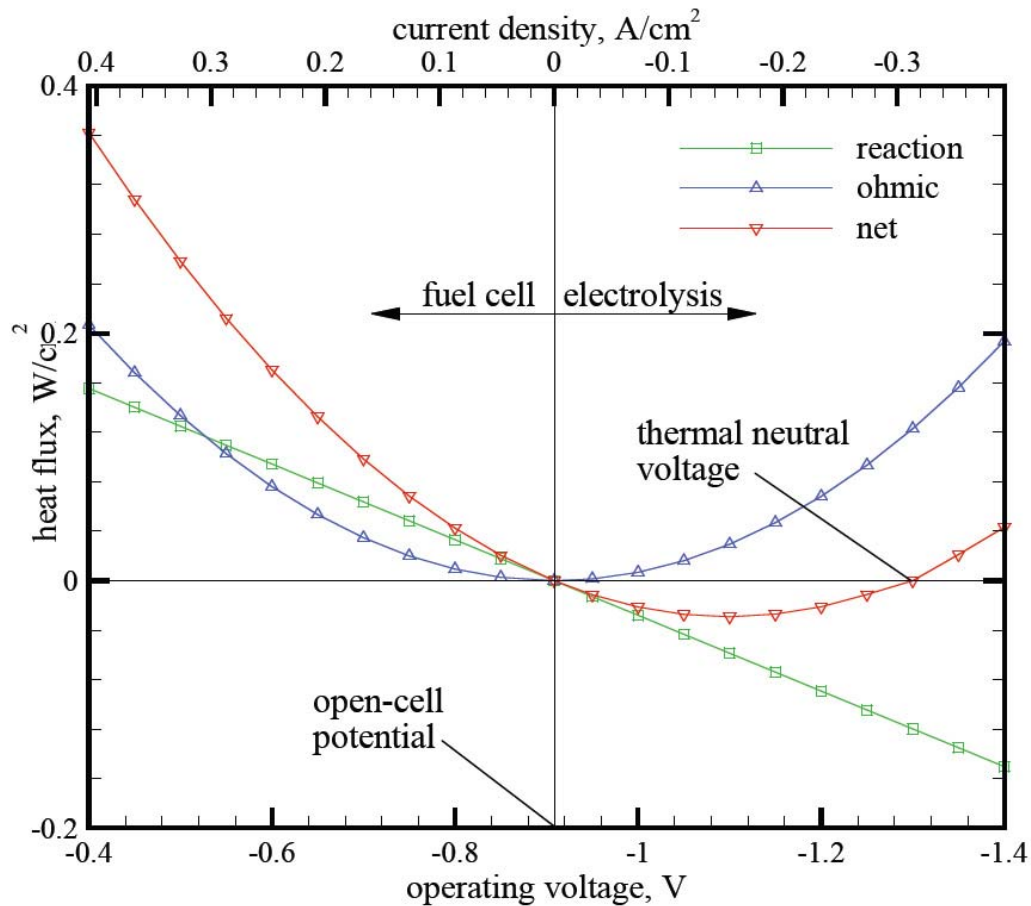


Figure Source: Reference 5.

Figure 1-10: Energy Budgets in Fuel Cell and Electrolysis Modes for Solid Oxide Cells

This highlights the greatest drawback of the HTSE technology as an application for nuclear process heat. The opportunity for the use of process heat per unit of hydrogen produced is strictly limited. At the thermal neutral point, the only use for nuclear process heat is for replenishing thermal losses to the environment due to insulation inefficiency. Attempting to operate to the left of the thermal neutral point, and thus use high temperature nuclear heat more effectively, requires that process heat be added to the cells at the highest temperature point in the system. This is at the entrance to the cells themselves or after all heat has been recuperated from the cell effluent. This poses severe engineering problems to the technology because of the need to distribute very high temperature heat to a large field of cells.

2 PROCESS DEVELOPMENT

If one were to procure a license for a fully-developed process technology, one would expect the licensor to provide – along with permission to practice the technology and guarantees regarding the yield, throughput, and utility usages – a set of basic information that would allow one to build and operate a plant based on that technology. Some of the key items that are typically provided are:

- Basic process chemistry, thermodynamics, and physical properties of process streams.
- Catalyst, if required, including the quantity required, approved manufacturers, expected life, poisons, etc.
- Mass and energy balance for a plant of the required production capacity. This includes the expected yields for the specified catalyst and separation efficiencies of unit operations upstream and downstream of the reactor, expected heat duties, etc.
- Process flow diagrams and a process description that include complete expected steady state process operating conditions, such as temperature, pressure, flow rates, and compositions; and complete list of required equipment including sizes of major equipment. This includes the recommended separation techniques and processing configuration, as well as the major control loops and a workable control strategy.
- Detailed mechanical, fabrication-ready designs of reactors and any special separation equipment if they vary from commonly used equipment such as distillation towers, packed bed or tubular reactors, and the like. Even when the equipment is ordinary process equipment, such critical parameters as the diameter, length, and number of tubes in a tubular reactor or a recommended packing or tray design for a critical distillation step are often specified by the licensor.
- Economic materials of construction for all major equipment and piping.
- Startup, normal shutdown, and emergency shutdown strategies, including recommended instrumentation.
- Recommended special Health, Safety, and Environmental precautions.
- Preliminary piping and instrumentation diagrams that embody much of the information listed above.

When this information can be provided, a process technology may be considered commercial. Each of the water-splitting technologies may be judged with respect to its approach to this goal of commercial status. As can be determined from this report, all of the technologies require extensive process development to reach this goal.

This section discusses some of the issues that have been identified previously and some that have been addressed in the course of this study to move toward this goal.

For each hydrogen production alternative considered in this study, the process data and design development are based on existing work completed under separate contracts for DOE. Specifically, published literature concerning existing research and, as applicable, prototype

development including Aspen Plus® simulation models were provided to the Westinghouse Team. In addition, the Westinghouse Team fostered a continuing dialog during the course of the study with the various scientists associated with the research to ensure that the work of this study captured the most recent technology developments.

Mass and energy balances and process flow diagrams developed for this study are based on these simulations models and other data to the greatest extent possible. However, there are instances where the models included features that either do not necessarily reflect good engineering practices or possibly jeopardize technical feasibility. Table 2-1 summarizes some of the common issues that were encountered and their resolution.

Table 2-1: Common Technology Design Basis Issues and Mitigation Measures

Design Basis Issue	Resolution
Unrealistic or missing pressure drops	Pressure drops incorporated for heat exchangers, estimated piping distances and corresponding friction losses.
No provision for pumping between vessels, where required	Pumps and mixing vessels added, as necessary
No provisions for purifying feed water or other chemicals included in the designs.	Ultrapure water treatment systems added. Chemical purity requirements are unknown and requirements for further purification and processing are not included in the reference designs.
No Provisions for liquid or solid waste treatment.	Final treatment and disposal methods will be dictated by the environmental requirements of the federal, state, and local regulations. At a conceptual level without a selected project site, these requirements cannot be defined. Appropriate baseline wastewater treatment has been assumed for each of the technologies. Disposal of solid, universal, and hazardous wastes have not been addressed
Purity requirements for the product gases are not defined and product purification systems are not included in the design	Product gases are assumed to be required to meet typical standards for industrial gases. Facilities were added to meet this goal.

Mitigation of these items required modification of the original Aspen Plus® simulation models and development of new converging models. The following subsections provide more specific details concerning the process development issues encountered for each of the separate technologies considered.

2.1 HYBRID SULFUR

The Hybrid Sulfur design used in this study is based upon a flowsheet developed by Savannah River National Laboratory for Pebble Bed Modular Reactor (Pty) Ltd. as part of a technology consulting agreement the results of which have not yet been published.^[Ref. 6] The

process flowsheet is modeled in Aspen Plus® and includes both the electrolysis and sulfuric acid decomposition sections. It does not include feedwater and product purification. The Westinghouse Team was involved in the evolution of the process model from its inception. Nevertheless, significant changes were made to that flowsheet during this study. Most of these changes involved simplifications such as consolidation of flash vessels and similar mitigation measures common to all technologies, as indicated in Table 2-1 above. Table 2-2 summarizes the design basis issues encountered with the HyS design and the Westinghouse Team's resolution of these issues.

Table 2-2: Hybrid Sulfur Design Basis Flow Sheet Issues and Mitigation

Design Basis Issue	Resolution
Unrealistic temperature approaches on heat exchangers	All temperature approaches were set at a minimum of 10°K.
Too many flash stages with inadequate vapor flow from some stages	Several flashes were consolidated, but additional consolidation is possible.
No provision for trapping scale and dirt before entering the electrolyzers	A bank of PTFE disposable filters have been added upstream of the electrolyzers.
Unrealistic heat integration scheme	An effort was made to minimize the number of streams used in heat integration, but additional consolidation is probably required for a realistic design.
No provision made for sulfuric acid blowdown. Recovery means for sulfur dioxide in the oxygen product not defined.	Losses were neutralized and replenished using market prices for the chemicals. However, in a real plant provisions would be made to recover sulfur, which is of value. It was judged that the cost of recovery and the cost of neutralization and replenishment would be approximately equal within the accuracy of the study economics. Extensive oxygen purification equipment was added to remove remaining traces of sulfur compounds and water to make this by-product saleable.
Utility steam injected directly into the process via the steam jet ejectors	Special equipment and provisions will have to be made to ensure pure steam if this scheme were to be used in a commercial plant. It was judged that either an alternative means of providing vacuum would be used in a commercial plant or the economic impact would be small in comparison to the precision of the estimate. Consequently, no additional provisions were added to the design.

2.1.1 Process Heat Usage

The Hybrid Sulfur Process uses process heat only for decomposition of sulfuric acid. The remainder of the energy required to split water is provided as work in the form of electrical energy to the electrolysis cells. For given helium supply temperature and reactor return

temperature, the amount of usable process heat is therefore set by the helium temperature exiting the sulfuric acid decomposer or the PCHX. The lower the temperature out of the PCHX, the more process heat is used. On the other hand, effective recuperation of heat is required so as not to use high temperature process heat to perform a task that could be carried out with lower temperature heat. The bayonet reactor designed by Sandia National Laboratory and described in Section 1 uses high temperature process heat very effectively. The thermal analysis shown in that discussion indicates the thermodynamic limits of process heat use. The PCHX effectiveness is set by the process pinch point. In essence, the minimum process temperature at which heat can be used is 500°C. This means that the minimum temperature of helium leaving the sulfuric acid decomposer must be about 520 to 550°C. The remainder of the nuclear heat must be used in processes that use lower temperature heat.

The heat remaining between this temperature and the helium return temperature is best used to raise and superheat steam for electricity generation. The design presented here is able to generate almost 70 kg/s of 125 bar steam at 480°C, as shown in the enthalpy-temperature diagram in Figure 2-1. The temperature of the helium leaving the PCHX sets the maximum temperature of the steam that can be generated.

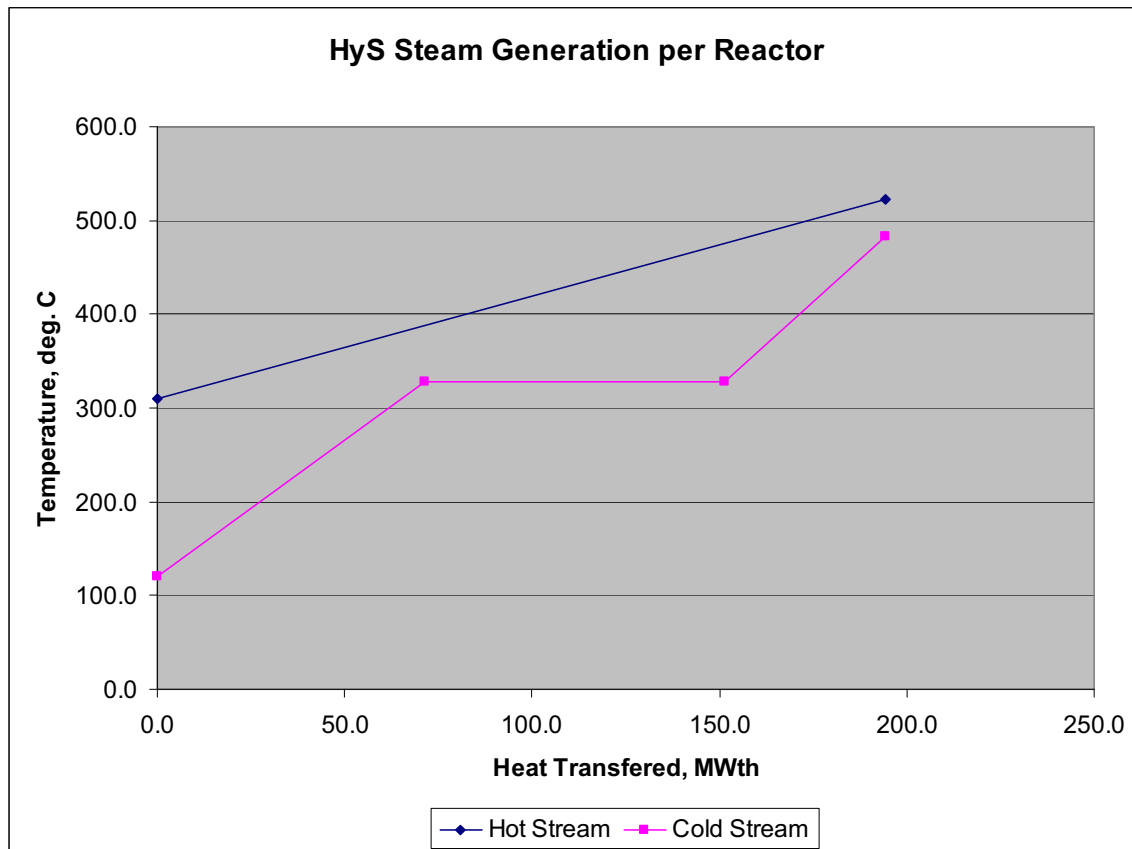


Figure 2-1: Enthalpy–Temperature Diagram for Steam Generation in the HyS Process

2.1.2 Sulfuric Acid Decomposer

Development of a mechanical design for the sulfuric acid decomposer vessel requires attention. The information used in this study is a combination of work on two different decomposer designs. The thermal analysis used in the flowsheet is based upon the bayonet design developed by Sandia National Laboratory. However, there has been little detailed work carried out on the mechanical design and cost of a commercial scale unit based on this concept.

A similar, but distinct design has been developed by the Westinghouse Electric Company. More effort has been expended in developing a mechanical design and cost for this unit, but less detail is available regarding its hydraulic and thermal characteristics. As described in Section 8.6, it was shown in the development of the Westinghouse decomposer cost that the cost of the decomposer will depend to a large degree on the silicon carbide heat transfer elements. Furthermore, the decomposition reaction is considered to be heat transfer limited. Therefore, regardless of differences in mechanical design, all decomposers using silicon carbide tubes should have commensurate costs proportional to the thermal capacity of the unit. For this study, the costs used are taken from the Westinghouse cost analysis, although the thermal analysis used is for the Sandia bayonet design.

2.1.3 Electrolyzer

Table 2-3 is a comparison of the sizing assumptions used in this study for the PEM electrolyzer cells and the corresponding simultaneous conditions achieved in the laboratory.

Table 2-3: Comparison of Sizing Assumptions

	Sizing Assumption	Achieved in the Laboratory
PEM current density	5000 A/m ²	5000 A/m ²
PEM cell voltage	0.6 V	0.75 V (narrow gap cell, 10/08)

The electrolyzer design is based on PEM electrolyzer concepts. Each electrolyzer unit is made up of a stack of 200 cells. Each cell has an active surface area of about one square meter. A unit therefore contains 200 cells and 200 m² of electrode surface area. Each cell is a unit comprised of an anode in an anode compartment, a cathode in a cathode compartment, and a membrane separating the two compartments. There is a sealing system between the anode and cathode compartments that prevents communication between the two, other than through the membrane.

Each cell contains a feed pipe that distributes the feed anolyte across the anode compartment and feed catholyte across the cathode compartment so that they flow uniformly across the face of the anode and cathode, respectively. Figure 2-2 shows a conceptual arrangement for a HyS cell. Both compartments are liquid flooded at all times. Hydrogen generated at the cathode flows with the catholyte and is collected in a cathode channel that exits the unit. The sulfuric acid generated leaves the cell with the anolyte.

Direct current flows between the anode and cathode pairs through the sulfuric acid solution. The electrolyzers may be either a monopolar or bipolar design. Monopolar cell arrangements suffer from the requirement for very large currents and low voltage. Bipolar connections give rise to the possibility of shunt currents developing in the electrolyte causing current by-passing and reduced efficiency. Cell arrangement optimization has not been carried out. The final cell design and current and voltage requirements will depend on the outcome of that optimization.

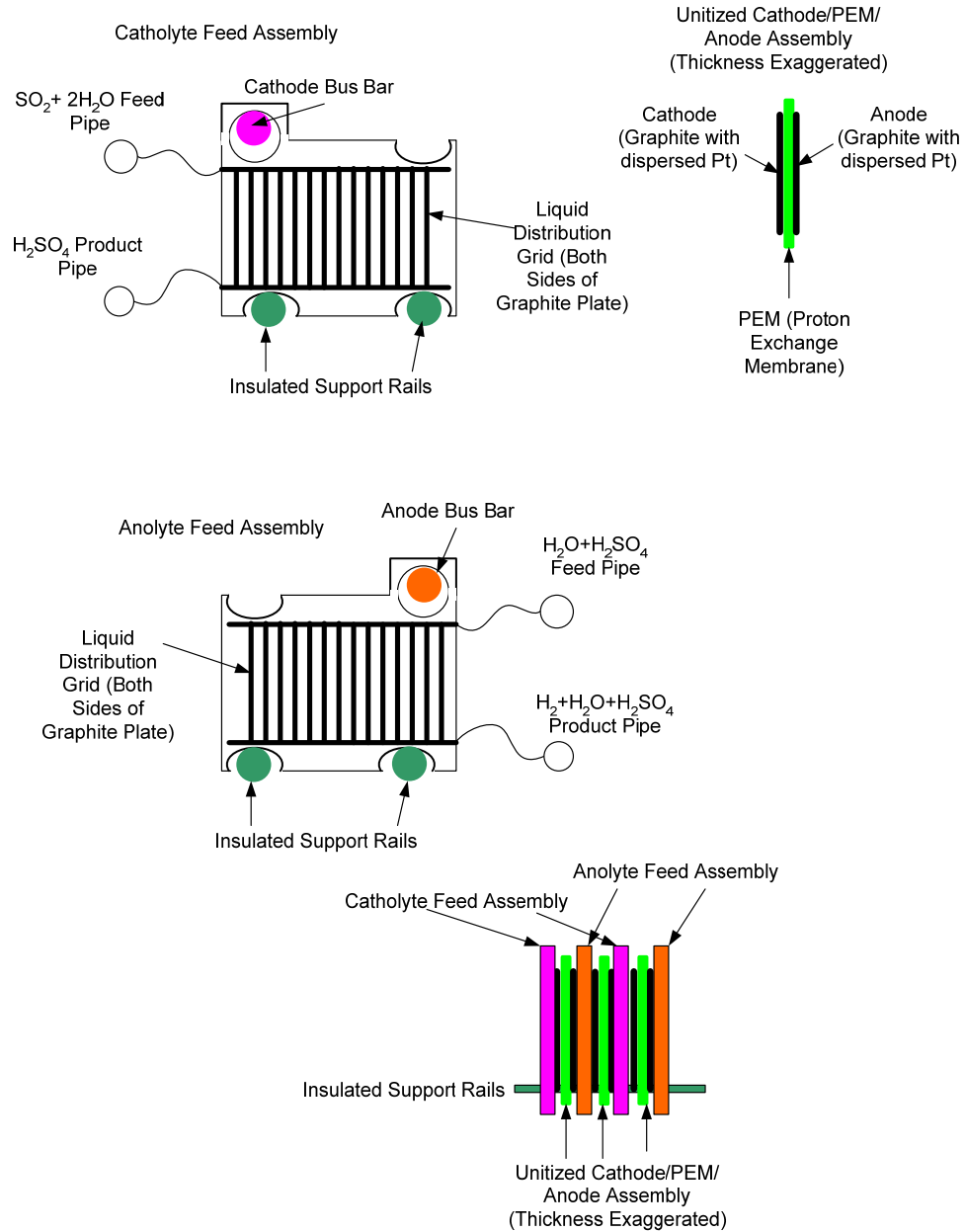
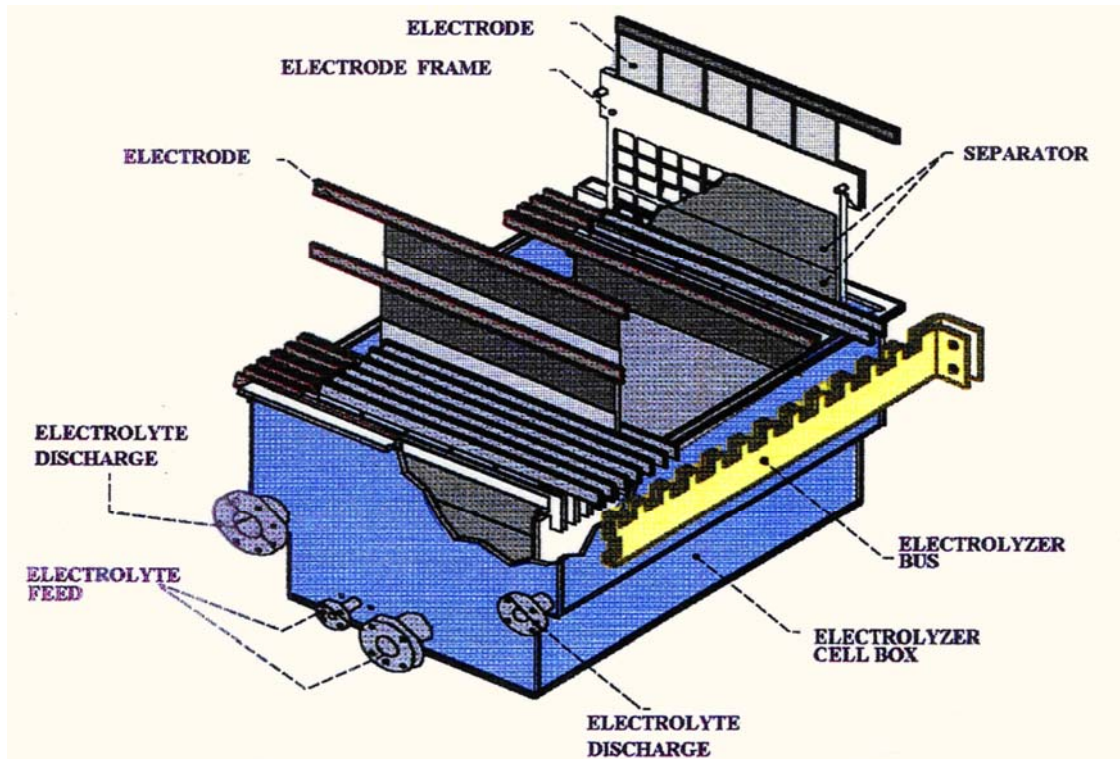


Figure 2-2: Electrolysis Cell Assembly Concept

The cells are contained in a frame or “cell rack,” as shown in Figure 2-3, which connects them electrically. The cell rack supports the individual cells and includes:

- The liquid inlet and distribution piping to the individual cells;
- The effluent liquid and collection piping from the cells;
- The hydrogen header piping collecting the hydrogen from each cell and carrying it to the main collection system, and;
- The bus bars connecting the anodes and cathodes to the direct current power grid.



Reference: www.spartanwatertreatment.com/eodsystems.html

Figure 2-3: Typical Electrolyzer Rack

Although it will operate at an elevated pressure, about 23 bar, it is expected that a stack enclosure will not be required. Industry experts at Giner Electrochemical Systems, LLC believe the seals can be designed to hold the operating pressure.

2.1.4 Materials of Construction

With the exception of the heated tubes in the Sulfuric Acid Decomposer, the conditions in the HyS process are similar to those encountered in a sulfuric acid manufacturing plant. The HyS process operates under higher pressures than in these plants, but adequate materials of construction should be available, albeit costly. Materials of construction for this study were based on handbook information with a corrosion expert selecting the most demanding service.

Information is not readily available for mixtures of sulfur dioxide, oxygen, and sulfuric acid and further investigation is required.

2.2 SULFUR IODINE

The SI process has been in development since the 1970's with continuing research being conducted to improve the technology. To date, the significant portion of continuing research focuses on laboratory studies and bench scale prototype testing at the SI Integrated Laboratory-Scale (ILS) experiment sponsored by an international effort with the NHI Program. The ILS is located at General Atomic's laboratories in San Diego. Recurring iterative development of mass and energy balances also continues using the limited laboratory data available to model the process and improve the cycle's efficiency.

The Sulfur Iodine design presented in this study is based a DOE report ^[Ref. 7] containing an integrated flowsheet for the process. This report was developed for DOE and presents a compilation of information from two other reports: one developed for General Atomics by P.M. Mathias concerning preliminary flowsheets for the SI Cycle; and the second a Master's thesis written by J.E. Murphy on the Sulfur Iodine Cycle.

The process flowsheets included in the report are modeled in Aspen Plus® and are separated into three distinct but integrated sections corresponding to the respective chemical reactions of the SI cycle: Section 1 for the Bunsen Reaction; Section 2 for Sulfuric Acid Decomposition; and Section 3 for Hydroiodic Acid Decomposition. The Section 1 flowsheet incorporates two major modifications from General Atomics original design. These modifications are the elimination of a boost reactor and the addition of scrubbing columns on the oxygen and hydrogen product streams. Section 2 is modeled using a multi-vessel Ozturk-style sulfuric acid decomposition. Section 3 utilizes reactive distillation for the decomposition and separation of HI to H₂ and I₂ and features two heat pumps that heat the distillation column reboiler and feed preheater.

The Westinghouse Team reviewed the above mentioned flow sheets with respect to good engineering practice and technical feasibility. Table 2-4 summarizes several significant issues identified with the flowsheets provided to the Westinghouse Team as the design basis for SI, and the modifications made to the process to mitigate them.

Table 2-4: Sulfur Iodine Design Basis Flow Sheet Issues and Mitigation

Design Basis Issue	Resolution
A Multi-vessel arrangement for Bunsen reaction and 3 phase product separation.	A single multi-stage tower for the Bunsen Reaction and vapor phase separation, featuring an integral bottom liquid reservoir. Separate decant vessels are provided for liquid separation.

Design Basis Issue	Resolution
A significant amount of heat is generated in the Bunsen reaction with no apparent means in the model to remove the heat.	A constant column bottoms recirculation cooling loop added to the Bunsen Reactor requiring the addition of pumps and heat exchangers.
Multi-vessel Ozturk style SAD	Replaced SAD section in its entirety with a bayonet reactor similar to HyS.
Overly complicated heat integration for HAD. Distillation column product vapor and liquid fractions required to be mixed and heat of mixing recovered and used in the process via a heat pump. Practicality of recovering heat of mixing on a large scale due to the volume of liquid stream is anticipated to be problematic.	Simplified heat integration scheme by eliminating the heat pump used to recover heat of mixing. Heat is recovered from the distillation column tops and bottoms via heat exchangers to preheat the column feed streams.
For HAD, reactive distillation column features a high temperature and pressure steam heat pump loop to provide heat to boil the column bottom liquid and condense reflux from the column vapor stream. This loop does not provide entire heat input required to boil the column bottom liquid. The remaining heat duty will therefore need to be provided by the NHSS and the secondary helium loop. This heat supply was not shown on the original flow sheets.	Helium loop process coupling heat exchanger reboiler added. Helium reboiler provides the balance of heat not provided by the distillation column's heat pump.
Engineering practicality of the reactive distillation column heat pump is questionable and may not be viable. Inlet and outlet temperature for the heat pump compressor, 256°C and 342°C respectively, as well as the 78 bar operating pressure, are higher than typical applications.	Heat pump retained in the design. This will undoubtedly consist of custom engineered equipment. Inclusion of the heat pump will be a continuing engineering challenge if retained in the design.

The above noted modifications were made to the original design basis Aspen Plus® simulation models provided to the Westinghouse Team. Flow sheets and mass and energy balances for the converged simulations, as well as PFDs developed for the modified SI cycle by the Westinghouse Team may be found in Section 8 of this report.

2.2.1 Process Heat Usage

Unlike the HyS Process, the process heat usage in the SI process is not constrained by the thermodynamic pinch point in the Sulfuric Acid Decomposer. This is because the thermal requirement of the HI decomposition step is high enough that when proportioned to the sulfuric acid decomposition load, the pinch point with the helium heat transfer medium is increased and this does not become a restriction except in unusual circumstances. All the reactor heat can therefore be used as process heat and no steam need be generated because of process heat usage limitations.

2.2.2 Process Integration and Quantity of Iodine

The SI ILS is configured as a skid-mounted system with a dedicated skid representing each of the three process sections. These skids have been run independently with simulated process integration between skids, meaning that products and effluents from skids are stored and then run through the next section or skid at a later time. Normally, one would expect some surge capacity to be built into a commercial-scale plant between units such as these to aid in dampening any process upsets. The quantity of iodine circulating between the Bunsen Reaction section and the HI Decomposition section is so large, however, that any appreciable hold up time for this stream is impractical. The ILS sections have not been operated as a fully integrated continuous system and further development is required. Therefore, a complete integrated scalable design is not considered available at this time.

At the SI ILS, the amount of iodine being used in the Bunsen reactor is 88% in excess of the amount being reacted. This results in a large recycle flow and iodine inventory. On a laboratory or bench scale application, the excess mass of iodine required may be manageable. A commercial scale version of the SI technology will require a massive stream of iodine to be circulating through the Bunsen and HI decomposition sections. Based on the design developed for this study, the total mass of iodine required for the process to meet the target hydrogen production rate is estimated to be approximately 7.3 million kilograms, or 30% of the annual global iodine production. The circulation rate for a single train is in excess of 3 tonnes per second. This corresponds to a liquid flow rate to the Bunsen Reaction of $0.96 \text{ m}^3/\text{sec}$ (i.e., ~15,300 gallons per minute). There are distinct design implications to utilizing this large mass of iodine in the process. These include:

- Significantly larger vessel capacities and pipe sizes;
- Increased pump capacities and operating costs, and
- Significantly higher heat recuperation requirements.

In addition, identifying and securing a large source of iodine meeting required purity requirements may be problematic. High purity iodine may be readily obtainable in small quantities required for laboratory and bench scale applications, but sufficiently pure iodine may not be available in the large quantities required for this technology. Design and construction of purification facilities may be necessary. Iodine purity requirements have not been established, but are expected to be stringent.

2.2.3 Design of Reactors and Associated Equipment

Development of designs for the Bunsen reactor and HI Decomposition reactor is ongoing and the configuration and mechanics of these vessels are currently preconceptual. Designs that have been proposed for the Bunsen reactor by the researchers are judged to be impractical to construct or to maintain. For this study, reactor configurations and vessels are based on proven technologies that are currently used in similar large scale applications. Specifically these are:

- For Section 100, the Bunsen reactor, a multi-stage tower with integral CSTR reactor;

- For Section 300, the Hydrogen Iodide Decomposition reaction, a multi-stage reactive distillation column.

Residence time in the Bunsen Reactor and liquid decanters is a concern. Laboratory experience has shown that there is significant sulfur formation with long residence times (i.e., greater than 16 hours). Sulfur appears to be fairly soluble in hydrogen iodide. The upper limit on reactor residence time is not yet known. Thirty (30) minutes to 4 hours may be acceptable. However, further research is required to document and establish a proper design requirement. For this study, residence times in vessels have been minimized to reduce the potential for sulfur formation.

One of the implications of the total mass of iodine required for the process is that there is an unusually high number of large, high pressure vessels such as decanters, reactive distillation columns, reboilers, condensers, and heat pumps. Fabrication and shipping restrictions limit shop-fabricated heavy-wall vessel sizes to about 5.5 m (18 ft) in diameter and approximately 15 m (50 ft) in length for drums and other mixing vessels. Tower and column diameters are also limited to 5.5 m as well. Larger vessels can be shop-fabricated and erected in locations that can be reached easily by water or field fabricated. Field fabrication of heavy-wall vessels would require stress relieving at a construction site, which is very difficult and costly. The Westinghouse Team chose to limit the vessel dimensions rather than attempt to estimate costs for field fabricated vessels. Therefore for a single production train there will be six (6) Reactive Distillation Columns (TO-04 A through F). Each column will have an associated heat pump loop (HP-C A through F) with:

- A condenser integral to the column (HP-QC A through F);
- An associated Steam drum (KO-301 A through F), and;
- Reboiler (HP-QH A through F).

In addition, each column will have a dedicated Helium Process Coupling Heat Exchanger (EX-06 A through F).

The reactive distillation column condenser selected for this design is an integral tube bundle located within the column shell. This design was selected to avoid the cost of multiple heavy-wall vessel heads and tubesheets in separate condenser shells. Condensate from the column reboiler flows to the steam drum. Boiler water circulates through the condenser tube bundle either by thermosyphon action or by pump, if necessary. Steam generated in the condenser coils is separated from boiler water in the steam drum and then flows to the suction of the heat pump compressor. This compressor conveys the steam to the column reboiler.

There are significant additional electrical loads associated with the SI process due to iodine circulation and heat pump operation. These loads are estimated to be:

- For the Bunsen Reaction (e.g., pumping) ~35.6 MW, and;
- For Hydrogen Iodide Decomposition (e.g., heat pump compressor) ~193.6 MW.

2.2.4 Materials of Construction

Previous studies for the SI cycle that considered such issues identified carbon steel or Teflon® lined carbon steel as the material of construction for most piping and vessels. These materials may be used in certain areas of the process where temperature and pressure requirements allow. However, they will not be suitable in many services. Teflon® lining, for example, is not recommended for heat transfer applications due to its insulating nature. Moreover, for some high temperature applications a more heat-resistant fluoropolymer is required. Some of these exotic polymers are very costly.

Several portions of the SI process require materials that must have corrosion resistance in very demanding and unusual services and perform at temperatures as high as 340°C and at pressures as high as 40 bar. The SI ILS experiment at General Atomic is currently using tantalum cladding for several of these applications. For the purposes of this study, it is assumed that tantalum cladding for vessels and tantalum tubes for heat exchangers are the sole material choice for these high temperature corrosive applications. The combination of the large size and number of vessels and heat exchangers, as well as the cost of the tantalum cladding and tubing, results in a very high capital cost. The estimate carried out in conjunction with this study indicates that the cost of these materials on a large scale is prohibitive and clearly affects the economic feasibility of this technology. For this technology, it is recommended that a materials of construction development program be implemented. Stainless steel is deemed appropriate for other non-corrosive high temperature applications in the process to prevent contamination of process fluids due to ordinary corrosion.

2.3 HIGH TEMPERATURE STEAM ELECTROLYSIS

The HTSE design presented in this study is based on a report provided by INL^[Ref. 8], which contains an optimized flow sheet developed by INL for a reference commercial scale hydrogen production facility. The reference plant design assumed a high temperature helium cooled reactor coupled to a direct Brayton power cycle. The reference design reactor power is 600 MW_{th} and the electrolysis unit consists of over 4 million cells. The intent of the report is to establish an optimized design for the reference nuclear-driven HTSE hydrogen production plant so that parameters can be compared with other hydrogen production methods and power cycles, as well as to evaluate relative performance characteristics and plant economics.

The Westinghouse Team used the Aspen Plus® simulation model, information contained in the report, and information gathered during meeting and correspondences with the report authors' to further develop the simulation models and develop a viable commercial scale process design. During the process development, the Westinghouse Team identified and modified aspects of the INL reference design. These aspects are described in Table 2-5.

Table 2-5: HTSE Design Basis Flow Sheet Issues and Mitigation

Design Basis Issue	Resolution
Sweep gas purity requirements are not defined and sweep gas purification systems not included in the design.	State-of-the-art Clean Dry Air (CDA) system added to the design to remove contaminants and provide dry air (sweep gas). CDA system requires a low pressure inlet compressor in addition to the high pressure Sweep Gas Compressor after the CDA system.
No provisions in the design to remove dissolved gases from the influent process feed water.	Deaerator added to remove dissolved gases. Inclusion of the deaerator necessitated a source of steam, thereby requiring further modifications to the heat integration.
Single Recuperator used to both condense and boil not viable for large scale application.	Significant modification to heat integration scheme. Parallel heat exchanger trains added that utilize the electrolyzer effluent hot hydrogen and sweep gas streams to preheat the inlet feed water and sweep gas prior to the respective PCHXs. Each train consists of a preheater, common thermosiphon boiler, and superheater.
Single process coupling heat exchanger is shown for both the cathode feed stream (i.e., water and hydrogen) and the anode feed stream (i.e., sweep gas). Shaw deemed that a single heat exchanger for this application is not viable.	Separate process coupling heat exchangers for cathode feed (water and hydrogen) and anode feed streams (Air)
A separate heat exchanger system is shown to add process heat directly into the electrolyzer modules in order to provide the required heat of reaction. A concept is not proposed for a cell module configuration and required distribution system to each individual cell in order to provide the required heat. Shaw deemed this approach to be problematic and not viable.	In lieu of adding heat directly to the cells, inlet feed stream temperatures maximized using the heat available with the PCHXs. The remaining heat is assumed to be generated by increasing the electrical energy to the cells via ohmic heating.

The above noted modifications were made to the original design basis Aspen Plus® simulation models provided to the Westinghouse Team. Flow sheets and mass and energy balances for the converged simulations, as well as PFDs developed by the Westinghouse Team may be found in Section 8 of this report.

2.3.1 Process Heat Usage

The process heat requirement for this technology is proportionally very low in comparison to the other water splitting technologies. At a fixed current density and plant capacity, the opportunity for use of process heat is reduced as the operating temperature decreases due to the increase in cell resistance and ohmic heating in the cells. Operating at the thermal neutral point by definition requires no process heat except that which is needed to account for thermal insulation losses and the inability to fully recuperate heat due to Second Law considerations. Even under the best of circumstances – operating at a voltage below the thermal

neutral point and introducing steam and sweep gas at a temperature above the cell operating temperature as was assumed for this study – the process heat requirement is low. To match the hydrogen production rate of the base case HyS plant, 142 MMSCFD, only 88 MW_{th} is required. The electrical requirement is 479 MW_e. This means that for a reasonably sized hydrogen plant, most of the thermal output of the HTGR will be used to generate electrical energy. If all of the heat from a 550 MW_{th} HTGR were used for process heat under the above operating conditions, the plant would have to be 12 ½ times the size of a HyS plant powered by a single reactor. Moreover, 3000 MW_e would have to be imported. For this reason, most of the heat from the HTGR in the base case for this technology is used to raise and superheat steam for electricity generation as shown in Figure 2-4 below.

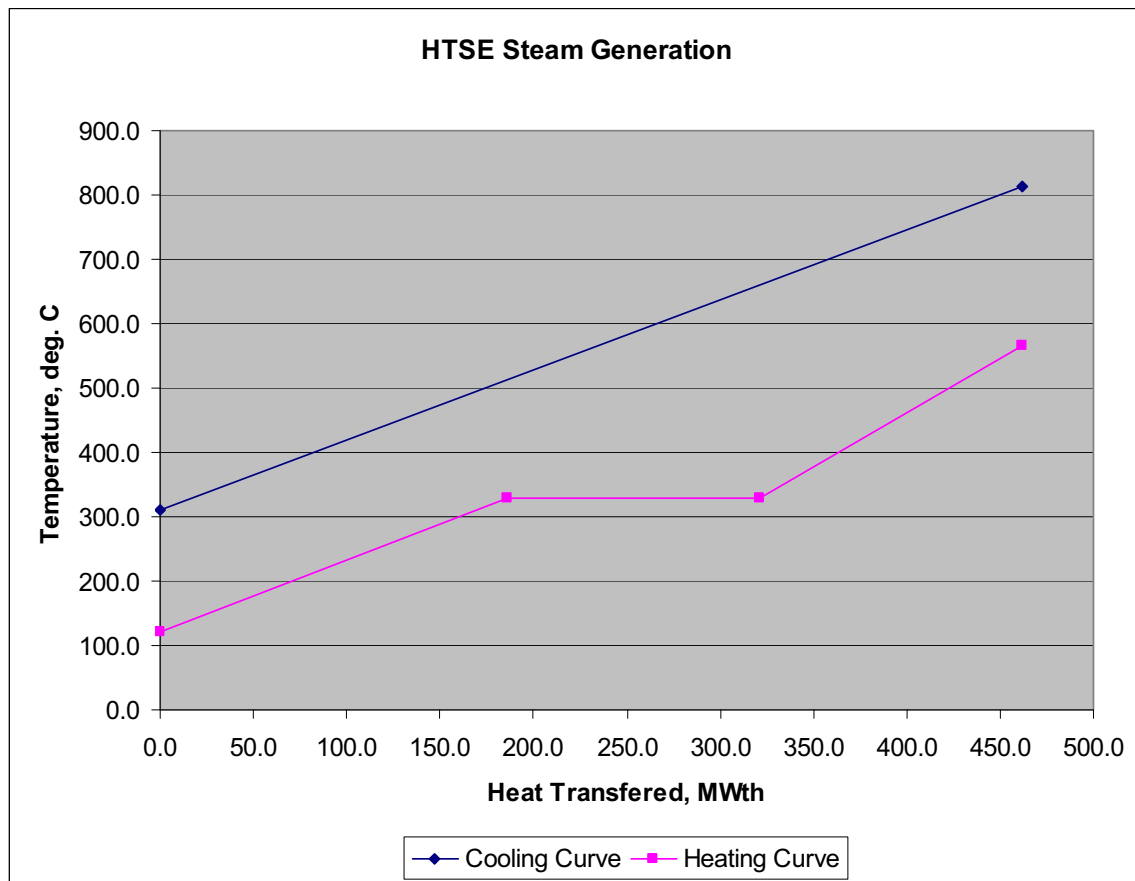


Figure 2-4: Enthalpy–Temperature Diagram for Steam Generation in the HTSE Process

2.3.2 Electrolyzer and Enclosure Design

The following is a comparison of the sizing assumptions used in this study for the PEM electrolyzer cells and the corresponding simultaneous conditions achieved in the laboratory.

Table 2-6: Comparison of Sizing Assumptions

	Sizing Assumption	Achieved in the Laboratory
SOEC current density	2500 A/m ²	2800 A/m ² (after 1000 hours, with continuing degradation, 9/06)
SOEC cell voltage	1.26V	1.3V

The cross section of a solid-oxide electrolysis cell is shown in Figure 2-5 below.

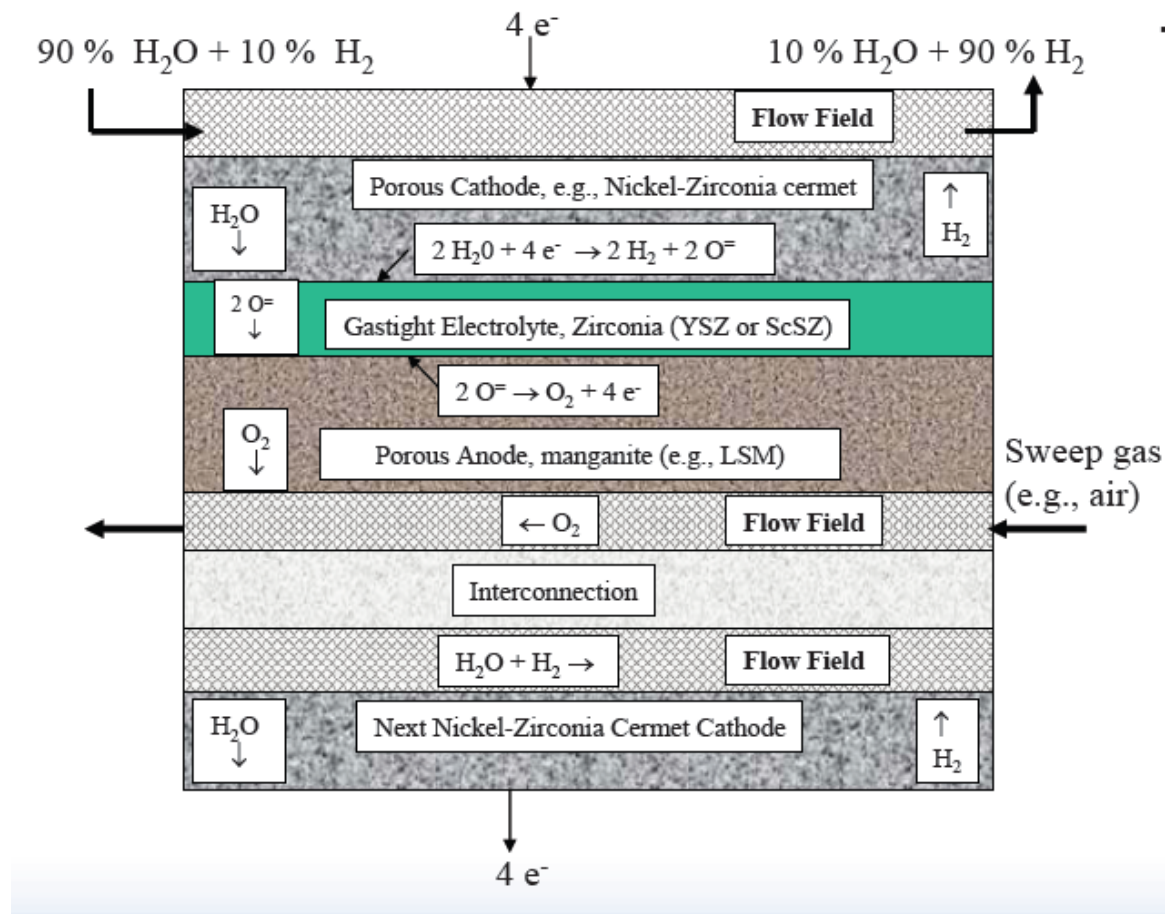


Figure Source: 2006 DOE Hydrogen Fuel Cells & Infrastructure Technologies Program Review [Ref. 9]

Figure 2-5: Planar Solid-Oxide Electrolysis Cell

Regarding the number and configuration of the electrolysis cells, work to date on a design for a large scale commercial application, such as the one being considered in this study,

has been conceptual at best. Therefore, as part of this study, the Shaw Team developed a conceptual electrolyzer module and cell arrangement and modeled the sweep gas and feed steam distribution within the electrolyzer modules. The concepts shown here are presumed to be viable based on the modeling conducted. However, more intensive study of the electrolyzer and electrolysis cell configuration is required.

As envisioned, the cells are assembled into 76 modules, including eight in-place spare modules. The inlet hydrogen/steam feed and the sweep gas streams must be distributed evenly amongst all the modules. Each module contains 4 stacks of 2500 cells each. Each cell is 50 cm by 50 cm in area for a total of 2500 m² of cell area per module. The above mentioned cell size is considerably larger than those currently under development. However, the 50 cm by 50 cm size was chosen because it is deemed that any cell size smaller than this will not be technically feasible in a large centralized installation. Figure 2-6 depicts a plan view of the module configuration, while Figure 2-7 is an elevation cross-section of a module.

The approximate dimensions of an electrolyzer module are 2.2 m in diameter by 7.3 m long.

Based on the target production rate, the total electricity demand of the electrolysis cells is estimated to be approximately 479 MW_e for a hydrogen production rate of 142 MMSCFD. Given a 550 MW_{th} nuclear reactor and a Rankine cycle, it is estimated that approximately 204 MW_e of electricity will be purchased in order to meet the required electricity demand of the electrolyzer.

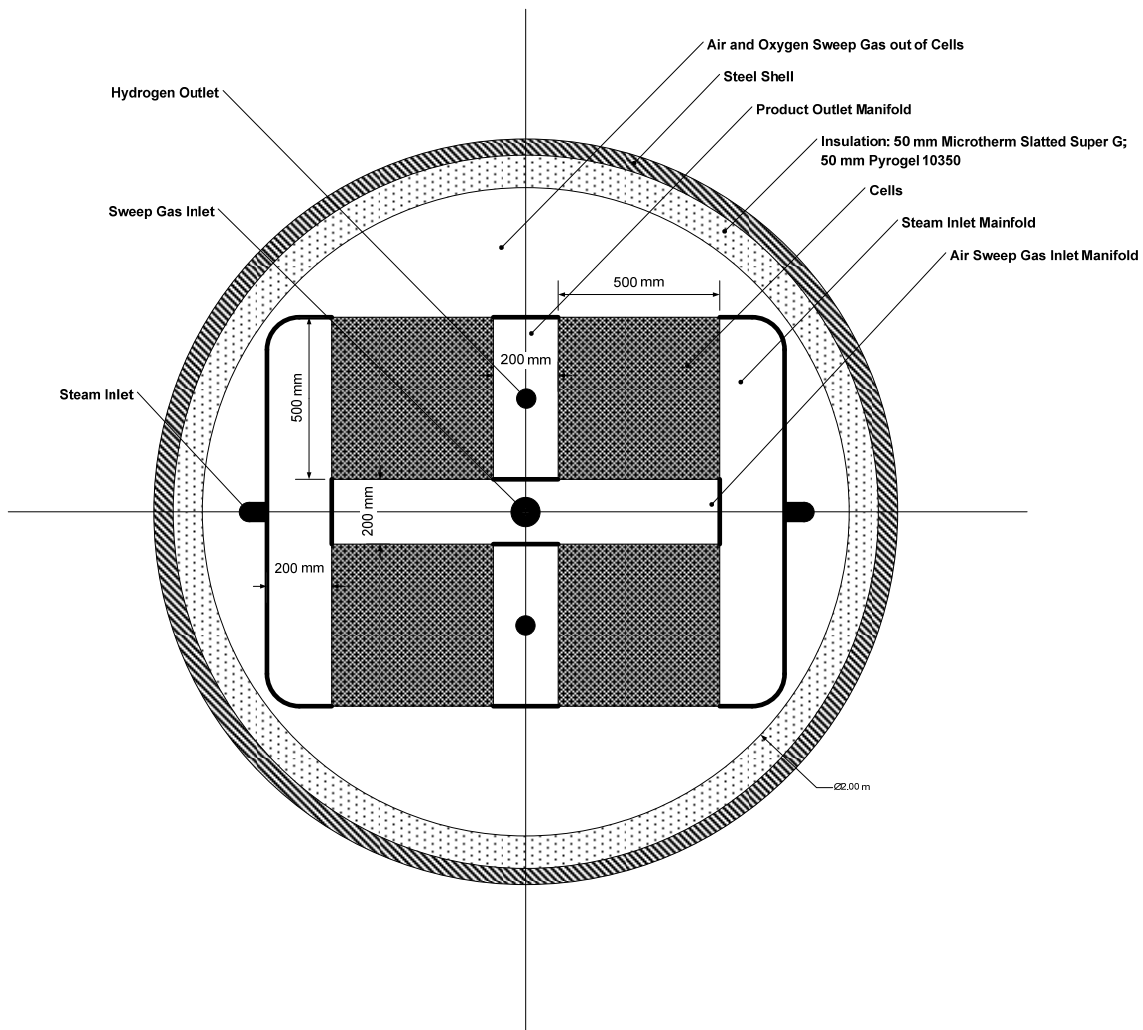


Figure 2-6: Plan View of Electrolysis Module

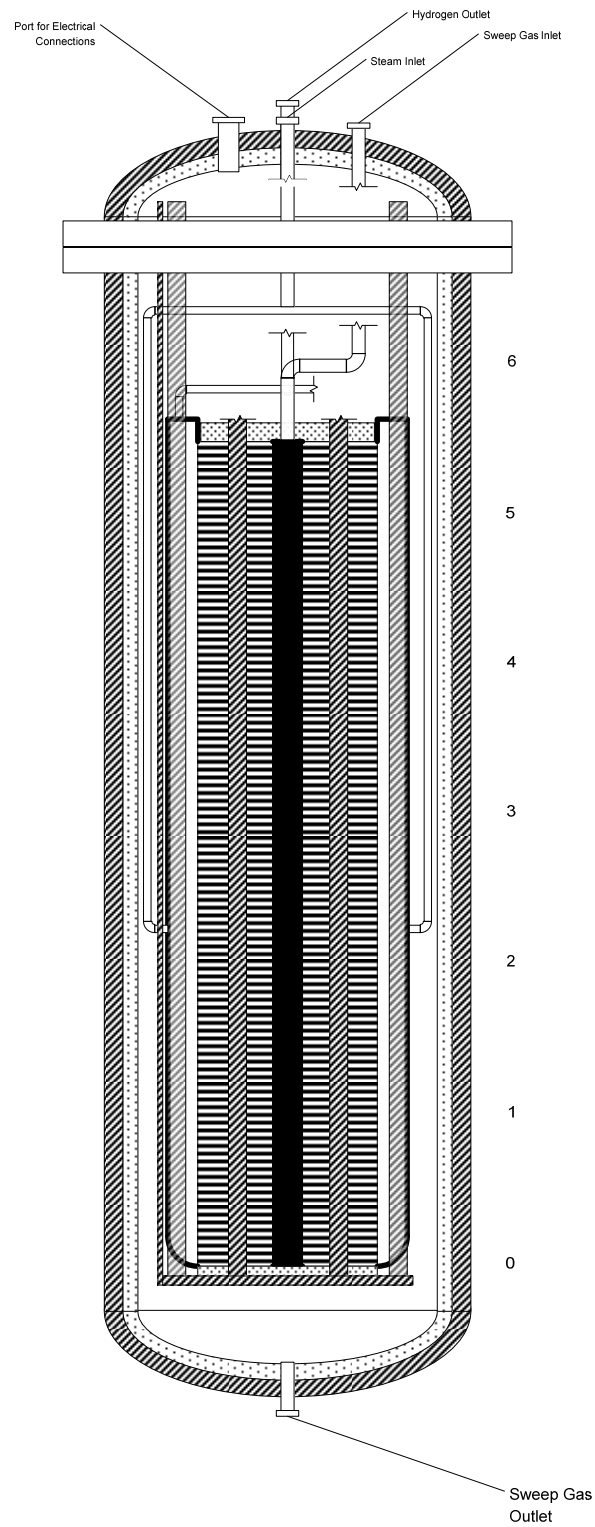


Figure 2-7: Cross Section of Electrolysis Module

Sweep gas enters the center manifold of each module and exits from the cells directly into the vessel enclosure where it is collected and sent on to heat recovery. This arrangement avoids the presence of moisture in the vessel enclosure and the possibility of condensation in the internal insulation. The steam/hydrogen feed enters in the end manifolds and exits from a center manifold. All connections to the cell stack, both fluid and electrical with the exception for the sweep gas exit, are made through the removable vessel head. This allows the enclosure vessel and piping to remain in place while the electrolyzer module can be lifted out for replacement or repairs. Use of internal insulation makes it possible to use carbon steel as a material of construction for this service. This is economically important due to the large number of vessels required.

Pressurized operation of the modules was selected to avoid the large cost of compressing product hydrogen generated at a low pressure. This enclosed pressurized design, however, raises several difficult module design problems:

- The mechanism for adjustment of pressure on the stack to ensure good sealing is inaccessible;
- Tension bars used to provide sealing pressure are located within the thermal boundary and are subject to thermal expansion;
- Hydrogen can leak into the enriched air sweep gas-filled enclosure;
- High pressure gas in the enclosure renders the thermal qualities of the vessel internal insulation largely ineffective;
- Large cables with high current loads must penetrate the pressure boundary, and;
- Electrical connections must be made to the stack in a very high temperature, enriched air environment.

Regarding the module thermal insulation, the insulating properties of any internal insulation will be an order of magnitude lower than expected due to the high operating pressure. The operating temperature and pressure of the electrolyzer modules is 870°C and 56 bar, respectively. Up to about 40 bar, the thermal conductivity of gases are affected only very slightly by pressure. As pressures rise above this level, however, the thermal conductivity increases very rapidly. The thermal conductivity of the insulation is entirely dependent upon the conductivity of the gas in the insulation. For internal insulation, this will be air and oxygen. For air and oxygen above 40 bar, the dependence of thermal conductivity on pressure changes dramatically and becomes quite strong. Although the effect on the Prandtl number is negligible, the effect on conductivity, and therefore presumably also on viscosity, is large. For gas trapped in the insulation, conductivity and not Prandtl number is important: heat transmission is mostly by conduction, not convection. The net effect is that the insulation becomes largely ineffective.

These disadvantages may outweigh the advantages of this design. Considerably more design work is required before an adequate cell enclosure design is achieved

2.3.3 Piping and Thermal Expansion

One troubling design issue facing this technology is the distribution of very high temperature gas from a central location, the steam and sweep gas PCHXs, to a multitude of electrolyzer vessels. The problem can be appreciated by examining the equipment layout of this technology included in Section 8.3.4. Long runs of high pressure, high temperature thick-wall piping made of an alloy such as 800H must be used to distribute hot gases to the electrolyzer enclosures. The thermal expansion of this pipe will be on the order of 1½ per cent. The material and heavy wall thickness render this pipe less flexible than would otherwise be the case. It has not yet been determined whether a workable piping design can be achieved. Until now piping at these temperatures has been limited to short runs at low pressures and even these piping designs are difficult.

The fundamental question is whether the difficulty and cost of solving these design problems is justified by the limited utility of process heat to this technology. Effective recuperators have been designed that can be easily integrated with the cell stacks. These can only be used when cell heating is provided electrically, by ohmic losses or otherwise. Process heat in excess of that recuperated must be introduced between the cell stacks and the recuperator. This introduces a myriad of issues that can be avoided by a small amount of electrical heating.

2.3.4 Materials of Construction

Materials experience with high temperature steam and hydrogen streams is well established, and will require alloy 800H. There is, however, only limited experience with material requirements for oxygen streams under high temperature and pressure (i.e., the outlet sweep gas). Further material testing and validation will be required for materials to be used in the high-oxygen sweep gas streams. Sweep gas piping and valves must be oxygen cleaned prior to service. Electrolysis cell design, constituent materials, and sealant materials, will need to be selected, or perhaps developed, for the process design temperature. These material requirements will need to be explored further during the course of the conceptual design.

3 SUMMARY PROCESS DESCRIPTIONS

3.1 HYBRID SULFUR

As noted previously in Section 2, the design basis for the HyS cycle consists of one flow sheet and its associated mass and energy balance. Study modifications expanded the number of major process sections to four. These sections are:

- Section 100 Feed and Utility Systems (FUS)
- Section 200 Sulfuric Acid Decomposition (SAD)
- Section 300 Electrolysis (ELE)
- Section 400 Product Purification System (PPU)

For Sections 200 and 300, stream and equipment identifiers have been kept consistent with the corresponding identifiers in the Aspen Plus® simulation model. Sections 100 and 400 include systems that produce the assumed feed water and product purity requirements, respectively. A brief process description for each section is provided below.

The simulation diagram, mass and energy balance, as well as PFDs for the HyS design used in this study may be found in the Section 8. Capacities described in the following discussion are for one production train, with two production trains required to meet the target hydrogen production rate. The hydrogen production capacity for one train is approximately 71 MMCFD.

3.1.1 Feed and Utility Systems

Due to the high degree of internal recycle in the HyS process, impurities contained within the feed water will remain within the process. The result of the concentration of these impurities in the process would cause negative consequences, at a minimum, in the Sulfuric Acid Decomposer (RX-01 A&B). Therefore, it is assumed that the feed water quality must be of the highest purity and that a state-of-the-art water treatment system will be required. At the time of this study, feed water purity requirements for the HyS cycle are not known. Therefore, this design assumes that the water quality requirements are ultrapure water.

The design of a water treatment system depends on the source water quality and its analysis. This study assumes that the water source is well water with a minimum hardness of 200 ppm as CaCO₃. The pretreatment system includes a multi-media filtration and softener system to remove suspended solids and hardness, respectively. The pretreatment system is followed by a demineralizer system consisting of a reverse osmosis and electro-deionization (EDI) system. All water treatment systems are considered packaged systems and are therefore shown as ‘black boxes’ on the PFDs. For the HyS cycle, the water treatment system capacity is estimated to be 130 m³/hr. Purified water storage for 48 hours of process water demand and feed water pumps to convey this water are provided.

The FUS also includes a wastewater treatment system to treat water treatment wastes and process wastes. The system is estimated to need to treat approximately 60 m³/hr of wastewater. The type of treatment required will depend on the effluent discharge limits imposed by the permitting jurisdiction. For this study, it is anticipated that the wastewater treatment system will consist of an oil/water separation system, final neutralization system, physical/chemical treatment system with mixing tank, and ancillary pumps, instrumentation, and equipment. The wastewater treatment system is also treated as a vendor supplied system or ‘black box’ on the PFDs.

The final components of the FUS consist of sulfuric acid and caustic bulk storage and transfers systems. The sulfuric acid system provides makeup to Sulfuric Acid Decomposition. Caustic is required to remove residual sulfur dioxide from the product oxygen in the PPU caustic scrubber. Both sulfuric acid and caustic are delivered as a 50 mass per cent liquid solution. Sulfuric acid is delivered to the Bunsen Reactor as is and caustic is diluted to a 10% by weight solution before being pumped to the scrubber.

3.1.2 Sulfur Dioxide Depolarized Electrolysis

Make up purified water feed is fed to the Catholyte Surge Drum (KO-15). After being filtered to remove any solid debris or products of corrosion, it is circulated through the cathode of the Electrolyzers (EL-01A:A-BB/ B:A-BB/ C:A-BB/ D:A-BB). There are four trains of electrolyzers each containing 54 units. Each unit consists of 200 PEM cells. Water is consumed in the electrolyzers forming hydrogen gas and oxygen ions. The ions pass through the cell membrane and react with dissolved sulfur dioxide to form sulfur trioxide ions, as described in Section 2. Catholyte and hydrogen gas leave the top of the electrolyzer units and are separated in the Wet Hydrogen Knockout Drum (KO-01A/B/C/D). Catholyte is returned to the Catholyte Surge Drum after being cooled by the Vacuum Column feed.

Anolyte consisting of 15.5 mass per cent sulfur dioxide dissolved in 43.5 mass per cent sulfuric acid is pumped to the electrolyzer units from the Anolyte Prep Tank (TK-01). After being cooled by the Vacuum Column feed, most of the anolyte is circulated back to the Anolyte Prep Tank. Approximately 20% of the anolyte is further cooled with cooling water and sent to the Sulfuric Acid Decomposition section. About 40% of the sulfur dioxide in the anolyte is converted to sulfuric acid.

3.1.3 HyS Sulfuric Acid Decomposition

Sulfuric acid feed at about 50% concentration by weight is sent from the ELE section to the SAD section to be decomposed into sulfur dioxide, water, and oxygen. Before being pumped to the decomposer, the acid is concentrated to 75% by weight to maximize the efficiency of the decomposition step. Because the per-pass conversion is only about 50%, a substantial amount of sulfuric acid is recycled. Process heat is recuperated by recovering heat from several flashed vapor and other streams to preheat Vacuum Column feed.

Acid feed to the section is flashed in two stages: the first stage is at atmospheric pressure, and the second stage under vacuum to remove as much sulfur dioxide as possible. The feed is then pumped to one of four Vacuum Columns (TO-01 A/B/CX/D) where water is removed to concentrate the decomposition feed. The vacuum towers operate at a top pressure of about 0.1 bar and a bottom temperature of about 127°C in order to reach the required 75 mass per cent concentration. To handle the column internal vapor load for each train, about 1160 m³/s, four very large vacuum towers are required along with reboilers, condensers, reflux drums, and pumps. Heat for the distillation, about 108 MW_{th} total for each train of four columns, is provided by imported steam at a pressure of 10 Bar. Condensing cooling for the tower, about 204 MW_{th} total for each train of four columns, and a vacuum steam ejector system is provided by imported cooling water. The two-stage steam ejector system provides the vacuum for the system. Uncondensed vapor, primarily sulfur dioxide, is collected from the column and flash drums and is compressed in the SO₂ Recycle Compressor (CO-01) and sent to the bottom of the Absorber Column (TO-02). The vapor flashed from several streams, both upstream and downstream of the decomposer, is partially condensed and flows to the Absorber Column.

Concentrated acid bottoms from the Vacuum Columns are pumped to the Sulfuric Acid Decomposers (RX-201 A&B). Here the decomposition of sulfuric acid into water, sulfur dioxide, and oxygen takes place. The heat for the endothermic reaction and feed heating is provided by helium at 910°C from the NHSS. The helium return temperature from the decomposers is 522°C for a duty of 356 MW_{th} per train. The design and operation of the decomposer is described in Section 2. Decomposer product is flashed in four stages to separate product sulfur dioxide and oxygen from unreacted sulfuric acid. Vapor from these flashes is partially condensed using the feed streams to the Vacuum Column and cooling water. The condensate and vapor are sent to the Absorber Column, while the liquid is recycled to the bottom of the Vacuum Column.

Liquid condensate and vapor from the flashed streams and Vacuum Column overhead product are all sent to the Absorber Column. The condensate is then used to scrub sulfur dioxide out of the product oxygen. The oxygen product flows to the Product Purification System and the liquid, primarily sulfur dioxide dissolved in water, flows to the Anolyte Prep Tank.

3.1.4 Product Purification Systems

Purification of the oxygen product from the SAD and the hydrogen product from ELE is required to meet industry standards for these product gases. For this study, the Westinghouse Team adopted purification system designs that are typical for industrial gases. The design of these systems assumes that the feedstocks of water and sulfuric acid are relatively pure and that there are no contaminants in the product gas streams that will require purification other than what is described below.

The oxygen produced by the SAD is assumed to be a saleable product and will be delivered to a user or pipeline at an offsite location. This oxygen is conveyed to the PPU and passes through a caustic scrubber to remove any remaining sulfur dioxide. The scrubbed oxygen stream then passes through a set of zeolite drying beds, followed by polishing adsorbers that

further remove any residual traces of sulfur dioxide. Both sets of adsorbers are regenerated using a portion of the oxygen product.

The hydrogen purification system is designed to remove sulfur species and water from the hydrogen product prior to being discharged to a pipeline. Precautions have been made to remove sulfur species because of the current experience of the migration of sulfur across the cell membrane. The hydrogen gas effluent stream is conveyed from the Wet Hydrogen Knockout Drum to the hydrogen purification system, where it is further compressed to sufficient pressure for discharge to a hydrogen pipeline. Prior to discharge to the pipeline, the hydrogen passes through a set of dryers followed by a hydrogenation reactor to ensure that any sulfur species in the gas are reduced to hydrogen sulfide. Hydrogen sulfide is captured in zinc oxide beds and water produced in hydrogenation is removed in zeolites drying beds. The system is designed to use a portion of the hydrogen product to regenerate the drying beds.

3.2 SULFUR IODINE

As noted previously in Section 2, the design basis for the SI cycle consists of three integrated flow sheets, or sections. Study modifications expanded the number of major process sections to five. These sections are:

- Section 000 Feed and Utility Systems (FUS)
- Section 100 Bunsen Reaction (BUN)
- Section 200 Sulfuric Acid Decomposition (SAD)
- Section 300 Hydroiodic Acid Decomposition (HAD)
- Section 400 Product Purification System (PPU)

For Sections 100 through 300, stream and equipment identifiers have been kept consistent with the corresponding identifiers in the Aspen Plus® simulation models. Sections 000 and 400 include systems that produce the assumed feed water and product purity requirements, respectively. A brief process description for each section is provided below.

The simulation diagram, mass and energy balance, as well as PFDs for the SI design used in this study may be found in the Section 8 of this report. Capacities described in the following discussion are for one production train, with three production trains required to meet the target hydrogen production rate. The hydrogen production capacity for one train is approximately 52 MMCFD.

3.2.1 Feed and Utility Systems

Due to high degree of internal recycle in the SI cycle and the absence of any process blowdown streams, it is surmised that any impurities contained within the feed water will remain within the process. The result of the build up of these impurities in the process would undoubtedly cause negative consequences for the operability of the process. Therefore, it is assumed that the feed water quality must be of the highest purity and that a state-of-the-art water treatment system will be required. At the time of this study, feed water purity requirements for

the SI cycle are unknown. Therefore, the Westinghouse Team assumes that the water quality requirements are ultrapure water.

Ultimately, the design of any water treatment system will depend on the source water quality and should be based on a source water quality analysis. This study assumes that the water source is well water with a minimum hardness is 200 ppm as CaCO_3 . The pretreatment system includes a multi-media filtration and softener system to remove suspended solids and hardness, respectively. The pretreatment system is followed by a demineralizer system consisting of a reverse osmosis and electro-deionization (EDI) system. All water treatment system are considered packaged systems and are therefore shown as ‘black boxes’ on the PFDs. For the SI cycle, the water treatment system capacity is estimated to be 140 m^3/hr . Purified water storage for 48 hours of process water demand and feed water pumps are provided.

The FUS also includes a wastewater treatment system to treat water treatment wastes and process wastes. The system is estimated to need to treat approximately 67 m^3/hr of wastewater. The type of treatment required will depend on the effluent discharge limits imposed by the permitting jurisdiction. For this study, it is anticipated that the wastewater treatment system will consist of an oil/water separation system, final neutralization system, physical/chemical treatment system with mixing tank and ancillary pumps, instrumentation, and equipment. The wastewater treatment system is also treated as a vendor supplied system or ‘black box’ on the PFDs.

The final components of the FUS consist of sulfuric acid and caustic bulk storage and transfers systems. The sulfuric acid system provides makeup to the Bunsen Reaction. Caustic is required to remove residual sulfur dioxide from product oxygen in the PPU caustic scrubber. Both sulfuric acid and caustic are delivered as a 50 mass per cent liquid solution. Sulfuric acid is delivered to the Bunsen Reactor as is and caustic is diluted to a 10 mass per cent solution before being pumped to the scrubber.

3.2.2 Bunsen Reaction

The Bunsen Reaction section of the process includes internal feed stream recycle, the Bunsen Reactor, reactor product separation, and a Reverse Bunsen Reactor to remove any residual sulfur from the HIX product stream. As noted in Section 2 of this report, the Westinghouse Team’s major modification to the Bunsen portion of the process is the design of the Bunsen Reactor and product separation.

The Westinghouse Team’s revised concept for the Bunsen Reactor (TO-101) is a multistage tower featuring bottom storage section to retain the required mass of iodine and dissolved sulfur dioxide for proper phase mixing and heat of reaction removal. The reactor features three distinct zones:

- **Scrubbing Zone.** Top third of the tower contains packing for final scrubbing of the vapor phase to remove any iodine. Feed streams to this zone are purified feed water and H_2SO_4 .

- **Final Reaction Zone.** Bottom two thirds of the tower with 9 stages of packing for completion of the Bunsen Reaction. Purified feed water and recovered water from the HAD section are feed at the top of this zone, while recycled SO_2 vapor and O_2 gas are fed at the bottom of the zone.
- **Bottoms Zone.** Holds the required mass of iodine and acts as a reservoir for the recirculating cooling loop. Iodine and recycled acid from the SAD section are fed into the Bottoms Zone. Most of the Bunsen Reaction takes place in this zone.

The Scrubbing Zone and Reaction Zone are separated by a liquid collection tray with capped chimneys. Liquid collected in this tray is directed to the Reverse Bunsen Reactor for further processing.

The Bottoms Zone of the reactor is essentially a CSTR with a residence time of 30 seconds. The iodine feed rate to the Bottoms Zone is approximately $3,400 \text{ m}^3/\text{hr}$. This zone also acts as a reservoir for the Bunsen Reactor's recirculating cooling system. This system consists of three parallel heat exchangers each with a dedicated pump. The cooling system withdraws the bottoms liquid from the reservoir, passes the liquid through the heat exchangers, and returns it back to the reservoir. The circulating pumps that pump the reaction mixture through the cooling heat exchangers keep the reservoir well-mixed. Two of the heat exchangers are considered full duty exchangers with the third heat exchanger being used as a trim cooler. Cooling requirements are estimated to be $181.5 \text{ MW}_{\text{th}}$. Based on the heat capacity of the reactor bottom liquids, the total cooling system process liquid recirculation rate is estimated to be $4,500 \text{ m}^3/\text{hr}$. The amount of cooling water required will be significant and will most likely necessitate a dedicated cooling water system. Air coolers may be considered as an alternative.

The Bunsen Reactor product liquid flow rate of approximately $3,750 \text{ m}^3/\text{hr}$ is conveyed via a 900 mm (i.e., 36 inch) pipe to one of two Decant Tanks (TK-102A/B) for liquid separation. These vessels are designed as decanters with overflow and underflow baffles and a sump for each of the separated phases. The retention time of the product liquid in each vessel, including sump volumes, is set at 8 minutes. Due to the large difference in the phase densities of the liquids, separation is judged to be an easy one. The iodine and HIx product phase is transferred to a Reverse Bunsen Reactor for further processing. The sulfuric acid phase is pumped to the Vacuum Column in the SI SAD section for concentration before being sent to the Decomposer.

The Reverse Bunsen Reactor (TO-102) converts any residual sulfuric acid that may be in the Iodine and HIx product liquid to SO_2 vapor. This vapor is recycled back to the Bunsen Reactor. The Reverse Bunsen Reactor design is essentially the same as the Bunsen Reactor with the exception that it does not have an iodine Scrubbing Zone, and the Reaction Zone consists of five stages instead of nine.

Iodine and HIx separated from the Bunsen Reactor product stream in the Decant Tanks is pumped to the first stage of the Reverse Bunsen Reactor at the top of the tower. A portion of the oxygen product stream exiting the Bunsen Reactor is directed to the bottom of the Reverse Bunsen Reactor. The I_2/HIx and oxygen flow within the tower section is countercurrent. The liquid collected in the reactor's bottom reservoir is pumped to the HAD section of the process.

The tower sections of the Bunsen and Reverse Bunsen Reactors are sized using estimation methods commonly used in the chemical and petrochemical industry. The unusual physical properties of the HI/ I₂/H₂O/ SO₂ system may render some of these methods somewhat inaccurate. In further design efforts, tower sizing should be reassessed using methods that take these properties into account.

3.2.3 SI Sulfuric Acid Decomposition

Sulfuric acid feed at about 60% concentration by weight is sent from the Bunsen Reaction to the SI SAD section to be decomposed into sulfur dioxide, water, and oxygen. Before being pumped to the Decomposer, the acid is concentrated to 75% by weight to maximize the efficiency of the decomposition step. Because the per-pass conversion is only about 50%, a substantial amount of sulfuric acid is recycled. Process heat is recuperated by recovering heat from vapor flashed from the reactor product with feed to the concentration step.

Acid feed to the section is first preheated in the HP Recycle Acid Flash Condenser (EX-201). It then flows to one of two Vacuum Columns (TO-201 A&B) where water is removed to concentrate the decomposition feed. The vacuum towers operate at a top pressure of about 0.1 bar and a bottom temperature of about 127°C in order to reach the required 75 mass per cent concentration. To handle the column internal vapor load for each train, about 680 m³/s, two very large vacuum towers are required along with reboilers, condensers, reflux drums, and pumps. Heat for the distillation for both columns, about 51 MW_{th} total for each train, is provided by imported steam at a pressure of 10 bar. A two-stage steam ejector system provides the vacuum for the system. Uncondensed vapor, primarily sulfur dioxide, is sent to the Bunsen Reaction section. Condensing cooling for the tower, both columns, and the vacuum ejector system is provided by imported cooling water. The cooling duty is about 88 MW_{th} total for each train.

Concentrated acid bottoms from the Vacuum Columns are pumped to the Sulfuric Acid Decomposers (RX-201 A&B). Here the decomposition of sulfuric acid into water, sulfur dioxide, and oxygen takes place. The heat for the endothermic reaction and feed heating is provided by helium at 910°C from the NHSS. The helium return temperature from the decomposers is 640°C for a duty of 247 MW_{th} per train. The design and operation of the decomposer is described in Section 3.1 above. Decomposer product is flashed in three stages to separate the sulfur dioxide product and oxygen from unreacted sulfuric acid. Vapor from these flashes is partially condensed using the feed streams to the Vacuum Tower and cooling water. Three streams are sent to the Bunsen Reaction section: low pressure sulfur dioxide, oxygen and sulfur dioxide vapor, and liquid water with dissolved sulfur dioxide.

3.2.4 Hydroiodic Acid Decomposition

As noted in Section 2, the revised heat integration recovery scheme for HAD eliminates the need for the heat pump for the mixing and provides approximately the same column feed temperature. The heat pump used for condensing reflux and reboiling in the Reactive Distillation Column is retained in the design. An additional benefit of the new recovery scheme

is that the phase separation in two of the columns separation drums is simplified since HIx in the feed streams to these drums is now completely dissolved.

With the new heat integration scheme, the Iodine and HIx stream from the Bunsen section is preheated to approximately 260°C using the heat from the vapor and iodine product streams from the Reactive Distillation Column (TO-04). The iodine/HIx stream is split to flow to either the Vapor Heat Recuperator (HX-1) or the Recovered Iodine Heat Recuperator (HX-2). A proportional flow control scheme is currently shown on the PFDs as the basis for splitting this flow. However, this may be changed to a temperature based control scheme upon further development. The two preheated streams are recombined in a mix tank prior to a final preheat to 272°C in the Distillation Column Reheater (HX-3) using heat from the liquid product of the distillation column.

The design of the Reactive Distillation Column has been improved and the number of columns increased, as discussed below. Each column consists of 15 stages and includes a condenser and reboiler, and utilizes ceramic packing. The preheated HIx feed is introduced to each column at stage 12.

The total heat demand for the decomposition reaction is approximately 980 MW_{th}, and the total cooling requirement for reflux is approximately 560 MW_{th}. The total cooling requirement and a majority of the heat demand is provided by the heat pumps associated with each column. Approximately 272 MW_{th} of heat is provided by the NHSS helium loop. The total electrical energy required for heat pump compressors is 61.8 MW_e. In consideration of the high column pressure of 37 bar, the heat pump and helium reboilers are designed as kettle reboilers. Residence time of the liquid at the bottom of the column is approximately 80 seconds. Column bottoms product, the iodine-rich stream, is returned to the Bunsen Reaction section after process heat is recovered and the stream is cooled and flashed to the required conditions.

The vapor product from the reactive distillation column along with vapor flashed from the column bottoms is cooled and condensed to remove water and iodine from the hydrogen product. Water and iodine are returned to the Bunsen Section. The hydrogen product flows to the Product Purification System.

3.2.5 Product Purification Systems

Purification of the oxygen product from the Bunsen Reaction and the hydrogen product from the HI Decomposition is required to meet industry standards for these product gases. For this study, the Westinghouse Team adopted purification system designs that are typical for the commercial specialty gas industry. The design of these systems also assumes that the feedstock of iodine, water, and sulfuric acid are relatively pure and that there are no other contaminants in the product gas streams that will require purification other than what is described below.

The oxygen produced by the Bunsen Reaction is assumed to be a saleable product and will be delivered to a user or pipeline at an offsite location. Oxygen produced in the Bunsen Reaction is conveyed to the oxygen purification system and passes through a caustic scrubber to

remove any remaining sulfur dioxide that may be present. The scrubbed oxygen stream then passes through a set of zeolite drying beds, followed by polishing adsorbers that remove any residual traces of SO₂. Both sets of adsorbers may be regenerated using a portion of the oxygen product.

Similarly, the hydrogen purification system is designed to scrub the hydrogen gas of iodine and water prior to being discharged to a pipeline. The hydrogen gas product stream is conveyed from the HAD separators to the hydrogen purification system, where it is further compressed to sufficient pressure for discharge to a hydrogen pipeline. Prior to discharge to the pipeline, the hydrogen passes through a set of iodine adsorbers followed by a set of drying beds. The system is designed to use a portion of the hydrogen product to regenerate the drying beds.

3.3 HIGH TEMPERATURE STEAM ELECTROLYSIS

Shaw's modifications to the design basis further expanded the number of major process sections to four. These sections are:

- Section 100 Feed and Utility Systems (FUS)
- Section 200 Heat Recovery System (HRS)
- Section 300 Electrolysis (ELE)
- Section 400 Product Purification System (PPU)

Sections 100 and 400 are the systems that produce the assumed feed water and product purity requirements, respectively. The HRS system essentially recovers as much heat as possible from the hot hydrogen and sweep gas streams exiting the electrolyzers to preheat the inlet water and sweep gas feed streams.

There are two significant recycle streams within the process. The first is the recycle of a portion of the hydrogen product that is mixed with the feed water in order to maintain reducing conditions at the cathode. The second is the recycle of water in the hydrogen product stream. The majority of the water in the process is converted to hydrogen but about 10% is recycled back to the process via the water purification system in the FUS.

The simulation diagram, mass and energy balance, as well as PFDs for the HTSE design used in this study may be found in the Section 8 of this report. A brief process description for each section is provided below. Capacities described in the following discussion are for one production train, which is required to meet the target hydrogen production rate of 142 MMCFD.

3.3.1 Feed and Utility Systems

Feed water and sweep gas purity requirements have not been established yet for the HTSE process, particularly with regards to operability of the electrolyzer cells. However, it is assumed that the feed water and sweep gas quality must be of the highest purity and that state-of-the-art treatment systems used for ultra-pure water and specialty gas production systems will be required.

Ultimately, the design of any water treatment system will depend on the source water quality and should be based on a source water quality analysis. This study assumes that the water source is well water with a minimum hardness is 200 ppm as CaCO_3 . The pretreatment system includes a multi-media filtration and softener system to remove suspended solids and hardness, respectively. The pretreatment system is followed by a demineralizer system consisting of reverse osmosis and electro-deionization (EDI) systems. All water treatment systems are considered packaged systems and are therefore shown as ‘black boxes’ on the PFDs. For the HTSE, the water treatment system capacity is estimated to be $150 \text{ m}^3/\text{hr}$ (i.e., ~670 gpm). Purified water storage for 48 hours of process water demand and feed water pumps are provided.

Prior to the RO/EDI system, the softened water is used to cool the product hydrogen stream sufficiently to condense the majority of water in the product gas stream. Condensed water is removed in a knockout drum and then directed to the water treatment RO/EDI system to remove any contaminants that may have been picked up in the process.

Purified water is stored and then pumped to the feed water deaerator. The hydrogen product gas stream is used to heat the purified water feed to approximately 117°C prior to entering the deaerator. The operating pressure of the deaerator is about 3 Bar, which is typical for this type of application. Deaerator materials of construction are 304 stainless steel. High pressure steam generated in the HRS is used to deaerate the feed water. Deaerated water is then pumped to the HRS for further conditioning.

The FUS also includes a wastewater treatment system to treat water treatment wastes and process wastes. The system is estimated to need to treat approximately $45 \text{ m}^3/\text{hr}$ (i.e., 200 gpm) of wastewater. The type of treatment required will depend on the effluent discharge limits imposed by the permitting jurisdiction. For this study, it is anticipated that the wastewater treatment system will consist of an oil/water separation system, neutralization system, physical/chemical treatment system with mixing tank and ancillary pumps, instrumentation, and equipment. The wastewater treatment system is also treated as a vendor supplied system or ‘black box’ on the PFDs.

The sweep gas is assumed to be air. Purity requirements for the sweep gas are not known at this time, but are assumed to be high. Therefore, a state-of-the-art Clean Dry Air (CDA) system is used to remove contaminants and water. The CDA system has a dedicated inlet air compressor. The clean dry air is then compressed by the Sweep Gas Compressor (PC-01) to a pressure of 58 Bar and a temperature of 176°C and is conveyed to the ELE.

As the sweep gas passes through the electrolyzers, it removes the oxygen generated at the anodes of the electrolysis cells. The exiting sweep gas is about 50% oxygen on a molar basis, and is at a temperature and pressure of 800°C and 55 Bar, respectively. The majority of the heat in the sweep gas is recovered in the HRS. However, the sweep gas still has significant energy after passing through HRS. The temperature and pressure of the sweep gas are 142°C and 53 Bar. The expansion turbine shown to utilize this energy in the original design basis is retained in this design study. Electricity generated by the expansion turbine is 13.3 MWe, and the exit temperature and pressure of the Sweep Gas is approximately -43°C and 2 Bar. The exit

Sweep Gas is assumed to be discharged directly to atmosphere. No consideration is given to recovery of the gas stream for refrigeration purposes.

3.3.2 Heat Recovery System

Deaerated feed water is preheated using the hot hydrogen product and outlet sweep gas from the electrolyzers. The HRS utilizes a complex series of parallel preheaters, boilers, and superheaters to raise the temperature of the inlet ultrapure feed water to 396°C. The hot hydrogen product and sweep gas streams pass consecutively from the superheaters, to the boilers, and then the preheaters.

Feed water is pumped from the deaerator at a pressure of 65 Bar to a pair of preheaters operating in parallel. The total feed water flow to the HRS preheaters is approximately 34 kg/s or 130 m³/hr. One preheater recovers heat from the hydrogen product gas stream, while the other recovers heat from the outlet sweep gas from the electrolyzers. The deaerated feed water flow is split based on a preset flow setpoint and is trimmed based on the outlet temperatures from each of the preheaters. The feed water is heated to just below the feed water boiling point, approximately 274.5°C.

The preheated feedwater then flows to the Feed Steam Drum (KO-03), which features two thermosyphon boilers: a sweep gas boiler (EX-03) that utilizes the hot outlet sweep gas to boil the feed water and a hydrogen boiler (EX-06) that utilizes the hot hydrogen product stream. Steam exits the feed drum at a temperature of 273.4°C and at a pressure of 58 Bar. Flow controllers split the exiting steam flow between the hydrogen and sweep gas superheaters also based on a preset flow setpoint. The superheated steam temperatures exiting the respective superheaters are used to trim this inlet flow control. Steam flows to the Hydrogen Feed Water Superheater (EX-07) and to the Sweep Gas Feed Water Superheater (EX-04) are estimated to be 18.2 kg/sec and 15.4 kg/sec, respectively. Approximately 0.25 kg/sec of the outlet steam from the steam drum is directed to the deaerator.

A portion of the hydrogen product is compressed and recycled back through the HRS to preheat and mix it with the steam feed. The recycled hydrogen flow is approximately 0.45 kg/sec, or 10% of the total inlet molar flow to the cathode. Hot hydrogen product is used to heat the recycled hydrogen from 46°C to 275°C in the Recycled Hydrogen Preheater (EX-08). The preheated hydrogen is then mixed with the steam flow exiting the Feed Steam Drum and the mixture is conveyed to the Hydrogen Feed Water Superheater. The Hydrogen Feed Water Superheater heats the hydrogen and steam flow to approximately 396°C.

3.3.3 Electrolysis

The Electrolysis section of HTSE essentially consists of the Process Coupling Heat Exchangers (PCHX) that heat the inlet feed steam and sweep gas to 870°C and the Electrolyzer. Separate PCHXs are provided for the Hydrogen/steam inlet stream to the electrolyzer cathodes, and the inlet sweep gas stream to the anodes. The electrolyzer comprises 760,000 solid-oxide electrolysis cells.

3.3.4 Product Purification System

The hydrogen purification system is designed to remove water prior to the hydrogen being discharged to a pipeline. The hydrogen gas product stream is conveyed to the hydrogen purification system via the HRS. The hydrogen product pressure and temperature after passing through the HRS is 51 Bar and 26°C, respectively. Prior to discharge to the pipeline, the hydrogen passes through a set of drying beds. The system is designed to use a portion of the hydrogen product to regenerate the drying beds, as required.

4 LIFE-CYCLE COST OF HYDROGEN

The development of a Hydrogen Economy is motivated by foreseen benefits of energy security, lower pollutant emissions, and reduced climate change. In the final analysis, the figure of merit for production of hydrogen by means of any technology is the minimum price that the product can be sold for. This is the price that will recoup the hydrogen production plant's initial and ongoing capital investment, fuel, feedstock, and other fixed and variable operating costs, and return a profit to the owner. The price calculated is strongly influenced by financial assumptions as well as specifics of the particular technology.

The resulting hydrogen prices are compared on an equivalent basis to the prices for hydrogen from alternate baseline technologies in Section 4.5.4.

4.1 DEVELOPMENT OF THE ECONOMIC MODEL

The focus of the study and the subject of this report is the hydrogen process plant and its alternate designs. The HPS is supplied heat from a HTGR in the form of hot helium. The nuclear reactor heat source technology is not studied directly, but power and temperature levels and energy costs used in the study are representative of a pebble bed core reactor at 500 MW_{th} and a prismatic core reactor at 565 to 600 MW_{th}. All configurations use a secondary helium loop to reduce tritium transport and to separate the process streams from the primary helium loop in the event of a leak in either the Intermediate Heat Exchanger (IHX) or the Process Coupling Heat Exchanger (PCHX). The reference helium delivery temperature to the PCHX is 910°C. The corresponding maximum bulk mean operating temperature on the process side of the PCHX is 870°C in all cases. The secondary helium heat source temperature, and therefore the reactor primary loop outlet temperature, varies correspondingly. The reference reactor outlet temperature is 950°C.

The cost of the thermal energy from the nuclear heat source is estimated for the reference case and charged to the hydrogen plant as a fixed operating cost. The heat available in the helium exiting the PCHX and not usable by the process is used to generate electricity. The cost of generating power from this heat is estimated separately. A Rankine cycle is used and generation efficiency is varied depending upon the maximum steam temperature available in each case. In this way, the value of the unused exported heat is estimated. Any electricity deficit or surplus is balanced by imports from or exports to the grid. Cost of imports from the grid in excess of that generated by the unused heat would include any carbon penalty reflecting the generation mix of gas, coal, and nuclear. These economic factors are discussed further in the following sections.

4.2 ECONOMIC FACTORS

4.2.1 Price of Hydrogen

Cost elements of the process plant are estimated with derivations documented in Sections 4.3 and 4.4. In Sections 4.5.1, 4.5.2 and 4.5.3, a price is calculated for hydrogen produced by each water splitting based HPS identified for HTGR applications. The calculation uses the H2A tool and documentation as it pertains to this study may be found in Section 8.5.1.

4.2.1.1 Economic Parameters

The major economic assumptions for the hydrogen price analyses are listed in Table 4-1.

The reference dollar year is in agreement with the cost estimates corresponding to the designs in Section 3. The reference financing arrangement of 100% equity at 10% IRR is the H2A default value. This is equivalent to a typical commercial financing structure of 50% equity/50% debt with 15% IRR and 8.25% debt interest rate. The plant life is as would be expected for a process industry plant. The construction period and startup time are reference values for future nuclear plants.

Table 4-1: Major Assumptions for Analysis of Economics

Parameter	Value
Reference Dollar Year	3 rd Quarter 2008
Assumed Start-up Year	2030
Plant Location	US Gulf Coast
Plant Maturity Assumption	N th -of-a-Kind plant
Financing	100% Equity
After-Tax Real IRR	10%
Project Overall Capital Cost Contingency	10%
Plant Life	30 years
Lifetime Capacity Factor	8,200 hr/yr (94%)
Construction Period	3 years
Costs in Construction Years	25% / 45% / 30%
Start-up Period	1 year
Income Tax Rate (composite)	38.9%
Property Tax Rate	1% of Overnight Capital Cost
Insurance Rate	1% of Overnight Capital Cost
Working Capital	15% of Incremental Change in Annual Operating Costs

A more extensive list of the ground rules for the economic modeling is in Section 8.5.2.

4.2.1.2 Alternate Parameters and Inputs

Two factors are recognized as notable assumed parameters and/or inputs and are considered separately from other calculated sensitivities. These are the real escalation rate of electricity cost and the credit for sale of oxygen byproduct in the cases where oxygen is practically recovered. These values are as shown in Table 4-2. The hydrogen price will be separately calculated for comparison by varying each separately from the reference case.

Table 4-2: Alternate Parameters and Inputs for Analysis of Economics

	Reference	Alternates	
Electricity Cost Escalation	1% per year	No	1% per year
Credit for Oxygen Byproduct	Yes	Yes	No

The H2A modeling tool, as published, is based on an assumption that all costs and the selling price have the same rate of inflation. Energy costs are expected to rise more rapidly than general inflation, and so a modification to the H2A model has been made to make the analysis more realistic. For the reference analysis, real escalation, over and above any inflation, is included at 1%/yr over the plant life for the electric power bought or sold.

In addition, the sensitivities to the value of electric power cost and the oxygen price is included in Section 4.2.1.4.

4.2.1.3 Overall Plant Capital Costs

The hydrogen plant capital costs include the helium regulating valves and process coupling heat exchanger isolation valves that will be required to regulate and protect the interface with the NHSS and the overall plant.

A Power Conversion System (PCS) generates electricity with the heat energy remaining in the NHSS helium circuit after the process coupling heat exchanger(s) and before the circulating gas returns to the heat source. It should be noted that all cases do not have such remaining usable heat. A steam generator converts the heat to superheated steam. The steam is converted into electric power with a steam turbine-generator in a conventional non-reheat Rankine water vapor cycle with regenerative feedwater heating. A final water circuit from the steam turbine condenser to a wet cooling tower provides the ultimate heat sink for the cycle. The capital cost and operating costs of the PCS are scaled from the system described in the preconceptual design commercial NNGP application report ^[Ref. 10].

Balance of Plant (BOP) costs are added to account for overall plant electrical service (i.e., substation and distribution), water systems (i.e., sanitary, storm, potable & fire), and common

buildings. Indirect capital costs are site preparation and overall project development and management. A contingency factor and cost of land are added to reach a total capital investment value that is used in the H2A analysis. The contingency factor is considered such that the resulting cost represents a mean or expected value. This serves as a baseline value to which variations with approximately 10% and 90% confidence values are used in the sensitivity analyses.

4.2.1.4 Sensitivities

Sensitivity analysis can provide indications of the priorities to be assigned for further development effort. The effect on hydrogen price is calculated for the expected range of uncertainties in the parameters that have a major impact on such prices. These analyses are divided into two groups – capital cost factors and other factors. The expected range of these uncertainties are provided in Table 4-3 and the resulting sensitivities of the parameters are presented in Sections 4.5.1.2, 4.5.2.2 and 4.5.3.2. The range of these parameters have been chosen using some engineering judgment and reasonable anticipation of future trends.

The influence of nuclear heat source outlet temperature on the processes is separately discussed in Section 5.3.

Table 4-3 presents the variable inputs for the sensitivity analysis. In the table, values on the left most side have the lowest H₂ price impact. The right most values have the highest. Shaded entries are base case values.

Table 4-3: Variable Inputs for Sensitivity Analysis

Variable	Analysis Value					
Reactor outlet temperature, °C	950	900	850	800	750	700
NHSS energy cost, \$/MW _{th} -hr of reactor core power	25		30		35	
IRR, % (with 100% equity case)	8		10		12	
Capacity factor, %	94			85		
Cost of electricity (incl. carbon penalty), \$/MW _e -hr	Buy: 60 Sell: 50		75 60		85 70	
Plant size, for SI and HyS; for HTSE base and maximum heat utilization cases	approx. double *			base		
CO ₂ “Credit”	30 \$/tonne			None		
Initial capital costs						
Overall Hydrogen Production System capital cost	-15%		base		+30%	
For SI						
Overall cost of materials	-20%		base		+50%	
Sulfuric acid decomposer	-20%		base		+50%	
Sulfuric acid decom. section	-15%		base		+30%	
Bunsen reactor	-20%		base		+50%	
Bunsen reaction section	-15%		base		+30%	
HI decomposition reactor	-20%		base		+50%	
HI decomposition section	-15%		base		+30%	
For HyS						
Overall cost of materials	-20%		base		+50%	

Variable	Analysis Value		
Sulfuric acid decomposer	-20%	base	+50%
Sulfuric acid decom. section	-15%	base	+30%
Electrolyzers	-20%	base	+50%
Electrolyzer section	-15%	base	+30%
For HTSE			
Overall cost of materials	-20%	base	+50%
Electrolyzers	-20%	base	+50%
Electrolyzer section	-15%	base	+30%
Hi-temp. heat exchangers	-20%	base	+50%
Heat recovery section	-15%	base	+30%
Replacement capital frequencies			
For SI and HyS, Sulfuric Acid Decomposer (tubes)			
Frequency, per year	5%	10%	20%
For HyS, Electrolyzers, per module			
Frequency, per year	5%	10%	20%
For HTSE, Electrolyzers, per stack			
Frequency, per year	2½%	5%	15%
For HTSE, Hi-temp. heat exchangers and pipe/ducts			
Period, years	30	15	8
O & M			
Costs of annual materials & services for maintenance and repair	-20%	base	+50%
Process plant staffing	-20%	base	+50%

* A plant of 300 MMSCFD, which is approximately twice the output of the base in all cases. For HTSE, a further scaled-up plant is evaluated where all of the heat from one nuclear reactor module is utilized.

Sensitivity to reactor outlet temperature is discussed in Section 5.3. In the original work plan, the reactor inlet temperature was to be varied also to determine economic effect. However, it has been determined that the nuclear reactor vessel must be SA 508/533 ^[Ref. 11], and so reactor inlet temperature cannot exceed 350°C. This limitation is in conformance with ASME Code requirements.

NHSS energy cost is treated as an input parameter charged as a fixed operating cost, and a reference value of 30 \$/MW_{th}-hr is applied, where the power in the denominator is the nuclear reactor core thermal power. While the concern of the process plant would be only the heat input to the PCHXs, this study uses the reactor core power so that the overall plant electric power balance includes the significant amount of power required to run the NHSS circulators and NHSS house load.

The 30 \$/MW_{th}-hr is in line with estimates of the NHSS cost developed from the base presented in the NGNP PCDR ^[Ref. 12] with due escalation in cost of materials of construction since the date of that costing effort.

The reference electric power cost and the oxygen price reference values are considered reasonable estimates typical of the current 2008 cost or price market data for industrial users, although these costs and prices will vary significantly with region.

Plant size for all three reference cases is approximately 150 MMSCFD, as used in the design study. Generally, this is the size of the largest hydrogen plant that users would want or that suppliers would build considering present norms of the petrochemical industry.

The sensitivities are presented for plants approximately twice the size of the study reference designs. Sulfur Iodine would have six rather than three reactor heat sources and Hybrid Sulfur four rather than two. For the HTSE base case, the HPS is not using all of the heat available at usable temperature from one reactor unit. A plant with double output would still not use the full heat from one reactor, and so another case is evaluated. A second, larger scale HTSE plant is included in the sensitivity analysis where the maximum input heat from one reactor unit is utilized. The large amount of electricity needed is still charged at the reference case rate. Although in the event such a plant was built, there would probably be a dedicated electric power-only plant included in the overall project.

The reference case H2A assessment does not account for any credit for avoiding emission of CO₂. This is because the selling price will be compared in Section 4.5.4 to alternative technologies for hydrogen, which include the costs for CO₂ management. One of these alternatives is natural gas steam methane reforming for which mitigation of CO₂ production is included as a cost or tax. The cost in that case is \$30/tonne CO₂ captured in the process and \$100/tonne CO₂ in the flue gas. Sensitivity to “carbon credit” is then calculated for an increment in “credit” for the nuclear H₂ over these values. In calculating the “credit,” the emission from the source of imported electricity for the hydrogen plant is also accounted for.

A second case to gauge CO₂ avoidance is comparison to conventional electrolysis. The comparison to conventional electrolysis is also made in Section 4.5.4. In calculating the credit compared to conventional electrolysis, the entire differential is from the “upstream” emissions from the source of imported electricity.

4.2.2 Availability

It is not possible to assess availability for a mature plant from the extremely limited performance data for any of the three HPS systems at this early stage of design and development. Meaningful availability analysis requires failure rate data from a statistically valid number of prototypical units. There are few high-temperature process systems of the same scale and functional similarity, and there are no known plants of any scale that have heat exchange between high temperature closed gas circuits to process fluids such as in these hydrogen production systems.

Nevertheless, a reference value of capacity factor of 94% is assumed as a goal and subject to sensitivity analysis. The reference value corresponds to 8,200 hours per year of full rated operation. Availability is addressed in the design of all three systems by 1) including spares of critical components, 2) accounting for periodic replacement and refurbishment of select components, and 3) allocations of labor, materials, and services for a program of regular maintenance and repairs. Each of these factors is highly judgmental since there is limited reliability data with which to do a quantitative assessment.

4.3 CAPITAL COST ESTIMATE BASIS

Capital costs are summarized in Section 4.5 along with the analyses of the life-cycle cost of hydrogen. The detailed capital costs are in Sections 8.1.7, 8.2.7 and 8.3.7 for conventional components and subsystems of the process plants. The costs for developmental equipment, in contrast to equipment for which data bases exist, are in Section 8.6.

4.3.1 Estimate Methodology

Study estimates of the costs for conventional components and subsystems of the process plant have been prepared using the Shaw Group's "FACES" software. The estimates are based on 3rd Quarter 2008 US Gulf Coast (USGC) site related costs.

Construction material costs are based on Shaw's USGC historical data. Design development allowances are not included in the equipment material costs. Freight and spares are estimated separately. Bulk material quantities are factored and then current USGC costs are applied. USGC construction labor hours are factored from equipment and bulk material. Current USGC rates are applied. Home office costs are factored from equipment counts.

Estimate accuracy is in the range of + 50%/-20% for all 3 processes due to indeterminants at this stage of design development. A 10% contingency is added to reflect a 50% confidence estimate, *i.e.* 50% chance of being either higher or lower.

4.3.2 Estimate Assumptions

The process plant capital cost estimates are based on the following assumptions:

- Third quarter 2008 US Dollars;
- Soil condition is suitable for spread footing foundations, and;
- Site is clear and level with suitable lay-down area adjacent to the site.

4.3.3 Estimate Exclusions

Excluded from the process plant cost estimates are the following:

- Licensor fees;
- Permits & Licenses;
- Owner's costs;
- Utilities during construction;
- Site environmental considerations such as;
 - Contaminated soil disposal
 - Asbestos abatement
 - Lead abatement

- Environmental clean up of demolition items
- Demolition.

Commissioning and start-up costs of operation and maintenance are modeled in the H2A tool, but training and extra staffing are not. Nuclear-related initial costs, such as licensing and staff training and continuing nuclear-related costs, such as security, are presumed included in the “over-the-fence” fixed nuclear heat cost.

4.4 OPERATING AND MAINTENANCE COST ESTIMATES

Operating and maintenance (O&M) costs for the hydrogen processes can be divided into fixed and variable costs, where variable costs are only incurred while the plant is operating to produce hydrogen.

Fixed costs, in approximate order from the largest to the smallest, are property tax and insurance, labor, and material costs for maintenance and repairs. The cost of nuclear heat is included in the H2A model as a fixed operating cost.

Variable O&M costs are generally the process inputs: electric power, process steam, cooling water, process water, water treatment (softening and deionization, as required), replacement catalysts, and make-up chemicals. Also, variable O&M includes any costs to handle effluents: liquid waste disposal and solid waste disposal. Note that cooling water and water treatment are modeled as costs in these analyses. Alternatively, they could have been included as process plant capital cost elements, such as a cooling tower instead of a charge per unit cooling service.

Several components or subsystems of the hydrogen systems are anticipated to have shorter lifetimes than the overall plant, and these will be replaced or refurbished on schedules that are different for each. For example, replacement could be on a period of 10 or 15 years, or alternatively, done every year or two with a frequency of 5 or 10% changed each year. The costs of replacements are modeled in the H2A tool as separate capital items with subsequent depreciation and tax treatment separate from the other maintenance costs. Therefore, while the labor for replacement and refurbishment is included in fixed O&M costs, the equipment costs are not. These replacement capital items are detailed in the next section for each system. Additionally, there is a general unplanned replacement capital cost factor of ½% applied to the total initial direct depreciable costs per year.

The operating and maintenance costs for the hydrogen process systems are developed and documented in Sections 8.1.8, 8.2.8 and 8.3.8.

4.5 ECONOMIC ANALYSIS AND LIFE-CYCLE COST OF HYDROGEN

A levelized selling price for hydrogen over the plant lifetime is calculated using the H2A analysis with the ground rules and cost elements detailed above for each HPS technology: Sulfur-Iodine, Hybrid Sulfur, and High Temperature Steam Electrolysis. Refer to Section 8.5.1. The reference case costs are for the hydrogen product with 1%/yr electricity cost escalation and credit for the parallel production of oxygen. The hydrogen prices for the reference case for each plant are summarized in Table 4-4.

Table 4-4: Calculated Hydrogen Price

Sensitivity Analysis Case	Selling Price of Hydrogen (\$/kg H ₂)		
	Sulfur Iodine	Hybrid Sulfur	High Temperature Steam Electrolysis
Reference Cases	10.71	6.83	6.04
Excluding Electricity Cost Escalation	10.12	6.43	5.31
Excluding O ₂ Credit	11.09	7.21	Reference Case has no O ₂ Credit

4.5.1 Sulfur Iodine

The Hydrogen Production System for SI is described in Section 3. Of the options considered for the SI HAD section, this study uses reactive distillation. The HPS consists of three process trains supplied with thermal energy from three 550 MW_{th} nominally rated nuclear heat sources and supplied with entirely imported electric power. Figure 4-1 is a schematic representation of the overall plant arrangement.

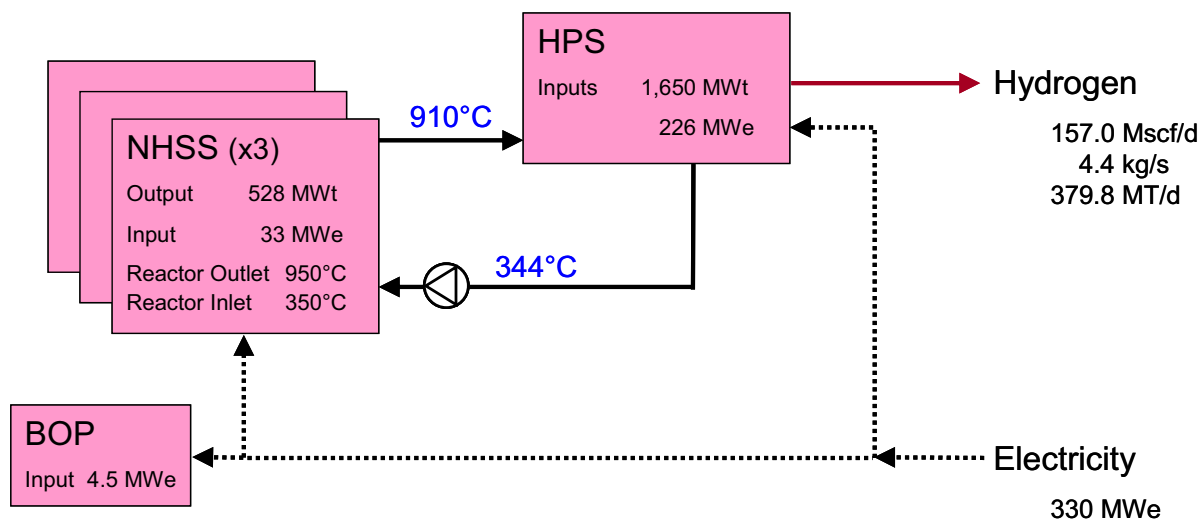


Figure 4-1: Schematic Diagram and Energy Balance for Sulfur Iodine

4.5.1.1 Reference Case H₂ Selling Price

Table 4-5 presents the major performance factors for the reference case. The NHSS energy cost, import electricity cost, and O₂ byproduct price are parameters subject to sensitivity analysis in each case.

Table 4-5: Sulfur Iodine – Overall Cost and Performance Factors for Analysis

Major Plant Parameters	
Nuclear Reactor Power	3 x 528 MW _{th} = 1,584 MW _{th}
PCHX Heat Input	1,650 MW _{th}
Plant H ₂ Output	4.4 kg/s 157 MMSCFD
Electric Power Generated	0 MW _e
Electricity Imported	330 MW _e
Major Input / Byproduct Costs ¹	
Cost of High-Temperature Heat	\$ 30 /MW _{th} -hr
Cost of Electricity, Levelized ²	\$ 101 /MW _e -hr
Cost of Water	\$ 0.0021 /gal
Price for O ₂ By-product	\$ 0.04 /kg O ₂

Notes:

¹ 2008 dollars

² \$75/ MW_e-hr in 2008, escalated at 1%/yr

Table 4-6 summarizes the capital cost of the reference case. The process system capital cost is extraordinarily high because of the apparent requirement that much of the interior surfaces exposed to concentrated HI at required temperatures will have to be lined with tantalum. As an indication of the sensitivity to this requirement, a case with only carbon steel throughout the entire plant was run, and numbers for this case are shown in Table 4-7.

Table 4-6: Sulfur Iodine, Reference Case – Capital Cost Summary

	Total Costs	Specific Costs
Hydrogen Plant Capital Cost	\$ 2,683M	\$ 7,060 /kg H ₂ /day \$ 5,090 /kW _{th} H ₂ (LHV)
BOP & Other Capital Cost	\$ 40M	--
Total Direct Capital Cost	\$ 2,723M	--
Indirect Capital Cost	\$ 63M	--
Base Construction Cost	\$ 2,786M	--
Contingency	\$ 272M	--
Total Depreciable Capital Cost	\$ 3,059M	--
Cost of Land	\$ 2.5M	--
Total Overnight Capital Cost	\$ 3,061M	\$ 8,060 /kg H ₂ /d \$ 5,800 /kW _{th} H ₂ (LHV)
Interest During Construction	\$ 398M	--
Total Capital Investment	\$ 3,459M	\$ 9,110 /kg H ₂ /d \$ 6,560 /kW _{th} H ₂ (LHV)

The capital costs summarized in Table 4-6, and in the capital summary tables for other cases, include more than the capital costs stated elsewhere in this report for the process plant alone, as described in Section 4.2.1.3. Details of the process plant capital cost are in Appendix 8.2.7.

Table 4-7: Sulfur Iodine, Carbon Steel Case – Capital Cost Summary

	Total Costs	Specific Costs
Hydrogen Plant Capital Cost	\$ 1,211M	\$ 3,190 /kg H ₂ /day \$ 2,300 /kW _{th} H ₂ (LHV)
BOP & Other Capital Cost	\$ 40M	--
Total Direct Capital Cost	\$ 1,251M	--
Indirect Capital Cost	\$ 63M	--
Base Construction Cost	\$ 1,315M	--
Contingency	\$ 125M	--
Total Depreciable Capital Cost	\$ 1,440M	--
Cost of Land	\$ 2.5M	--
Total Overnight Capital Cost	\$ 1,442M	\$ 3,800 /kg H ₂ /d \$ 2,730 /kW _{th} H ₂ (LHV)
Interest During Construction	\$ 187M	--
Total Capital Investment	\$ 1,630M	\$ 4,290 /kg H ₂ /d \$ 3,090 /kW _{th} H ₂ (LHV)

Periodic replacement costs that are accounted in the analysis are shown in Table 4-8. The Sulfuric Acid Decomposer is the process coupling heat exchanger where the highest temperature nuclear source helium transfers heat to the highest temperature in the process, and these silicon carbide tubes and their seals are not expected to operate for the full 30-year expected plant lifetime. Details of the replacement and operating costs are in Section 8.2.8. Note that labor costs for replacement are included in the basic staffing.

Table 4-8: Sulfur Iodine – Replacement Capital Summary

Sulfuric Acid Decomposer Tube Replacement	
Replacement frequency	every 2 yrs
Unit life	10 yrs
Unit replacement cost	\$ 23,800
Number	2,250
Equip. cost per replacement	\$ 53,550,000

The calculated hydrogen selling price for the economic ground rules summarized in Table 4-1 and the parameters in shaded columns of Table 4-3 is calculated using the H2A modeling tool for the reference case (i.e., with tantalum lining) to be 10.71 \$/kg H₂ with escalation of the cost of imported electric power. Without the escalation, the price would be 10.12 \$/kg H₂, and with the escalation but without the oxygen credit the price comes to 11.09 \$/kg H₂.

The alternative all-carbon steel case was run to demonstrate the sensitivity to tantalum lining and to quantify a floor value for comparison. The resulting hydrogen prices are summarized in Table 4-9, and as can be seen the tantalum cost is on average approximately 18% of the total price of the hydrogen produced.

Table 4-9: Calculated Sulfur Iodine Hydrogen Prices

Sensitivity Analysis Case	Selling Price of Hydrogen (\$/kg H ₂)	
	Reference Case (tantalum lining)	All Carbon Steel Case
Reference Cases	10.71	9.07
Excluding Electricity Cost Escalation	10.12	8.48
Excluding O ₂ Credit	11.09	9.46

Table 4-10 shows the breakdown of the components of the hydrogen selling price for the reference case (i.e., with tantalum lining).

Table 4-10: Sulfur Iodine – Hydrogen Price Components Summary

	\$/kg H₂	%
Capital Charge	4.23	40
Fixed O&M: Labor, Taxes, Insurance, Annual Licensing, Permits and Fees, Material Costs for Maintenance And Repairs, Nuclear Decommissioning Funding, Helium Make-up	0.70	7
Variable O&M: Process Catalyst and Chemical Consumption and Waste Disposal	0.60	6
Nuclear Heat	3.21	30
Electric Power	2.22	21
Process & Cooling Water	0.11	1
Byproduct Credit (O ₂)	- 0.38	- 4
Total Hydrogen Cost (Year 2008 Real \$/kg H ₂)	10.71	100

4.5.1.2 Sensitivity analysis

The sensitivities of the SI hydrogen cost to the parameters listed in Table 4-3 are presented as “tornado” diagrams in Figure 4-2 and Figure 4-3. The first figure presents the sensitivities to variation in capital cost elements, and the second figure shows sensitivities to other cost elements. Sensitivity to reactor outlet temperature is covered in Section 5.3.

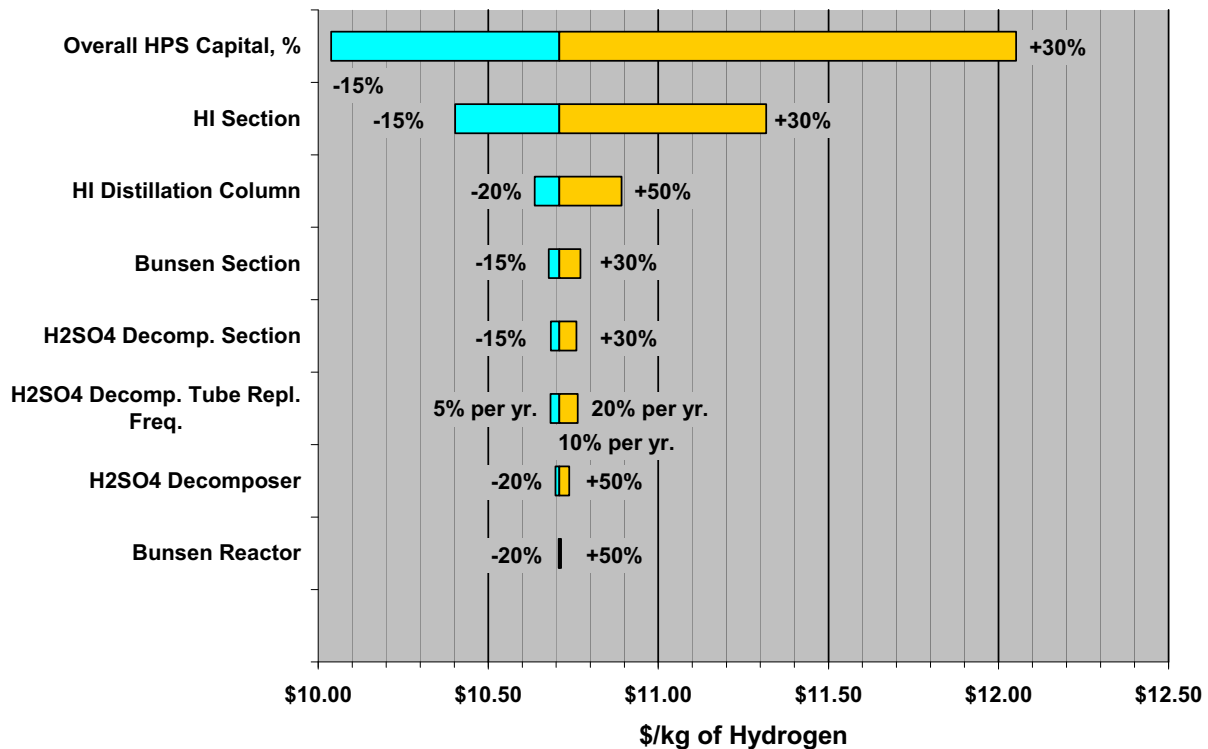


Figure 4-2: Tornado Chart for Sulfur Iodine Initial and Replacement Capital Cost Factors

The capital cost, particularly the cost of the HI section, is the most influential of the selected sensitivity parameters. The HI section cost is due to the tantalum linings needed to resist the concentrated high-temperature acid.

In Figure 4-2, the hydrogen cost can be seen to be most sensitive to the two factors most closely associated with the capital investment – the rate of return and the capacity factor. This is also a manifestation of the high capital cost of the process plant. The next most sensitive cost driver is the nuclear energy cost followed by the electric energy cost. A plant double the size shows significant cost effectiveness, but as discussed elsewhere in this report, the reference plant size is at the limit of what is foreseen to fit the hydrogen market.

The credit for CO₂ avoidance relative to future ambient temperature electrolysis as calculated is significant. In that comparison, the CO₂ emission comes from “upstream” generation of electricity, and SI hydrogen production consumes less imported electricity than the electrolysis. However, a similar calculation for comparison to Steam Methane Reforming (SMR) showed that the combination of direct CO₂ emission plus “upstream” emission from natural gas production and delivery, and electricity generation for SMR, is less than that from the “upstream” generation of import electricity for SI. “Upstream” emissions are taken from data available in DOE’s H2A analysis model^[Ref. 13].

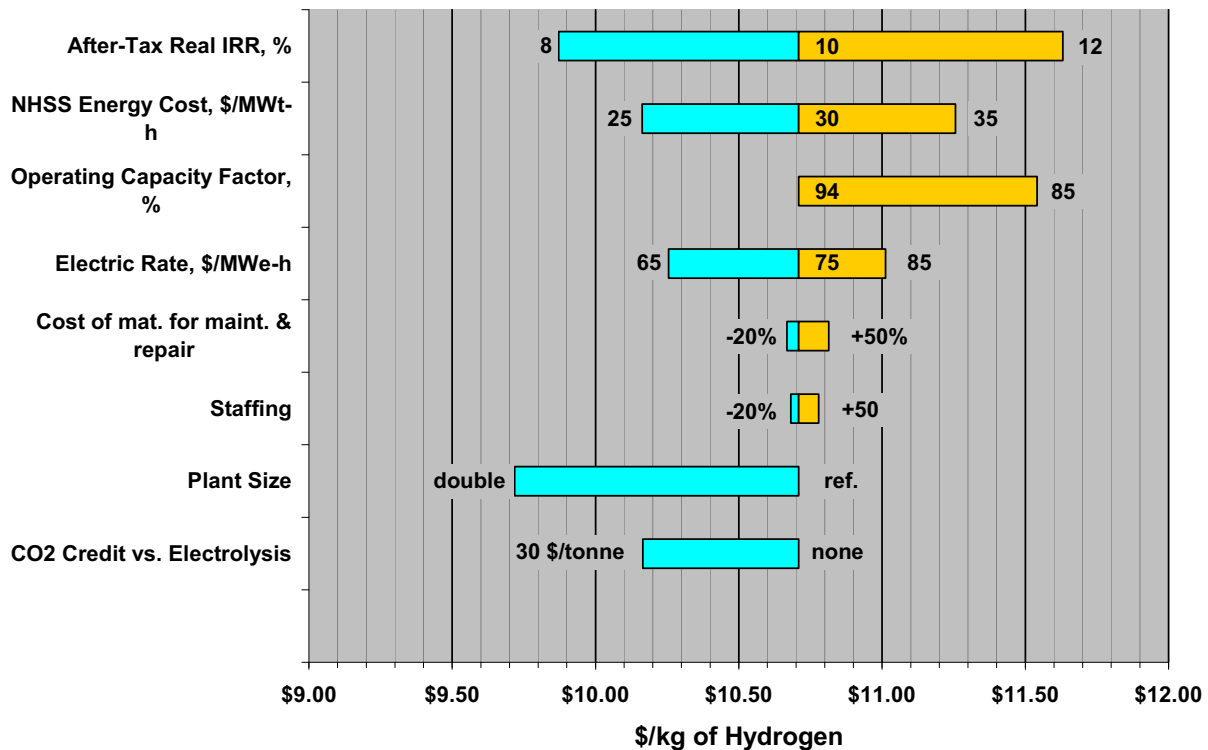


Figure 4-3: Tornado Chart for Sulfur Iodine's Other Cost Factors

4.5.2 Hybrid Sulfur

The Hybrid Sulfur HPS modeled for this study is as described in Section 3. For this case, the HPS consists of four process trains supplied with heat from two 550 MW_{th} nominally rated nuclear heat sources. Electricity is supplied from a steam turbine-generator system within the plant and also imported electricity. Figure 4-4 is a schematic representation of the overall plant arrangement.

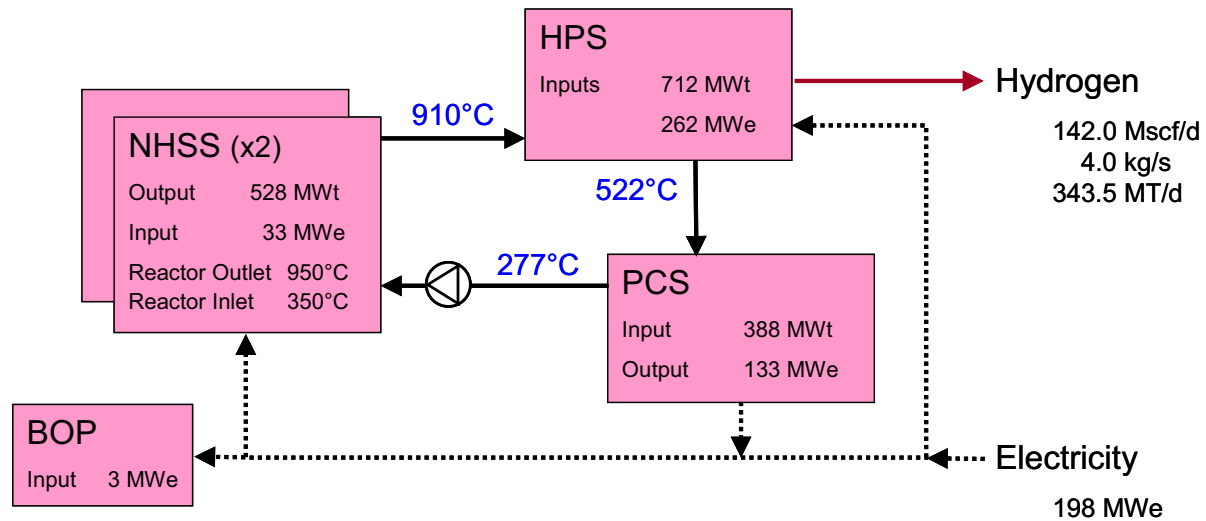


Figure 4-4: Schematic Diagram and Energy Balance for Hybrid Sulfur

4.5.2.1 Reference Case H₂ Selling Price

Table 4-11 presents the major performance factors for the reference case. The NHSS energy cost, import electricity cost and O₂ byproduct price are parameters subject to sensitivity analysis in each case also.

Table 4-11: Hybrid Sulfur – Overall Cost and Performance Factors for Analysis

Major Plant Parameters	
Nuclear Reactor Power	2 x 528 MW _{th} = 1,056 MW _{th}
PCHX Heat Input	712 MW _{th}
Plant H ₂ Output	4.0 kg/s 142 MMSCFD
Electric Power Generated	136 MW _e
Additional Electricity Imported	198 MW _e
Major Input / Byproduct Costs ¹	
Cost of High-Temperature Heat	\$ 30 /MW _{th} -hr
Cost of Electricity, Levelized ²	\$ 101 MW _e -hr
Cost of Water	\$ 0.0021 /gal
Price for O ₂ By-product	\$ 40 /tonne

Notes:

¹ 2008 dollars

² \$75 /MW_e-hr in 2008, escalated at 1%/yr

Table 4-12 summarizes the capital cost of the reference case. Details of the capital cost are in Section 8.1.7.

Table 4-12: Hybrid Sulfur – Capital Cost Summary

	Total Costs	Specific Costs
Hydrogen Plant Capital Cost	\$ 918M	\$ 2,670 /kg H ₂ /day \$ 1,925 /kW _{th} H ₂ (LHV)
Power Conversion System Capital Cost	\$ 188M	\$ 1,170 /kW _e
BOP & Other Capital Cost	\$ 40M	--
Total Direct Capital Cost	\$ 1,146M	--
Indirect Capital Cost	\$ 63M	--
Base Construction Cost	\$ 1,209M	--
Contingency	\$ 115M	--
Total Depreciable Capital Cost	\$ 1,324M	--
Cost of Land	\$ 2.5M	--
Total Overnight Capital Cost	\$ 1,326M	\$ 3,860 /kg H ₂ /d \$ 2,780 /kW _{th} H ₂ (LHV)
Interest During Construction	\$ 172M	--
Total Capital Investment	\$ 1,498M	\$ 4,360 /kg H ₂ /d \$ 3,140 /kW _{th} H ₂ (LHV)

The capital costs summarized in Table 4-12 include more than the capital costs stated elsewhere in this report for the process plant alone. This is described previously in Section 4.2.1.3.

Periodic replacement costs that are accounted for in the analysis are shown in Table 4-13. As with the Sulfur Iodine process, the Sulfuric Acid Decomposer is the process coupling heat exchanger and is where the highest temperatures are present in the process. The Sulfuric Acid Decomposer utilizes silicon carbide tubes. The tubes and the associated seals are not expected to operate for the full 30-year expected plant lifetime. Additionally, the electrolyzer cells and the electrolyzer modular units will require replacement or refurbishment on a periodic schedule, as indicated in Table 4-13.

Details of the replacement and operating costs are in Section 8.1.8.

The calculated hydrogen selling price for the economic ground rules summarized in Table 4-1 and the parameters in shaded columns of Table 4-3 is calculated using the H2A modeling tool to be 6.83 \$/kg H₂ with escalation of the cost of imported electric power. Without the escalation the price would be 6.43 \$/kg H₂, and with the escalation but without the oxygen credit the price comes to 7.21 \$/kg H₂.

Table 4-13: Hybrid Sulfur – Replacement Capital Summary

Parameter	Value
Sulfuric Acid Decomposer Tube Replacement	
Unit life	10 yrs
Replacement frequency	every 2 yrs
Number	1,500
Equip. cost per replacement	\$ 35,700,000
Cell Replacement	
Replacement frequency	5 yrs
Unit replacement cost	\$ 984
Number	48,400
Equip. cost per replacement	\$47,625,600
Electrolyzer Replacement	
Replacement frequency	20 yrs
Unit replacement cost	\$ 300,000
Number	392
Equip. cost per replacement	\$ 117,600,000

Table 4-14 shows the breakdown of the components of the hydrogen selling price.

Table 4-14: Hybrid Sulfur – Hydrogen Price Components Summary

	\$/kg H ₂	%
Capital Charge	2.20	32
Fixed O&M: Labor, Taxes, Insurance, Annual Licensing, Permits and Fees, Material Costs for Maintenance And Repairs, Nuclear Decommissioning Funding, Helium Make-up	0.43	6
Variable O&M: Process Catalyst and Chemical Consumption and Waste Disposal	0.58	9
Nuclear Heat	2.36	35
Electric Power	1.48	22
Process & Cooling Water	0.15	2
Byproduct Credit (O ₂)	- 0.38	- 6
Total Hydrogen Cost (Year 2008 Real \$/kg)	6.83	100

4.5.2.2 Sensitivity analysis

The sensitivities of the HyS hydrogen cost to the parameters listed in Table 4-3 are presented as “tornado” diagrams in Figure 4-5 and Figure 4-6. In the first figure are sensitivities to variation in capital cost elements, and the second figure shows sensitivities to other cost elements. Sensitivity to reactor outlet temperature is covered in Section 5.3.

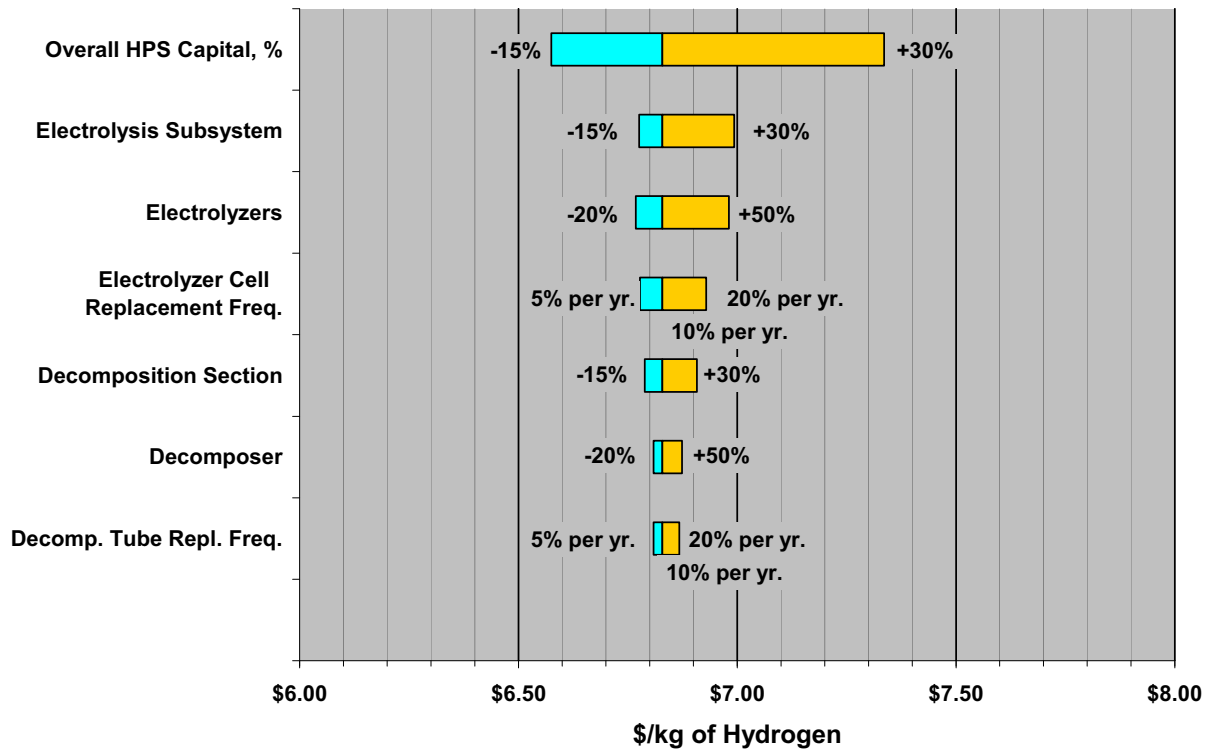


Figure 4-5: Tornado Chart for HyS Initial and Replacement Capital Cost Factors

The overall HPS capital cost is the most influential of the selected sensitivity parameters. The electrolyzer cost and electrolyzer replacement frequency are next most significant. The costs of the decomposer and its replacement are less significant.

In Figure 4-6, the hydrogen cost can be seen to be most sensitive to the IRR, nuclear heat cost and capacity factor, and, following those, to the electric power cost.

While the HyS hydrogen production cost looks very good compared to conventional electrolysis, it is to be expected because it uses less electricity. The HyS analysis also shows hydrogen price advantage over SMR, when considering increased CO₂ penalties. This is not the case for SI or HTSE because of the lower relative imported electricity consumption.

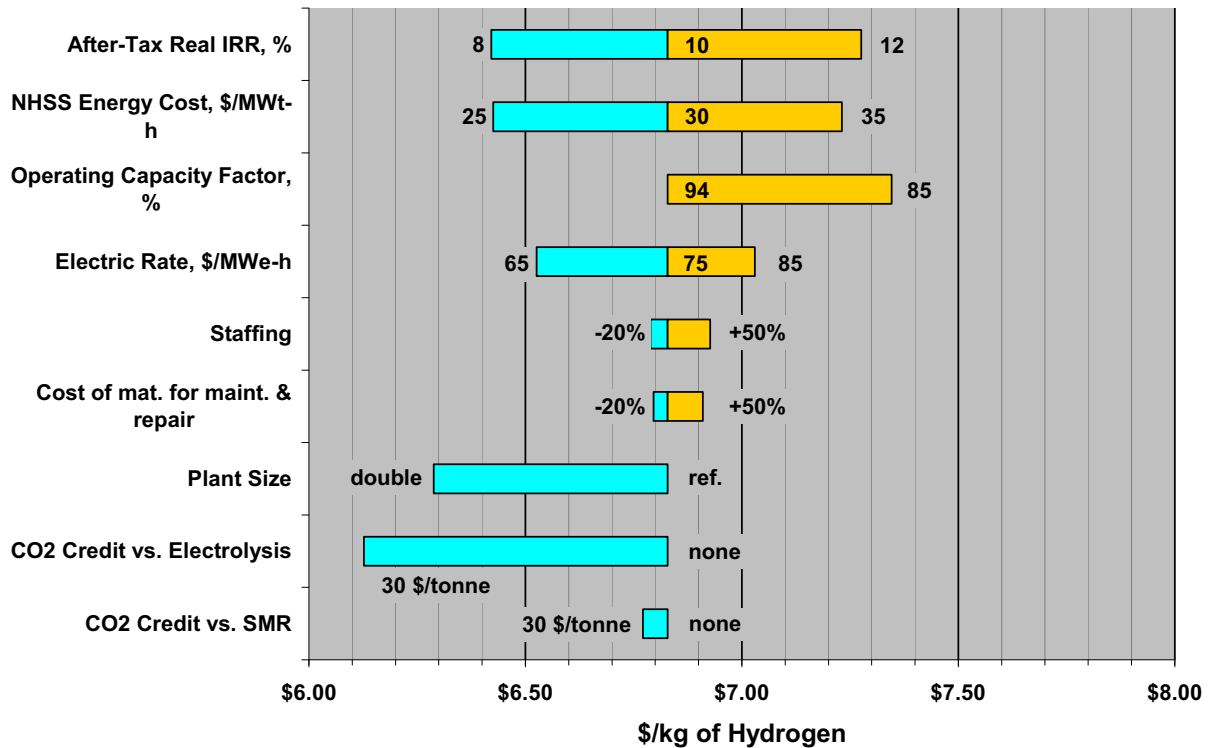


Figure 4-6: Tornado Chart for Hybrid Sulfur's Other Cost Factors

4.5.3 High Temperature Steam Electrolysis

For this case, the HPS is described in Section 3. The case consists of one process train supplied with thermal energy from one nominal 550 MW_{th} nuclear heat source, with electric power from a steam turbine-generator system within the plant and with imported electricity. Figure 4-7 is a schematic representation of the overall plant arrangement.

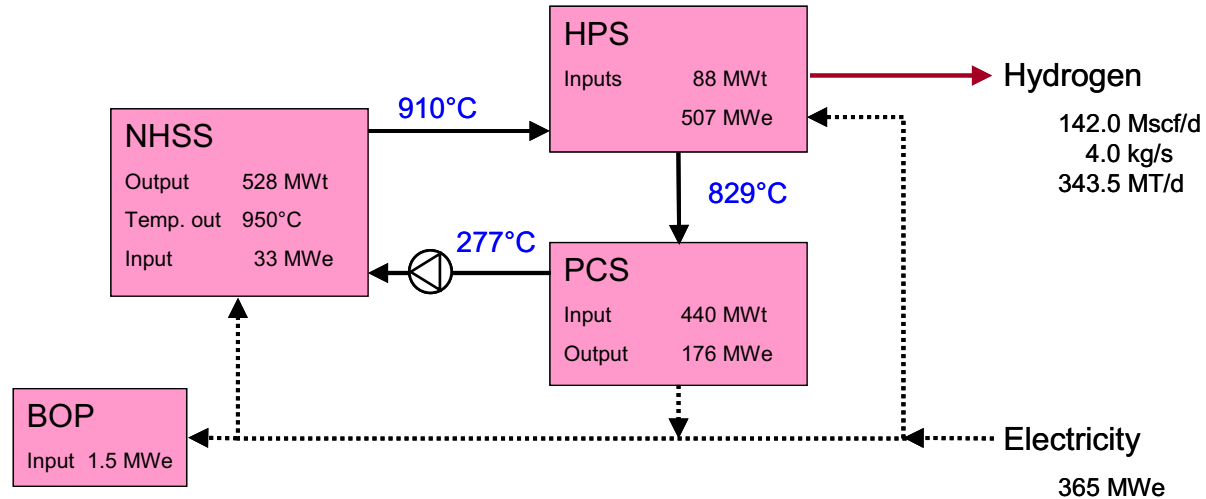


Figure 4-7: Schematic Diagram and Energy Balance for HTSE

4.5.3.1 Reference Case H₂ Selling Price

Table 4-15 presents the major performance factors for the HTSE reference case. The NHSS energy cost, import electricity cost, and O₂ byproduct price are parameters subject to sensitivity analysis in each case.

Table 4-15: HTSE – Overall Cost and Performance Factors for Analysis

Major Plant Parameters	
Nuclear Reactor Power	528 MW _{th}
PCHX Heat Input	88 MW _{th}
Plant H ₂ Output	4.0 kg/s 142 MMSCFD
Electric Power Generated	180 MW _e
Additional Electricity Imported	365 MW _e
Major Input/Byproduct Costs ¹	
Cost of High-Temperature Heat	\$ 30 / MW _{th} -hr
Cost of Electricity, Levelized ²	\$ 101 / MW _e -hr
Cost of Water	\$ 0.0021 /gal

Notes:

¹ 2008 dollars

² \$75 /MW_e-hr in 2008, escalated at 1%/yr

Table 4-16 summarizes the capital cost of the reference case. Details of the capital cost are in Section 8.3.7.

Table 4-16: HTSE – Capital Cost Summary

	Total Costs	Specific Costs
Hydrogen Plant Capital Cost	\$ 509M	\$ 1,480 /kg H ₂ /day \$ 1,070 /kW _{th} H ₂ (LHV)
Power Conversion System Capital Cost	\$ 212M	\$ 1,175 /kW _e
BOP & Other Capital Cost	\$ 40M	--
Total Direct Capital Cost	\$ 761M	--
Indirect Capital Cost	\$ 63M	--
Base Construction Cost	\$ 824M	--
Contingency	\$ 76M	--
Total Depreciable Capital Cost	\$ 900M	--
Cost of Land	\$ 2.5M	--
Total Overnight Capital Cost	\$ 903M	\$ 2,630 /kg H ₂ /d \$ 1,890 /kW _{th} H ₂ (LHV)
Interest During Construction	\$ 117M	--
Total Capital Investment	\$ 1,020M	\$ 2,970 /kg H ₂ /d \$ 2,140 /kW _{th} H ₂ (LHV)

Periodic replacement costs that are accounted for in the analysis are shown in Table 4-17. As with the Hybrid Sulfur process, the electrolyzer's modular units will require replacement or refurbishment on a periodic basis. Table 4-17 summarizes the replacement schedule and costs. Details of replacement and operating costs are in Appendix 8.3.8.

Table 4-17: HTSE – Replacement Capital Summary

Parameter	Value
Electrolyzer Replacement	
Cell Stacks	
Replacement frequency	4 per year
Unit replacement cost	\$ 1,880,000
Cost per replacement	\$ 7,520,000
Stack Assemblies	
Replacement frequency	7 per year
Unit replacement cost	\$ 184,000
Cost per replacement	\$ 1,288,000
Module Enclosures	
Replacement frequency	2 per year

Parameter	Value
Unit replacement cost	\$ 270,000
Cost per replacement	\$ 540,000
High-Temperature Heat Exchanger Replacement	
Replacement frequency	15 yrs
Equip. cost per replacement	
Heat exchangers	\$ 2,321,000
Connecting pipe	\$ 1,160,500
Equipment cost total	\$ 3,481,500
Replacement labor cost	\$ 19,200
Piping Replacement	
Replacement frequency	15 yrs
Equipment cost total	\$ 7,000,000
Replacement labor cost	\$ 23,040

The calculated hydrogen selling price for the economic ground rules summarized in Table 4-1 and the parameters in the shaded columns of Table 4-3 is calculated using the H2A modeling tool to be 6.04 \$/kg H₂ with escalation of the cost of imported electric power. Without the escalation, the price would be 5.31 \$/kg H₂.

Table 4-18 shows the breakdown of the components of the hydrogen selling price.

Table 4-18: HTSE – Hydrogen Price Components Summary

	\$/kg H ₂	%
Capital Charge	1.52	25
Fixed O&M: Labor, Taxes, Insurance, Annual Licensing, Permits and Fees, Material Costs for Maintenance And Repairs, Nuclear Decommissioning Funding, Helium Make-up	0.34	6
Variable O&M: Process Catalyst and Chemical Consumption and Waste Disposal	0.27	5
Nuclear Heat	1.18	19
Electric Power	2.72	45
Process & Cooling Water	0.01	0.1
Byproduct Credit (O ₂)	0.00	0
Total Hydrogen Cost (Year 2008 Real \$/kg H ₂)	6.04	100

4.5.3.2 Sensitivity analysis

The sensitivities of the HTSE hydrogen cost to the parameters listed in Table 4-3 are presented as “tornado” diagrams in Figure 4-8 and Figure 4-9. The first figure presents sensitivities to variations in capital cost elements, and the second figure shows sensitivities to other cost elements. Sensitivity to reactor outlet temperature is discussed in Section 5.3.

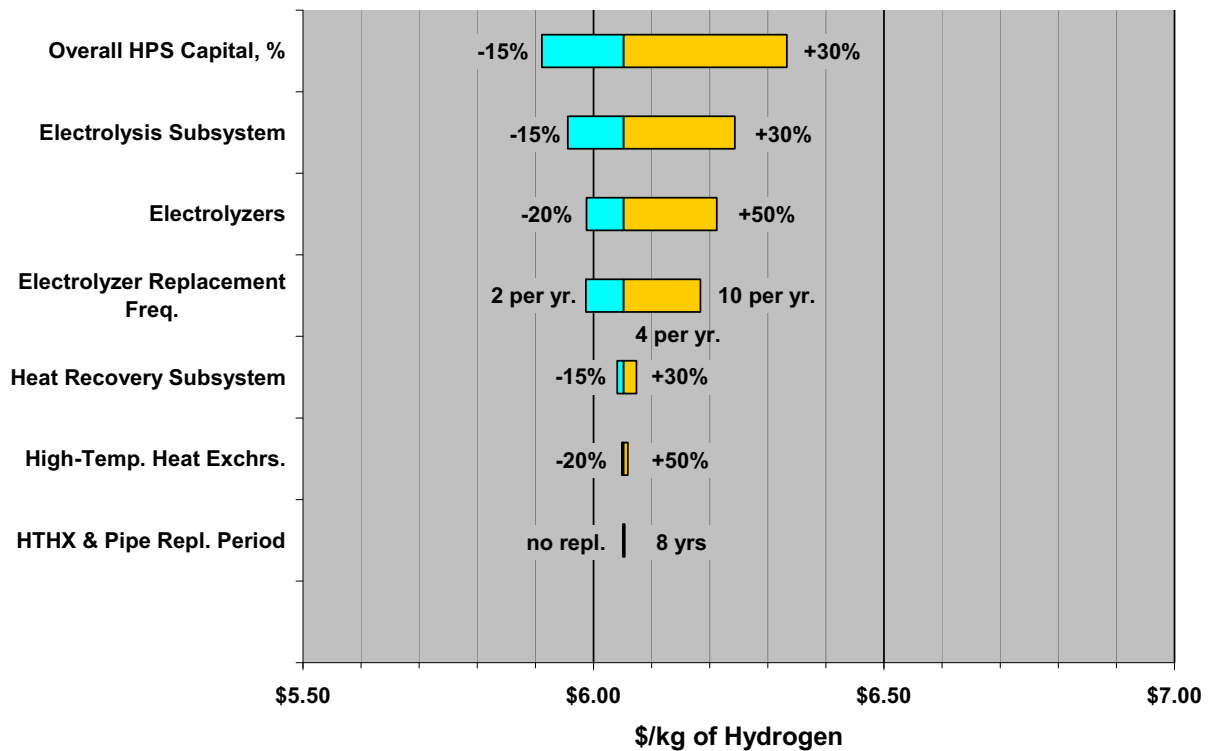


Figure 4-8: Tornado Chart for HTSE's Initial and Replacement Capital Cost Factors

The overall HPS capital cost is the most influential of the selected sensitivity parameters. The electrolyzer cost and electrolyzer replacement frequency are the next most significant.

The high-temperature heat exchangers in the process include the Sweep Gas Feed Water Superheaters, Hydrogen Feed Water Superheaters, Superheated Steam Process Coupling Heat Exchangers, and the Sweep Gas Process Coupling Heat Exchangers. These vessels and the pipe between them will require replacement during the life of the plant because of their high operating temperatures (i.e., up to 910°C on the hot sides). However, the hydrogen cost is not very sensitive to this replacement requirement.

In Figure 4-9, the hydrogen cost is most sensitive to the cost of electricity, as one might expect for an electrolysis system. The results compare favorably to conventional electrolysis, which is to be expected because of the lower electric power needed.

Two values of hydrogen cost are plotted for larger plant sizes. The first is for an approximate doubling in the plant output to 300 MMSCFD. The second shows the economy of scale for a plant producing 893 MMSCFD, which correlates to an HPS that uses the entire nuclear heat from one HTGR nuclear unit and imports all needed electricity. It should be noted that this would be an unreasonably large plant and not one likely to suit the hydrogen market.

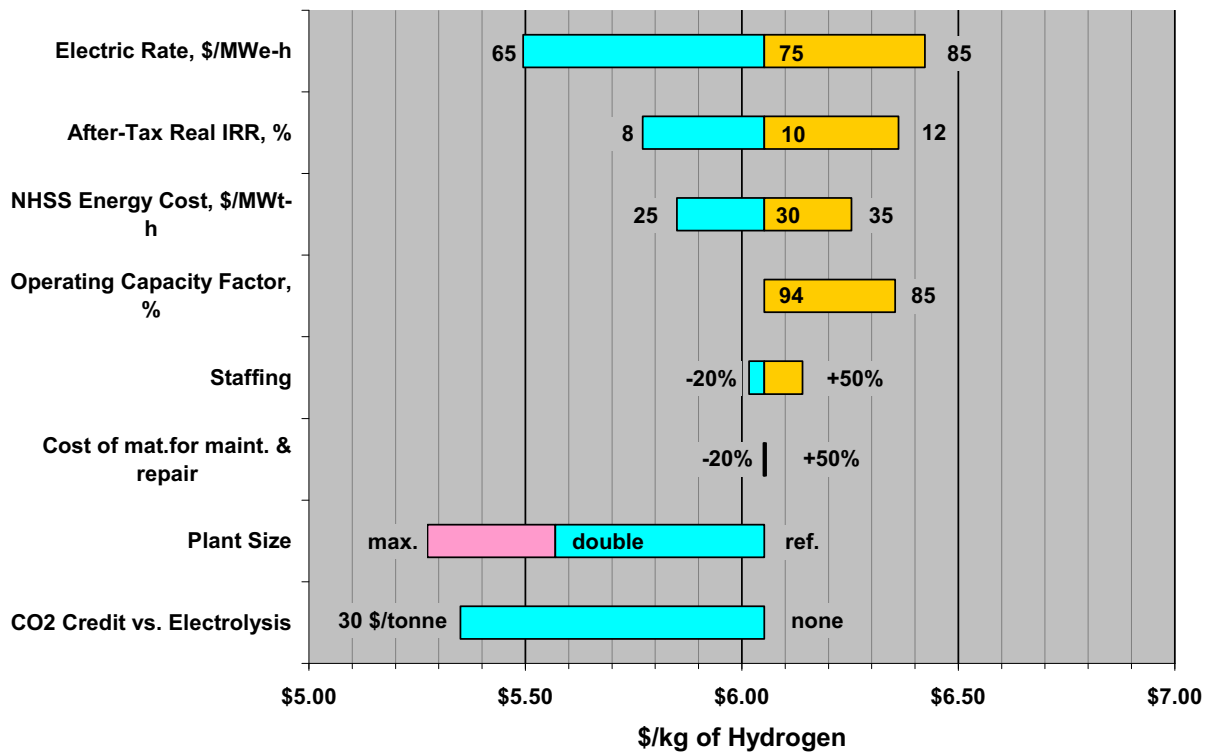


Figure 4-9: Tornado Chart for HTSE's Other Cost Factors

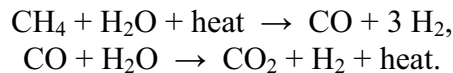
4.5.4 Comparison to Baseline Alternates

The resulting reference case hydrogen prices for the three production technologies are compared on an equivalent basis to the prices for hydrogen from alternate baseline technologies. These baselines are natural gas steam reforming and alkaline water electrolysis. The authors caution that although these alternative baseline economic analyses were performed using the H2A economic model, the bases of the capital costs utilized by the model for these alternatives have been developed using unknown methodologies and assumptions.

4.5.4.1 Natural Gas Steam Reforming Baseline

The SMR process is used to convert natural gas into hydrogen. As distributed commercially, methane generally constitutes 95% of natural gas by molar fraction. Methane

reacts with steam in a two-stage chemical process according to the following equations, producing hydrogen and CO₂:



The CO₂ produced in these reactions can be captured relatively easily.

Natural gas is both the feed to the process and the heat source for the first of the two reactions. The heat is generated from simple atmospheric combustion, as follows:



The CO₂ produced from combustion, which would ordinarily go out up a stack, is difficult and expensive to capture.

SMR is the conventional industrial process for large-scale hydrogen production today. This is hydrogen primarily used in the oil refining and petrochemical industries. Future SMR plants will use essentially the same technology, but with some expected improved efficiency and anticipated lower capital cost. An H2A analysis of advanced SMR^[Ref. 14] is used for the baseline calculation. The case used corresponds to present technology for SMR with CO₂ capture and sequestration with efficiencies and costs projected for 2025. The CO₂ is captured from both the syngas product stream and the combustion stack by aqueous amine solution. CO₂ capture efficiencies for the product stream and the combustion products leaving the stack are 99% and 90%, respectively. The reference model was used with minimal changes. One input change to the model was to factor plant capital costs from 2005 to mid-2008 dollars by a multiplier of 1.25 based upon changes to costs of chemical equipment, labor, and engineering^[Ref. 15].

The SMR hydrogen selling price will be most sensitive to the cost of natural gas. Since the natural gas price is expected to rise at a higher rate than general inflation in the future, the H2A calculation tool was modified to enter a fixed percentage real escalation rate for natural gas, which is an escalation above the rate of general inflation. The range of recent historical natural gas cost is \$8.00/MMBtu, which reflects the 2007 year price for industrial gas^[Ref. 16], to \$10.00/MMBtu, which is a data point from mid 2008^[Ref. 17]. For real escalation, a rate of 2% is estimated based on the recent annual price increase of natural gas. Because the input cost is escalated, the hydrogen selling price is a levelized cost over the 40-year plant lifetime deflated back to 2007 dollars.

Future natural gas price, and to a lesser degree CO₂ costs, are the two main driving factors for SMR economics. Table 4-19 shows the results of the analysis for the hydrogen price from SMR with these factors varied. The SMR technology is based upon the advanced technology case. Costs are in 2008 dollars, as per the ground rules described in Section 8.5.2.

The sensitivity of the hydrogen price to natural gas cost is further demonstrated in Figure 4-10 for cases with and without the 2% gas price escalation in the model. Escalation is also included for the small amount of electricity used by the modeled SMR plant and for the CO₂

costs. In such an analysis that includes real escalation, the forecast selling price of hydrogen may increase significantly, depending on the escalation rate.

Table 4-19: Hydrogen from Natural Gas by Advanced Steam Methane Reforming

Sensitivity Analysis Case	Natural Gas Cost * \$/MMBtu	CO ₂ Emission Penalty * † \$/MT	Hydrogen Selling Price \$/kg H ₂
Reference Case	8	30	2.16
Increased Natural Gas Cost	12	30	2.93
Increased CO ₂ Cost	8	100	2.26
Both Higher Natural Gas and CO ₂ Costs	12	100	3.02

* No real escalation in natural gas cost

† \$30/MT CO₂ is \$110/MT C; \$100/MT CO₂ is \$367/MT C

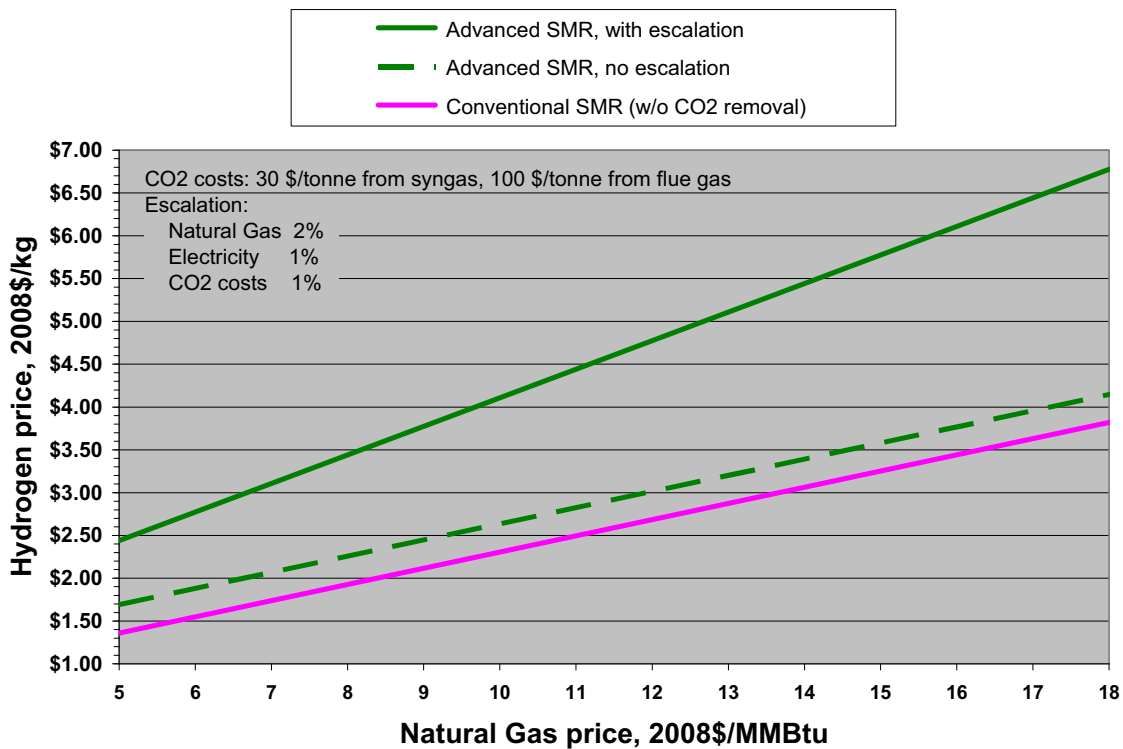


Figure 4-10: H₂ Price from SMR as a Function of Natural Gas Cost with Escalation

4.5.4.2 Alkaline Water Electrolysis Baseline

Water electrolysis uses direct electric current to split water, as in the classic tabletop school experiment. Historically, it has been occasionally used for industrial hydrogen generation where electricity is economically priced. It is referred to as alkaline electrolysis because potassium hydroxide (KOH) is added to the water as an electrolyte. There is one manufacturer of large-scale electrolysis units, Hydrogen Technologies, a division of StatoilHydro, formerly Norsk Hydro^[Ref. 18]. Their production plants comprise multiple units having many electrolysis cells. In conventional electrolysis cells, the electrodes utilize non-platinum group catalysts, and a membrane separates the electrodes so that the hydrogen and oxygen products do not mix. Significant effort is underway to improve the performance of conventional alkaline electrolysis. With partial DOE funding, General Electric has been pursuing two avenues – improved electrodes and lower manufacturing cost^[Ref. 19].

Two H2A cases posted on the DOE website utilize grid electricity for conventional electrolysis^[20]. One change made is an increase in capital costs from 2005 to 2008, as done for the SMR baseline case. The two cases are current conventional alkaline electrolysis technology and future electrolyzer technology. In the analysis of current electrolysis, the model uses performance data from StatoilHydro of an efficiency of 74% on a HHV basis. An electrolyzer cost of \$1000/kW_e in 2008 dollars was used herein based on specific pricing^[Ref. 21].

For future grid electrolysis, considered to be in 2030, the H2A model includes an electrolyzer cost of \$375/kW_e in 2008 dollars. The cost of \$375/kW_e (i.e., \$300/kW_e in 2005 dollars) is a DOE H2A program consensus^[Ref. 22] based on a target for fuel cell costs set in the DOE fuel cell vehicle program.

For all cases, a credit is included in the hydrogen price for byproduct oxygen from the electrolysis process at \$40/MT.

The dominant cost input factors for the electrolysis baseline case are the capital cost of the electrolyzers and the cost of electric energy used. The input electricity cost for a reference point baseline calculation is \$60/MW_e-hr, which is representative of recent industrial electricity pricing^[Ref. 23]. Although unlike natural gas pricing, for which there is a nationwide market, the price of electricity is highly variable region-to-region. Table 4-20 shows the results of the analysis for the hydrogen price from electrolysis with the capital and electric cost factors varied. These cases do not have any escalation of electricity cost. Costs are in 2008 dollars, as per the ground rules discussed in Section 8.5.2.

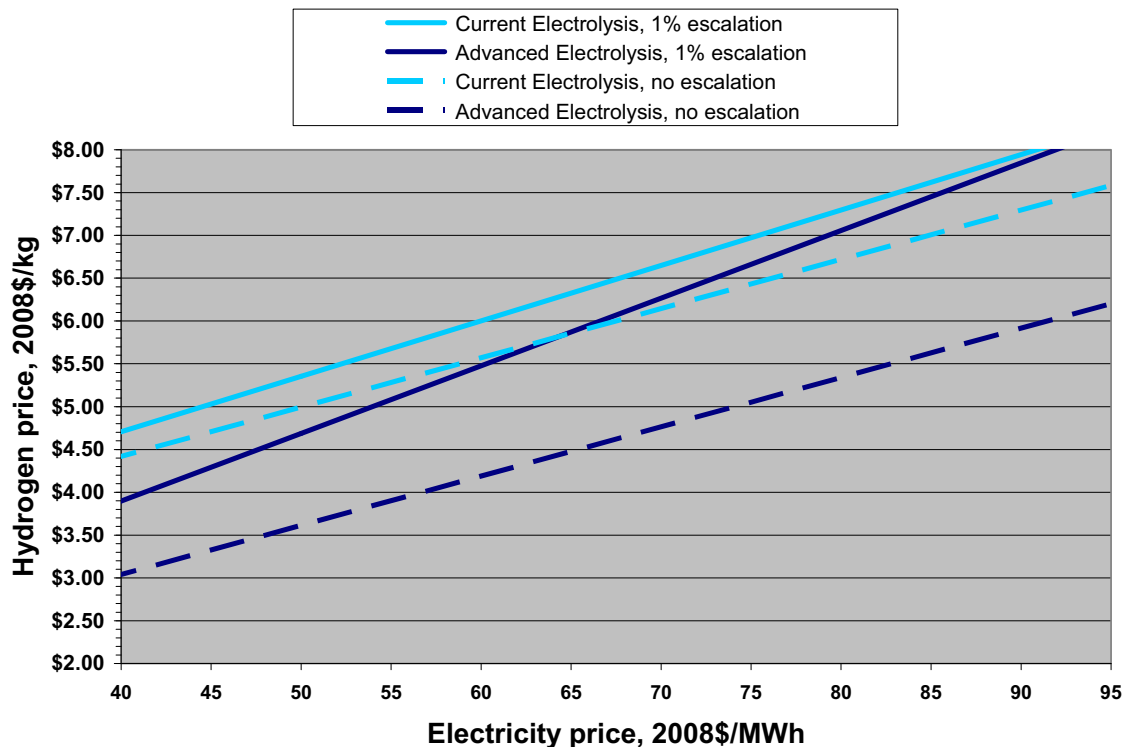
Table 4-20: Hydrogen from Conventional Alkaline Electrolysis

Sensitivity Analysis Case	Electrolyzer Capital Cost* \$/kW _e	Electricity Cost† \$/MW _{th}	Hydrogen Selling Price \$/kg H ₂
Reference Case	1000	60.00	5.57
Future Electrolyzer	375	60.00	4.19
Future Electrolyzer and Higher Electricity Cost	375	90.00	5.92

* uninstalled modular equipment cost, 2008 dollars

† no real escalation in electricity cost

As with the natural gas cost in the SMR baseline analysis, the H2A model was modified to include a 1% real escalation in the electric power cost as an option. Figure 4-11 shows the effect of electricity cost on the hydrogen selling price with and without real electricity price escalation for the current electrolyzer cost and the projected most optimistic future case.

**Figure 4-11: Hydrogen Price from Electrolysis as a Function of Electricity Cost**

4.5.4.3 Comparison to Reference cases

It is useful then to compare the calculated price for hydrogen with Sulfur Iodine, Hybrid Sulfur and HTSE processes with calculations on the same bases of hydrogen production from the baseline alternative technologies (i.e., natural gas SMR and ambient temperature electrolysis).

This includes evaluation of the variations of the SMR and electrolysis prices to the most significant driving factors comprising them. However, it should be noted that while the H2A economic tool uses a consistent methodology in the analyses, the capital and operating cost bases underlying the alternatives may not use commensurate design assumptions and reference conditions.

Figure 4-12 shows the comparison of nuclear high-temperature hydrogen cost to SMR hydrogen for a range of natural gas prices. Figure 4-13 shows the comparison of the three to grid power electrolysis for a range of electricity prices. For SMR, the natural gas, electricity, and CO₂ costs are escalated at 2%, 1%, and 1%, respectively. For the HyS and electrolysis, the cost of electricity is escalated at 1%.

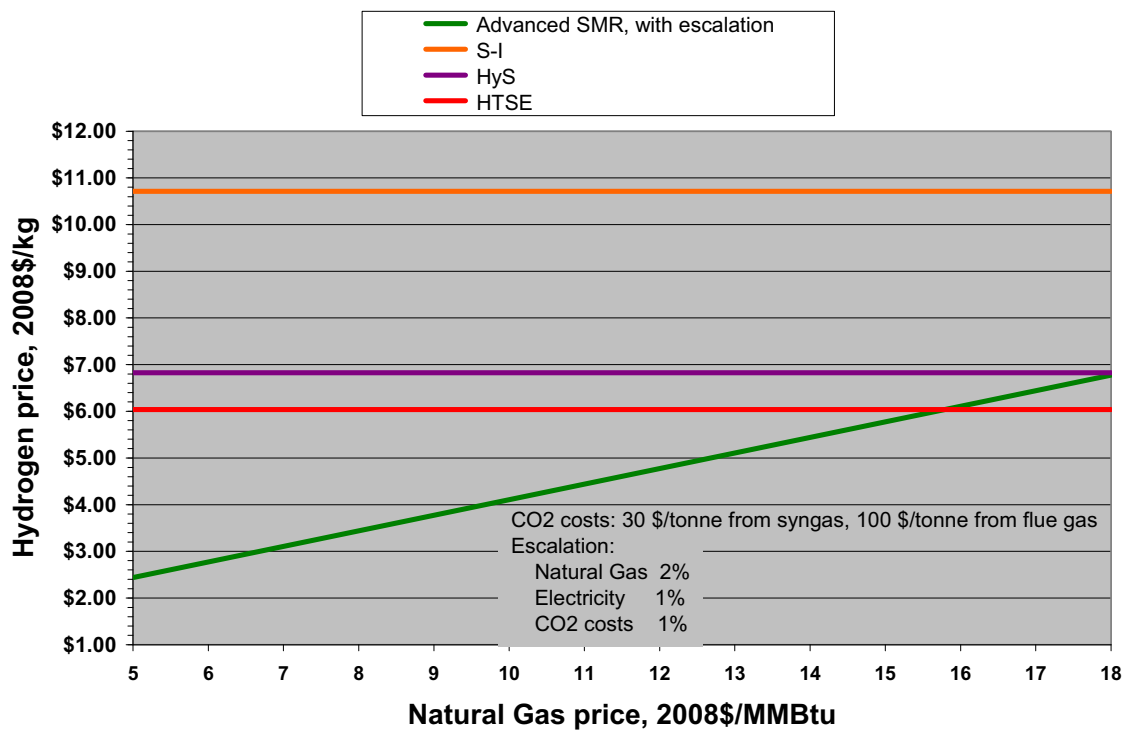


Figure 4-12: Hydrogen Price and SMR Baseline, All with Escalation

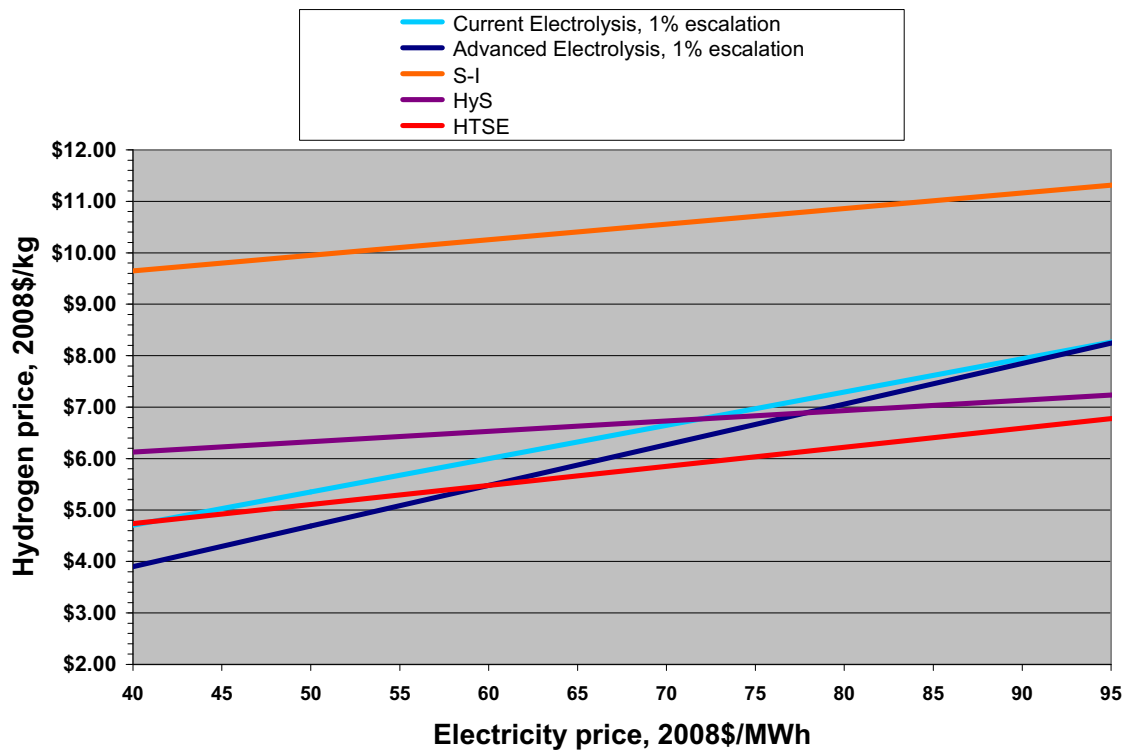


Figure 4-13: Hydrogen Price and Electrolysis Baselines, All with Escalation

As indicated earlier, reference values for recent historical prices of natural gas are \$8/MMBtu and for industrial electricity \$60/MW_e-hr. Higher values for comparison might be the spot price ranges as of this writing, which are \$9.25 to \$10/MMBtu and \$75 to \$90/MW_e-hr^[Ref. 24]. In June 2008, natural gas prices reached \$13/MMBtu with the price of crude oil peaking then as well. Also, because of seasonal variations, the spot price of natural gas is not an indicator of the annual average.

4.6 FINANCING HURDLES

A measure of the difficulty of executing a project to produce hydrogen is the imposing level of investment that must be assured. This is the amount of capital needed for construction of a mature HPS facility. The total capital requirement would include the cost for the hydrogen production equipment, the power conversion system and the capital to build the reactor plant. Table 4-21 illustrates the relative magnitude of this financing hurdle for the three hydrogen production systems.

Table 4-21: Project Capital Financing Hurdle

	HTSE	HyS	SI
Plant Capacity, MMSCFD	142	142	157
Hydrogen Plant Capital Cost (no contingency), \$million	509	918	2,683
Power Conversion System Cost, NNGP-19-RPT-001 Section 19.1.2.4 (Scaled & Escalated), \$million	212	188	N/A
Total Capital Cost for Hydrogen Production Facility (incl. BOP, Other Costs and Contingency; not including interest during construction), \$million	903	1,326	3,061
Number of HTGRs required	1	2	3
Reactor Thermal Output, MW _{th}	550	550	550
Capital Cost of reactor plant(s) from NNGP-19-RPT-001 Section 19.2 (Scaled & Escalated), \$million	1,349	2,192	2,912
Total Capital Required for ~150 MMSCFD Hydrogen Production Facility, \$million	2,252	3,518	5,973
Imported Power, MW _e	365	198	330
Capital allocation for new nuclear generation at 3,599 \$/kW _e , \$million	1,177	410	813
Total Capital required for Hydrogen Production, \$million	3,429	3,928	6,786

5 OTHER FACTORS AFFECTING COMMERCIAL POTENTIAL

5.1 SAFETY, HEALTH AND ENVIRONMENTAL ASSESSMENT

5.1.1 Hybrid Sulfur Process

The Hybrid Sulfur HPS is described in Sections 2 and 3. The process feed material is water and a small amount of 50% by weight sulfuric acid. The process products are hydrogen and oxygen gas. Process intermediates include large amounts of sulfur dioxide, sulfur trioxide, and sulfuric acid. Sodium hydroxide (NaOH) is used as a scrubbing agent.

HyS is a process in which 50% by weight sulfuric acid from the electrolyzers, which contains dissolved sulfur dioxide, is stripped of the sulfur dioxide, and further concentrates the sulfuric acid to 75% by weight. The sulfuric acid is then decomposed to steam, oxygen, and sulfur dioxide at high pressure and high temperature. The product and stripped sulfur dioxide is dissolved in water and is sent as anolyte to the electrolyzer. Water is supplied to the cathode where it is separated into hydrogen and oxygen ions and converts the sulfur dioxide water solution into sulfuric acid.

The HyS process involves hazardous chemicals that are commonly used in chemical processing and manufacturing, and the process products are either explosive or an oxidizer, as shown in Table 5-1. In process chemicals are toxic and aggressively corrosive.

Table 5-1: Hazardous Chemicals – Hybrid Sulfur Electrolysis

Chemical	Hazards	Hybrid Sulfur	
		Sulfuric Acid Decomposition	Electrolysis
	Temperature, °C	870	99
	Pressure, Bar	86	23
Air			
Water		X	X
Oxygen, 50% with Diluent Gas	Oxidizer	X	
Oxygen, pure	Strong Oxidizer		
Hydrogen, pure	Explosive, Asphyxiate		X
Sulfur Dioxide	Toxic, Corrosive	X	X
Sulfur Trioxide	Toxic, Corrosive	X	

Chemical	Hazards	Hybrid Sulfur	
		Sulfuric Acid Decomposition	Electrolysis
Hydroiodic Acid	Toxic, Corrosive		
Iodine	Toxic, Corrosive, Strong Oxidizer		
Sodium Hydroxide (aq. sol)	Toxic, Corrosive	X	
Sulfuric acid	Toxic, Extreme Corrosive	X	X

The HyS process utilizes 800 pieces of equipment, including installed spare capacity, to produce 142 MMSCFD of hydrogen gas. The breakdown of equipment by type and process section is shown in Table 5-2.

Table 5-2: HyS Process Equipment Summary

Equipment	Hybrid Sulfur (2 Production Trains)			
	Feed & Utility Equipment	Sulfuric Acid Decomp.	Electrolysis	Product Purification
Electrolyzer Modules			432	
Towers		10		2
Vessels & Reactors	2	40	16	32
Low Pressure Tanks	6			
Pumps	20	56	10	
Blowers, Compressors & Turbines		6		4
Steam Ejector				
Heat Exchangers		40	6	26
Filters			82	
Compressors & Air Dryers				
Deionized Water Treatment	1			
Water Treatment RO System				
Oil Water Separator				
Waste Treatment System (Undefined)	1			
Iodine Feed Stock Preparation System				
Total Equipment	30	152	546	72
Grand Total	800			

The principal hazard associated with the HyS process is loss of confinement of hydrogen resulting in a fire or explosion. Other hazards include pressure vessel failures causing loss of confinement of the oxygen resulting in oxygen induced fire. Additional hazards include loss of confinement of sulfuric acid, sulfur dioxide, and sodium hydroxide, potentially resulting in personal injury and damage to both equipment and the environment. Table 5-3 is a preliminary hazard assessment of the HyS hydrogen production process.

The HyS process' operating risk is assessed ***MEDIUM HIGH*** due to the use of hazardous chemicals in the process, the large number of process equipment and the number of hazards associated with the process.

Table 5-3: Preliminary Hazard Assessment, Hybrid Sulfur Hydrogen Production Process

Item	Hazard	Discussion
Concentrated H ₂ SO ₄ At High Pressure And Temperature	Loss of containment of a highly corrosive acid resulting in a release to the environment. High pressure can result in a jet or spray leak.	Concentration of sulfuric acid is practiced industrially. However, the high pressure employed in this process present a hazard over the low pressure industrial process in that leaks have a potential to spray personnel at a significant distance from the leak point. Since the corrosion resistances of metals to sulfuric acid are strong functions of temperature, fluid velocity, and concentration, care must be taken to ensure that operating conditions are well understood before equipment is specified and that actual operating conditions do not significantly vary from design. Joints should be minimized to minimize the potential for leaks. Splash guards should be employed around pumps and any joints located near where personnel may work or pass
Concentrated SO ₂ At High Pressure	Loss of containment of a toxic gas resulting in a release to the environment. High pressure can result in a jet or spray leak	Large quantities of concentrated SO₂ at high pressure represent a serious toxicity hazard. Industrial experience with the safe operation of Claus plants may be a useful reference. The possibility of the release of large quantities of SO₂ from the anolyte solution given a change in temperature or pressure should be considered in the hazards review.
H ₂ Purification And Compression	Loss of containment of a flammable gas at high pressure and temperature resulting in a fire or explosion	The conditions of these operations are within industrial gases industry experience. Standard safety measures should be incorporated into the design. Due to the flammability of H₂, joints, and fittings should be avoided in this piping system. The possibilities of a jet fire or a confined vapor cloud explosion in the region of potential leak points should be considered in the development of the plant layout.

Item	Hazard	Discussion
O ₂ Purification and Compression	The enhanced flammability of materials in O ₂ resulting in an equipment fire	All piping, fittings, and equipment exposed to > 25% oxygen must be oxygen-clean before start up. Fittings that are oxygen-cleaned at the factory must be shipped sealed. The use of soft materials and lubricants should be minimized with oxygen-enriched streams. Fluorinated compounds such as Teflon™ and Viton™ are normally used for seals and per-fluorinated materials as lubricants. The use of O₂ as the regeneration gas for the TSAs will require that the maximum regeneration temperature and pressure be considered in the specification of the materials of construction for the adsorber vessels and piping that will be exposed to the hot gas. It is standard industry practice to place O₂ compressors inside of barriers for containment and personnel protection in case of a fire. The frequency of fires in such equipment should be considered in plant layout
Sulfuric Acid Decomposer	Loss of containment of high pressure He. Contamination of He stream due to tube leaks and acid corrosion of He heat exchange equipment	Keeping the pressure of the He stream above that of the decomposer should minimize acid leakage into the He in the event of a leak.
Water Treatment	No extra ordinary risk	This system should be standard equipment routinely used in industry with standard safety measures.

5.1.2 Sulfur Iodine Process

The Sulfur Iodine hydrogen production process is described in Sections 2 and 3. The process feed material is water, small amounts of 50% by weight sulfuric acid, and iodine. The process products are hydrogen and oxygen gas. Process intermediates include large amounts of sulfur dioxide, sulfuric acid, sulfur trioxide, iodine, and hydroiodic acid. Sodium hydroxide is used as a scrubbing agent.

SI is a process in which water, sulfur dioxide, and iodine are reacted in the presence of oxygen to form hydroiodic acid and sulfuric acid (i.e., Bunsen Reaction). These acids are separated in immiscible liquid phases. The heavy phase, containing large amounts of both hydroiodic acid and iodine, is thermally decomposed into hydrogen and additional iodine. The iodine stream is returned to the Bunsen Reaction. The light phase consisting of 60 % sulfuric acid by weight is concentrated to 75 weight % and is decomposed to oxygen, steam, and sulfur dioxide at high pressure and high temperature. The resulting sulfur dioxide is dissolved in water and is returned to the Bunsen Reaction.

With the exception of iodine and hydroiodic acid, the SI process involves hazardous chemicals that are commonly used in chemical processing and manufacturing, as shown in Table 5-4. The process products are either explosive or an oxidizer.

Table 5-4: Hazardous Chemicals – Sulfur Iodine Process

Chemical	Hazards	Sulfur Iodine		
		Sulfuric Acid Decomposition	Bunsen Reaction	HI Decomposition
	Temperature, °C	870	120	288
	Pressure, Bar	86	12	40
Air				
Water		X	X	X
Oxygen, 50% with Air	Oxidizer			
Oxygen, pure	Strong Oxidizer	X	X	
Hydrogen, pure	Explosive, Asphyxiate			X
Sulfur Dioxide	Toxic, Corrosive	X	X	

Chemical	Hazards	Sulfur Iodine		
		Sulfuric Acid Decomposition	Bunsen Reaction	HI Decomposition
Sulfur Trioxide	Toxic, Corrosive	X		
Hydroiodic Acid	Toxic, Corrosive		X	X
Iodine	Toxic, Corrosive, Strong Oxidizer		X	X
Sodium Hydroxide (aq. sol)	Toxic, Corrosive			
Sulfuric acid	Toxic, Extreme Corrosive	X	X	

The SI Process utilizes 519 pieces of equipment, including installed spare capacity, to produce 157 MMSCFD of hydrogen gas. The breakdown of equipment by type and process section is shown in Table 5-5.

The principal hazards associated with the SI process is loss of confinement of hydrogen resulting in a fire or explosion. Other hazards include pressure vessel failures and loss of confinement of the oxygen resulting in oxygen induced fire. Additional hazards include loss of confinement of sulfuric acid, sulfur dioxide, iodine, and hydroiodic acid resulting in personal injury and damage to both equipment and the environment. Due to the large volumes of hazardous chemicals in the SI process, a loss of confinement event has very high consequences that will require mitigation features to reduce the risk to an acceptable level. Table 5-6 is a preliminary hazard assessment of the SI hydrogen production process.

Table 5-5: Sulfur Iodine Process Equipment Summary

Equipment	Sulfur Iodine (3 Production Trains)				
	Feed & Utility Equipment	Sulfuric Acid Decomp.	Bunsen Reaction	HI Decomposition	Product Purification
Electrolyzer Modules					
Towers	1	6	6	18	3
Vessels & Reactors	1	36	6	30	33
Low Pressure Tanks	9				
Pumps	39	30	45		6
Blowers, Compressors & Turbines		6	6	21	12
Steam Ejector		9			

Equipment	Sulfur Iodine (3 Production Trains)				
	Feed & Utility Equipment	Sulfuric Acid Decomp.	Bunsen Reaction	HI Decomposition	Product Purification
Heat Exchangers	6	30	21	108	27
Filters					
Compressors & Air Dryers					
Deionized Water Treatment	1				
Water Treatment RO System	1				
Oil Water Separator					
Waste Treatment System (Undefined)	1				
Iodine Feed Stock Preparation System	1				
Total Equipment	60	117	84	177	81
Grand Total	519				

The SI process' operating risk is assessed **HIGH** due to the volume and number of hazardous chemicals involved the process, the number of chemical processes required to produce hydrogen, the large number of process equipment and the hazards associated with the process.

Table 5-6: Preliminary Hazard Assessment, Sulfur Iodine Hydrogen Production Process

Item	Risk	Comments
Concentrated H_2SO_4 at high pressure and temperature	Loss of containment of a highly corrosive acid. High pressure can result in a jet or spray leak.	Concentration of sulfuric acid is practiced industrially. The high pressure employed in this process presents a hazard over the low pressure industrial process in that leaks have a potential to spray personnel at a significant distance from the leak point. Joints should be minimized to minimize the potential for leaks. Splash guards should be employed around pumps and any joints located near where personnel may work or pass. Since the corrosion resistances of metals to sulfuric acid are strong functions of temperature, fluid velocity, and concentration, care must be taken to ensure that operating conditions are well understood before equipment is specified and that actual operating conditions do not significantly vary from design.
Concentrated SO_2 at high pressure	Loss of containment of a toxic gas	Large quantities of concentrated SO_2 at high pressure represent a serious toxicity hazard. Industrial experience with the safe operation of Claus plants may be a useful reference.
Hydroiodic acid at high pressure	Loss of containment of corrosive liquid	The high pressures employed in some parts of this process present a hazard in that leaks have a potential to spray personnel at a significant distance from the leak point. Joints should be minimized to minimize the potential for leaks. Splash guards should be employed around pumps and any joints located near where personnel may work or pass. The risk is mitigated by the relatively low concentrations used.
I_2 in vapor and liquid streams	Loss of containment of a toxic gas	A leak of a high temperature, high pressure stream containing dissolved I_2 would likely result in the release of some gaseous I_2 upon pressure letdown.
I_2 containing streams in heat exchangers	Excessive corrosion	The possibility of localized corrosion resulting from “boil to dryness” at points in exchangers and reboilers should be investigated and appropriately considered in equipment design.
H_2 purification and compression	Loss of containment of a flammable gas at high pressure and temperature resulting in a fire or explosion	The drying of H_2 at elevated pressures is within industrial gases industry experience. Standard safety measures should be incorporated into the design. The compression of H_2 to > 100 bar is within industrial gases industry experience. Standard safety measures should be incorporated into the design. Due to the flammability of H_2, joints, and fittings should be avoided in this piping system. The possibilities of a jet fire or a confined vapor cloud explosion in the region of potential leak points should be considered in the development of the plant layout.

Item	Risk	Comments
O ₂ purification and compression	The enhanced flammability of materials in O ₂ resulting in an equipment fire	All piping, fittings, and equipment exposed to > 25% oxygen must be oxygen-clean before start up. Fittings that are O₂-cleaned at the factory must be shipped sealed. The use of soft materials and lubricants should be minimized with oxygen-enriched streams. Fluorinated compounds such as Teflon™ and Viton™ are normally used for seals and per-fluorinated materials as lubricants. The use of O₂ as the regeneration gas for the TSAs will require that the maximum regeneration temperature and pressure be considered in the specification of the materials of construction for the adsorber vessels (and piping that will be exposed to the hot gas). It is standard industry practice to place O₂ compressors inside of barriers for containment and personnel protection in case of a fire. The frequency of fires in such equipment should be considered in plant layout
He exchanger at decomposer	Loss of containment of high pressure He or cross contamination between primary and secondary He streams due to acid corrosion of He heat exchange equipment	Keeping the pressure of the He stream above that of the decomposer should minimize acid leakage into the helium in the event of a leak.
Water treatment		This system should be standard equipment routinely used in industry with standard safety measures.

5.1.3 High Temperature Steam Electrolysis

The High Temperature Steam Electrolysis HPS is described in Sections 2 and 3.

The process feed materials are water and air. The process products are hydrogen gas and oxygen enriched air (50% Air & 50% oxygen). HTSE is a relatively simple process where water is converted to steam at high pressure and high temperature and conveyed to an electrolyzer where it is converted into hydrogen and oxygen at the electrolysis cells' cathodes and anodes, respectively. A portion of the hydrogen gas product is recycled back into the process and mixed with the steam in order to promote reducing conditions at the cathodes. Air is compressed to high pressure and heated to a high temperature prior to being conveyed to the anodes of the electrolysis cells where it reduces the partial pressure of the oxygen.

The HTSE process does not involve hazardous chemicals, but the process products are either explosive or an oxidizer. A summary of hazardous chemicals is shown in Table 5-7.

Table 5-7: Hazardous Chemicals – High Temperature Steam Electrolysis

Chemical	Hazards	HTSE		
		Steam Generation	Sweep Gas Compression	Electrolysis
	Temperature, °C	274	176	870
	Pressure, Bar	58	56	56
Air			X	
Water		X		X
Hydrogen/Water		X		X
Oxygen, 50% with Air	Oxidizer			X
Oxygen, pure	Strong Oxidizer			
Hydrogen, pure	Explosive, Asphyxiate			X

The HTSE process utilizes 120 pieces of equipment, including installed spare capacity, to produce 142 MMSCFD of hydrogen gas. The breakdown of equipment by type and process section is shown in Table 5-8.

Table 5-8: HTSE Process Equipment Summary

Equipment	HTSE (1 Production Train)			
	Feed & Utility Equipment	Heat Recovery	Electrolysis	Product Purification
Electrolyzer Modules			76	
Towers				
Vessels & Reactors	5	1		3
Low Pressure Tanks	1			
Pumps	4			
Blowers, Compressors & Turbines	2	1		
Steam Ejector				
Heat Exchangers	6	7	2	2
Filters				
Compressors & Air Dryers	6			
Deionized Water Treatment	1			
Water Treatment RO System	1			
Oil Water Separator	1			
Waste Treatment System (Undefined)	1			
Iodine Feed Stock Preparation System				
Total Equipment	28	9	78	5
Grand Total	120			

The principal hazard associated with the HTSE process is loss of confinement of hydrogen resulting in a fire or explosion. Other hazards include pressure vessel failures and loss of confinement of the oxygen enriched air resulting in an oxygen induced fire. Table 5-9 is a preliminary hazard assessment of the HTSE hydrogen production process.

The HTSE process' operating risk is assessed to be **MEDIUM** due to the use of non-hazardous chemicals in the process, the limited number of process equipment and the likelihood and severity of seal failure in the electrolyzer.

Table 5-9: Preliminary Hazard Assessment, High Temperature Steam Electrolysis Hydrogen Production Process

Item	Hazard	Discussion
Electrolytic Cell	Leak between H ₂ and O ₂ enriched streams resulting in a fire	Need to consider the safety consequences of a crack in the solid electrolyte or at any of the seals within the electrolyzer. Since the H₂ is above its auto-ignition temperature, one would expect a leak in either direction to result in an immediate fire. As the fire raised the temperature of the contained gas, equipment rupture could occur if the relief devices were not sized for an internal fire. Fortunately, the leak rate should be low due to the lack of significant pressure difference between the H₂ and sweep streams. Since routine inspection of the electrolyzer internals will be difficult, a means of leak detection should be considered (perhaps a high temperature alarm) and a means devised for shutting down appropriate sections. The minimization of non-ceramic materials in the design of the electrolyzer will minimize the fuel present in the case of a fire.
Sweep Gas- 50% O ₂ at High Temperature and Pressure	The enhanced flammability of materials in O ₂ enriched air resulting in an equipment fire	All piping, fittings, and equipment exposed to > 25% oxygen must be oxygen-cleaned before start up. Fittings that are oxygen-cleaned at the factory must be shipped sealed. At 56 bar and < 300°C, carbon steel might be used but velocity limits would need to be imposed to minimize the impact energy of any particles carried by the gas stream. The pipe should have a minimum thickness of 4.8 mm to minimize flammability. Special attention must be given to the material of construction of thin metal items such as filters and strainers and items in high velocity regions such as valve stems. 50% O₂ at 870°C and 56 bar is far outside of the range of industrial experience. Certainly a Ni alloy would be required. At 50% oxygen, stainless steel may be acceptable with velocity limits. Testing would be recommended before final specification. The Marshall Space Flight Center has appropriate equipment for such testing. The electrical connections and wiring within the electrolyzer must be designed for exposure to the O₂ enriched sweep gas within the electrolyzer vessel. The use of soft materials and lubricants should be minimized with oxygen-enriched streams. Fluorinated compounds such as Teflon™ and Viton™ are normally used for seals and per-fluorinated materials as lubricants. Temperature limits must of course be considered when using these materials.

Item	Hazard	Discussion
Sweep Gas Turbine	Fire resulting from rotating machinery acting on an O ₂ enriched stream	Expansion turbines are routinely used within the industrial gases industry with streams of 50 to 70% O ₂ . There is no industrial experience of fires in such equipment. The inlet temperature and pressure in the present application, however, are both higher than normally seen. The use of a fire barrier around this equipment, as is used with O ₂ compressors, should be considered. 50% O ₂ at 53 bar is at the upper limit of streams that can be treated as “oxygen enriched” rather than “oxygen.” The classification affects design criteria including materials of construction, seal configuration, and cleaning/inspections specifications.
H ₂ containing Piping and Vessels	Loss of containment of a flammable gas at high pressure and temperature resulting in a fire or explosion	Materials of construction: Per API Publication 941, steel cannot be used with H ₂ at 56 bar above about 600°C. More exotic materials such as Inconel will need to be identified for the higher temperature equipment. Due to the flammability of H ₂ , mechanical joints should be avoided in this piping system. The identification of appropriate seals may be an issue. The possibilities of a jet fire or a confined vapor cloud explosion in the region of potential leak points should be considered in the development of the plant layout.
Processing Coupling Heat Exchangers	Loss of containment of high pressure air, steam or He. Contamination of He stream due to tube leaks and materials incompatibility.	Keeping the pressure of the He stream above that of the electrolyzer feed should prevent leakage into the He.
Steam Generation Heat Recuperation And Steam Generation Equipment	Equipment fires, vessel failures, hydrogen leaks resulting in fire	Aside from the H ₂ and O ₂ enriched air materials of construction issues noted above, this system should be composed of standard equipment routinely used in industry with standard safety measures.
Water treatment	No extra ordinary risk	This system should be standard equipment routinely used in industry with standard safety measures.

Item	Hazard	Discussion
Air Compressor	No extra ordinary risk	This system should be standard equipment routinely used in industry with standard safety measures.
CDA system	No extra ordinary risk	This system should be standard equipment routinely used in industry with standard safety measures.
H ₂ compressor	Hydrogen leaks resulting in fire	This design is within industrial gases industry experience. Standard safety measures should be incorporated into the design.
H ₂ Driers	Hydrogen leaks resulting in fire	This system should be standard equipment routinely used in industry with standard safety measures.

5.2 OPERABILITY ASSESSMENT

An operability review of each of the three hydrogen production processes was undertaken to assess the operating complexity of the processes. This review identified operability elements that will require future investigation and development.

The review identified the following:

- Integrated control systems have not been developed for any of these processes. Sophisticated integrated process controls will be required for each of the processes. The SI process may require additional controls in order to properly integrate the three interdependent chemical processes.
- Control of heat recuperation and steam generation for the HTSE process can be based on proven control concepts from the power generation industry involving feedwater heating, steam generation, and steam superheating.
- Startup and shut down of each process has not been included in the conceptual PFDs. Startup and shut down will require modification of the PFDs to address reduced flow rates during heat-up, means to add and remove the chemical inventory during startup and shut down, and means to bypass equipment during startup and shut down. Start up and shut down is more complex when an inadvertent change of state could occur, such as solidification of iodine in the SI process.
- There is currently limited buffer storage between process operations. Lack of buffer storage will tend to propagate a small perturbation through the system causing complete shut down of the hydrogen production system.
- Features required to prevent iodine from solidifying in process lines during shutdown and in instrument sensing lines during shutdown and operation may result in the need to heat trace all iodine containing components.
- Process responses to control system and component failures have not been analyzed.
- Operational integration with the NHSS, including response to loss of load due to hydrogen production system upsets and hydrogen production system response to emergency reactor shutdown, has not been analyzed.
- Safety instrumented systems have not been integrated into the PFDs.
- Pressure relief devices to prevent vessel failure as a result of pressure transients, as required by Code, will require capture and treatment of the chemical releases for the HyS and SI hydrogen production processes.

Based on the above findings, the operating complexities of the hydrogen production processes are assessed to be **MEDIUM-LOW** for HTSE, **MEDIUM-HIGH** for HyS and **HIGH** for SI.

5.3 SENSITIVITY TO REACTOR OUTLET HELIUM TEMPERATURE

As well as changing the performance of the HPS, a reduction in the temperature of helium from the NHSS to the HPS will mean alteration to the NHSS design. Intuitively, the lowering of the Reactor Outlet Temperature would have an effect of increasing the contribution of the HPS to the hydrogen selling price and reducing the contribution of the NHSS to the price.

5.3.1 Effect on Nuclear Reactor Heat Source

There would be numerous cost factors changed in the NHSS due to lowering ROT. The most significant change would be reductions in capital cost due to changes in materials of construction. Generally, countering those reductions would be increases in operating cost due to altered design conditions.

5.3.1.1 NHSS Capital Cost

Based on analyses completed to date, the HTGR fuel and core appear to be capable of steady operation at up to a maximum helium temperature of about 950°C to 1000°C for the 500 to 600 MW_{th} configurations. However, the combination of maximum power level and outlet temperature also depends on overall cost optimization and the consideration of accident analyses addressing licensing basis events. In the case of accident analyses, the dependence is on transient conditions, rather than steady-state operation. From the broader plant perspective, limits on normal operating conditions will depend not on the reactor, but on the capabilities of components that are located downstream of the reactor.

Where the outlet helium flow is enveloped in graphite, carbon fiber reinforced composite (CFRC) or ceramic materials, temperature limits would be well above 1000°C. However, the helium flow must be directed to and flow through a heat exchanger in one or more chained heat transfer loops to deliver its heat to the hydrogen production system. CFRC materials for ducting and, in particular, ceramic heat exchanger components are in development. But for plant designs that could be built today, metallic materials would be necessary at least for the heat transfer core materials of the IHX.

The database for high temperature materials capability has evolved from the development of alloys for such applications as aircraft engines. The materials of the high temperature nuclear reactor are preferably among those accepted by and under conditions recognized in the ASME Boiler and Pressure Vessel Code, or in the Code qualification process. The intersection of high-temperature materials and the ASME Code presently includes only a few materials. Alloy 800H, a nickel/chromium/iron alloy, is the material of choice for the IHX core up to approximately 750°C service temperature. The present Code limit is 760°C. Alloy 800H is also the present reference material for duct liners, which are passive non-load bearing components, up to about 900°C. At 950°C, the material for the duct liner is Hastelloy X, and at this higher temperature consideration of CFRC for the duct liner is an alternative.

Above approximately 750°C, the reference material for the IHX core changes to Hastelloy X because of the ASME Code limit. This represents an increase in the component cost, but not a significant increase in the overall plant cost since the IHX core material costs comprise a relatively small part of the total cost. Hastelloy X, a nickel/ molybdenum alloy, is about twice as expensive as Alloy 800H.

Similarly, above approximately 850°C, the reference metallic material for the hot end of the IHX core changes to Inconel 617, a nickel/chrome/cobalt alloy. An alloy change to Inconel 617 would be reflected in plant cost by a further step change due to Inconel 617 being about four times more costly than Alloy 800H. As the temperature is increased further above 850°C, Inconel 617 would be subject to life-shortening factors. These factors will depend on the service temperature and details of the IHX design and operation that are yet to be defined, up to an upper limit corresponding to a ROT of 950°C. Shortened life span would be addressed by replacement or partial replacement of the IHX over the plant lifetime, with frequency and cost impact increasing with higher temperature.

A recent NGNP conceptual design study^[Ref. 25] included the evaluation of materials selections for the reactor outlet to IHX duct liner, and enclosing pipe for the IHX and its vessel. In addition, the study evaluated the possibility of using two IHXs in series in each NHSS (i.e., IHX A for the hot end and IHX B for lower temperature flows). For ROTs greater than 850°C, this would have the effect of reducing the replacement cost of life-limited IHX components. At ROT temperatures of 800°C and below there would only be one IHX (i.e., IHX B). The relevant study results are reproduced in Table 5-10.

As shown in Table 5-10, there is a factor applied to the nuclear fuel as a function of reactor temperature. A reference factor, 100% in the table, is applied to the fuel that would see a similar environment as fuel in actual test and demonstration reactor cores using particle fuel. Then for ROTs above 800°C, a multiplicative factor on overall fuel cost is used to account for differing manufacture and/or shortened lifetime. This factor can be up to 100% at 950°C. This was done in a previous study that evaluated cost variation as a function of ROT^[Ref. 26].

Table 5-10: Effect on NHSS Costs of Lower ROT

Parameter ↓ → ROT	700°C	750°C	800°C	850°C	900°C	950°C
Reactor to IHX Duct *						
Material	Alloy 800	Alloy 800	Alloy 800	Alloy 800	Alloy 800	Hastelloy
Lifetime	full	full	full	full	full	full
IHX *						
Arrangement	single	single	single	A&B	A&B	A&B
IHX A core						
Material	N/A	N/A	N/A	Hastelloy	Alloy 617	Alloy 617
Lifetime	N/A	N/A	N/A	full	14 yrs	8 yrs
IHX B core						
Material	Alloy 800	Alloy 800	Hastelloy	Alloy 800	Alloy 800	Alloy 800
Lifetime	full	full	full	full	full	full
IHX Vessel A						
Material	N/A	N/A	N/A	SA508/533	SA508/533	SA508/533
Lifetime	N/A	N/A	N/A	full	14 yrs **	8 yrs **
IHX Vessel B						
Material	SA508/533	SA508/533	SA508/533	SA508/533	SA508/533	SA508/533
Lifetime	full	full	full	full	full	full
Fuel						
Cost factor	100%	100%	100%	103%	105%	110%

* Excepting fuel cost factor, from Ref. 25

** Assumed to be replaced with heat exchanger core

The overall cost factor considering the NHSS changes discussed above is plotted in Figure 5-1 in terms of the energy cost charged to the NHSS, similar to the analyses in Section 4. The resulting cost reduction is slight but not entirely insignificant, and this cost factor must be traded-off against NHSS operating costs, such as changes in the helium circulator power requirements, and any decline in HPS hydrogen yield as a function of the lower core outlet temperature.

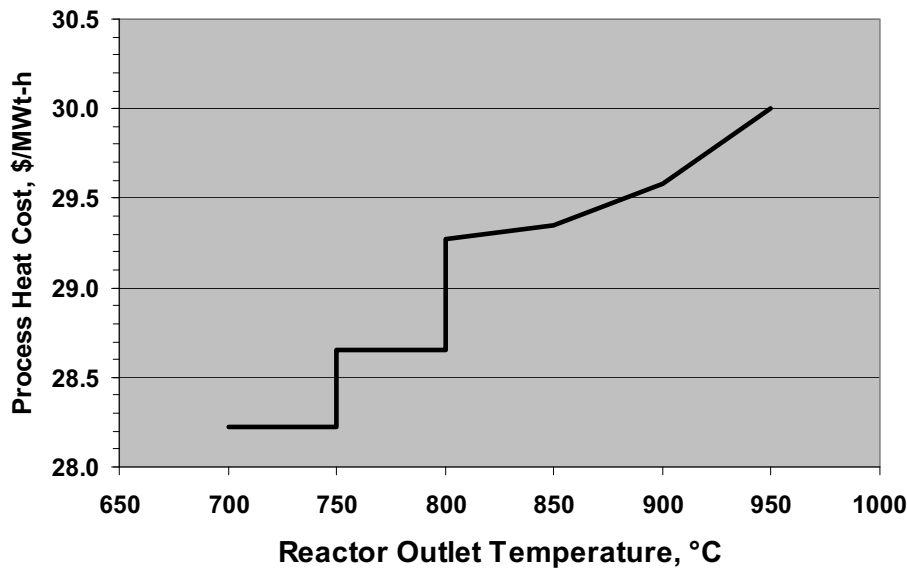


Figure 5-1: Cost of Heat from the NHSS

For the cases presented in the next section with lower ROT, additional nuclear reactor modules need to be added to maintain the same HPS output for SI and HyS. Some capital and operating costs are logically saved by constructing multiple nuclear reactor units together at the same site. These cost savings come from learning and sharing. Learning includes such factors as reduced construction labor, system modularization, product improvements, lower regulatory burden, and volume procurement of factory components. All of these savings are considered to have been “learned” for the Nth-of-a-Kind plants that are the subject of this report. However, there would still be savings from sharing in modular configuration. Sharing cost savings come from efficiencies in construction that are reflected in capital savings, such as common facilities for reactor services that result in capital and operating cost savings and staff and management efficiencies that reduce operating cost. Studies have considered the combined effects of learning and sharing^[Ref. 27], but the authors find no straightforward basis for separating the two factors. For this study, an assumed sharing benefit in terms of the energy cost charged to the NHSS, similar to the analyses in Section 4, is plotted in Figure 5-2. A maximum savings of about 8% is the asymptote at 6 units or more.

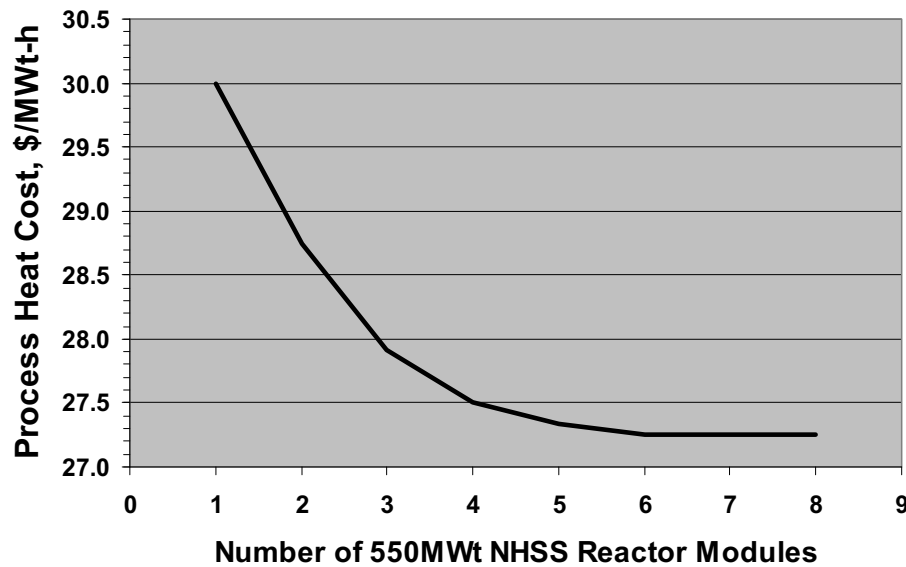


Figure 5-2: Cost Savings from Sharing between Multiple Reactor Modules

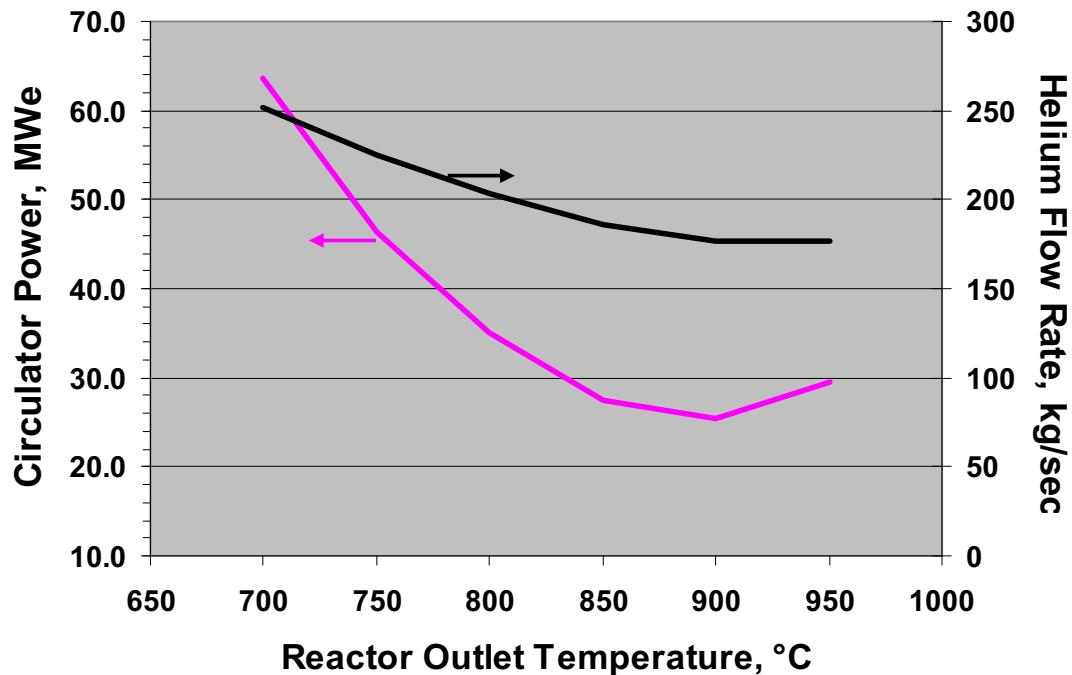
5.3.1.2 NHSS Operating Cost

A study has been performed on the effect of lowering ROT of the NGNP from 950°C to 700°C [Ref. 28]. The minimum reactor inlet temperature (RIT) is set at 280°C to order to have margin with respect to the ductility limits of the low-alloy steel (i.e., SA508/SA533) of the reactor pressure vessel. Inlet and outlet temperatures can be reduced together down to a RIT of 280°C. At ROTs below the point where the RIT is 280°C, the lower reactor outlet temperature for the same reactor inlet temperature and heat generation necessitates higher primary and secondary helium flow rates. These rates are proportional to the ratio of temperature differences across the core. Table 5-11 shows the resulting temperatures and flows. These higher flow rates have the effect of increasing the power required by the helium circulators, and that lowers overall plant efficiency.

Figure 5-3 plots the helium flow rate, which is assumed to be essentially equal for the reactor primary coolant and the secondary helium loop, and the calculated combined primary and secondary circulator power consumption as a function of ROT. Note that lowering the RIT has the effect of lowering circulator consumption because the pumping power is inversely proportional to density.

Table 5-11: Effect on Reactor Core Operating Parameters of Lower ROT

ROT	700°C	750°C	800°C	850°C	900°C	950°C
RIT	280°C	280°C	280°C	280°C	300°C	350°C
Flow, kg/s	252	225	204	186	177	177

Adjusted for 550MW_{th} from Ref. 27**Figure 5-3: Effect of ROT on NHSS Flows and Circulator Power**

5.3.2 Effect on Hydrogen Production System

For temperature sensitivity calculations the same H2A calculation tool was used as in Section 4. In all cases, the output of the HPS is held constant at the values in the Section 4 analyses. HPS equipment is resized and process trains added as needed to maintain the hydrogen output. If the resizing results in reaching a limit on the heat supply from the NHSS, then the calculation is based on an increment of nuclear reactor modules.

5.3.2.1 Sulfur Iodine

The principal impact of NHSS helium supply temperature on the SI process is in the sulfuric acid decomposition section. Lower peak temperature for the process cycle gives lower conversion per pass through the decomposition section. This results in an increase in the flow through the sulfuric acid decomposition reactor and the recycle feed concentration loop. This is accounted for in the calculation model by an increased capital cost for the HPS to accommodate the greater flow and higher electric power input to provide the circulation.

The helium source heat leaving the Acid Decomposer goes to the HI section in the reference SI plant configuration and not to a bottoming PCS as in HyS. The reference process is described in Section 3, and consists of three HPS trains delivering 157 MMSCFD of hydrogen and receiving heat from three NHSS units.

As ROT declines, the same NHSS heat is applied to both the H_2SO_4 and HI sections. All of the reactor heat is used for the HPS and helium is returned directly to the NHSS. Therefore, down to a certain level of ROT there is no PCS. In the Sulfuric Acid Decomposition section, heat can be recuperated in the bayonet tubes of the decomposition reactor down to a helium temperature exiting the decomposer of 522°C . This value is set by the pinch point in the heat transfer, as shown in Figures 1-5 and 1-6. Below 522°C , the outlet from the decomposer the H_2SO_4 section can take no more heat because of the pinch, and so a fourth NHSS is added. This is calculated to be a ROT of approximately 785°C . Below that ROT, a Rankine PCS is included in the design to utilize the excess heat.

Figure 5-4 shows the hydrogen price result. The upper curve is the hydrogen selling price calculated for a constant cost of heat from the NHSS, and the lower curve is the total hydrogen price taking into account lower cost of the NHSS heat. The increasing process system cost contribution is driven by the capital cost for the revised operating conditions and increased electric power consumption. For the total cost, small downward step changes are seen at 800°C and 750°C where configuration and/or materials changes yield lower cost for the IHX. A large step change upward, at around 785°C , is the impact of demand for nuclear heat from four reactor units instead of three.

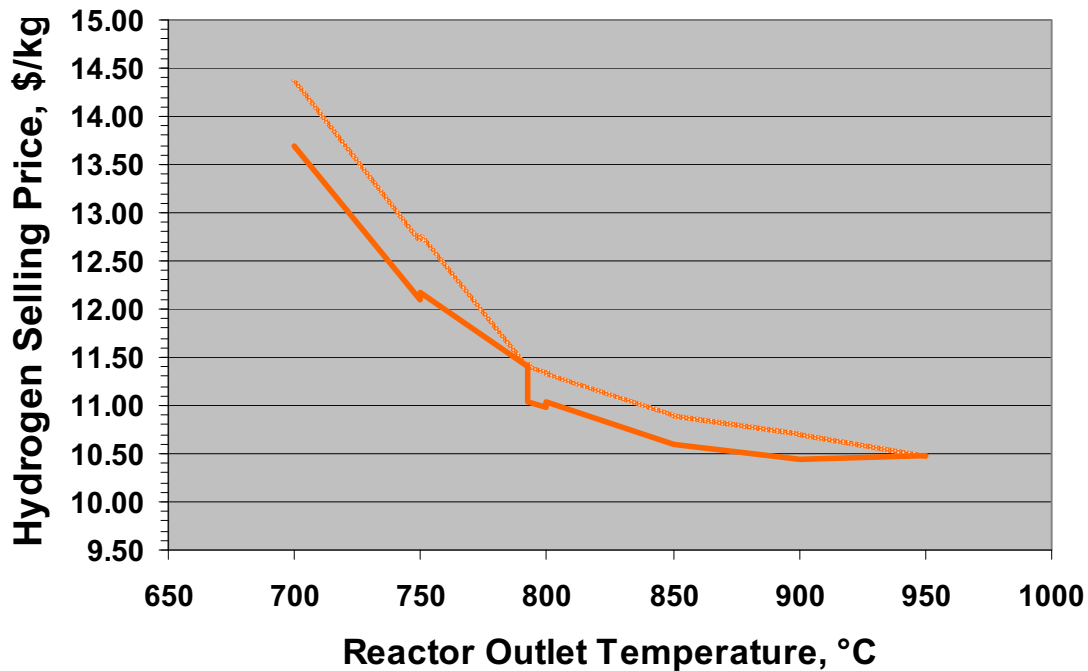


Figure 5-4: Influence of Reactor Outlet Temperature for SI

5.3.2.2 Hybrid Sulfur

The Hybrid Sulfur process plant takes heat from the NHSS in one high-temperature exchange in the sulfuric acid decomposition section. The sulfuric acid decomposition section in the HyS plant is essentially the same as in the SI plant. Lower peak temperature for the process cycle would give lower conversion per pass through the decomposition section, as in the case for the SI plant.

Sensitivity is based on the reference size plant described in Section 3.1, which consists of two HPS trains delivering 142 MMSCFD of hydrogen, receiving heat from two NHSS units and a Rankine PCS utilizing the heat not used by the process directly.

As the helium temperature from the NHSS declines, the same hydrogen production is maintained while the circulation through the feed and recycle circuits of the HPS increases. This is accounted for in the calculation model with increased capital cost for the HPS to accommodate the greater flow and higher electric power input to provide the circulation. In the Sulfuric Acid Decomposition section, heat is recuperated in the bayonet tubes of the decomposition reactor down to a helium exit temperature of 522°C. This value is set by the pinch point in the heat transfer, as shown in Figures 1-5 and 1-6. The temperature of helium exiting the sulfuric acid decomposer is constant to maintain the difference at the process interface pinch point. Therefore, the process heat duty per train declines with lower NHSS output temperature. Overall thermal power required from the NHSS remains essentially constant, but since only heat down to 522°C is usable, reactor modules must be added to supply that useful heat. As more total NHSS heat is

available due to the increase in modules, there is more heat available for the PCS. Consequently, as the reactor outlet temperature goes down, the import of electric power to the overall plant is reduced.

Plotted in Figure 5-5 is the result of the sensitivity analysis. The upper curve is the hydrogen selling price calculated for a constant cost of heat from the NHSS, and the lower curve is the price including the variation in cost of the NHSS heat. Large step increases at 950°C and 775°C are due to the addition of NHSS modules from 2 to 3 and 3 to 4, respectively. Slight reductions in the hydrogen selling price at 800°C and 750°C reflect cost savings associated with changes in the NHSS IHX material and/or configuration.

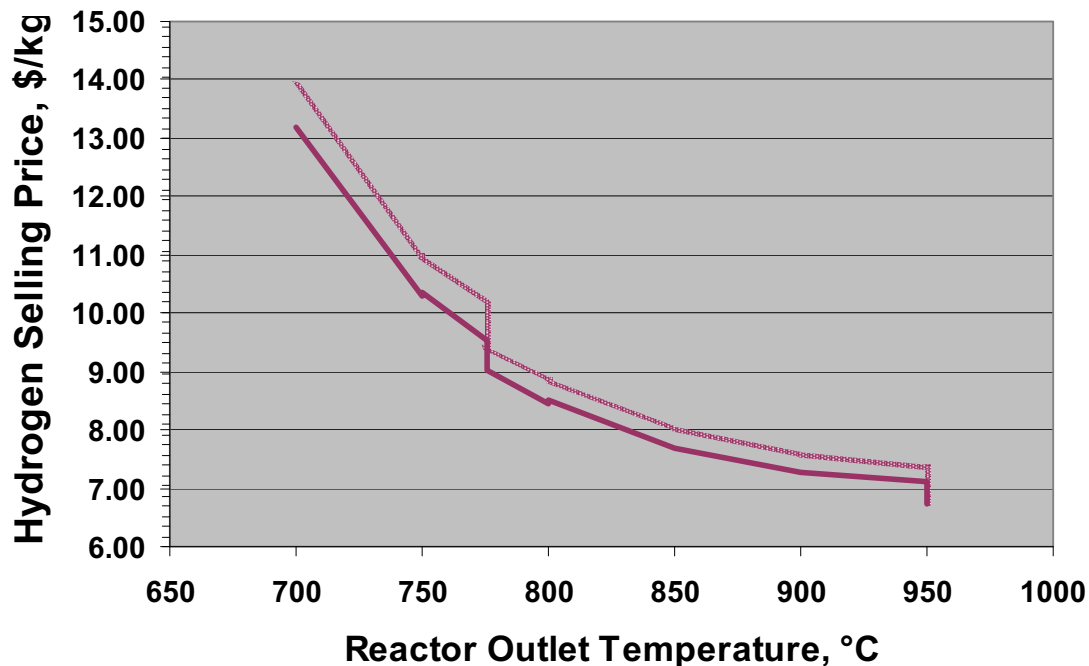


Figure 5-5: Influence of Reactor Outlet Temperature for HyS

5.3.2.3 High Temperature Steam Electrolysis

The two benefits of HTSE are: 1) the thermodynamic advantage that comes with higher temperature of the reaction of using progressively more heat and offsetting electric power for a portion of the energy needed to split water and 2) the lower overvoltage that results from operating the electrodes and electrolyte at higher temperature. Insofar as the second effect, lower temperature operation will increase the optimum operating cell voltage. Since hydrogen production is proportional to current in electrolysis, lower temperature will directly increase input power for a given output of hydrogen. This function of HTSE efficiency with temperature has been quantified in experimental work^[Ref. 29].

However, between the reference operating point of the design from this study and the “thermoneutral” operating point, where the heat required by thermodynamics comes from excess ohmic heating in the cell, there is an operating range for which the reaction temperature does not have to be reduced. In this range, the process efficiency suffers only from the additional electric power for the excess ohmic heating.

The reference process is described in Section 3, and consists of one HPS train delivering 142 MMSCFD of hydrogen gas, receiving heat from one NHSS unit. Electric power for the electrolyzers is generated in a bottoming cycle as well as being imported.

In the calculation of HTSE, as in the SI and HyS sensitivity calculations, the hydrogen production rate is held constant. The electrolysis cell current density is held constant, so that the number of electrolysis cells and the HPS size are not changed. As the temperature in the electrolyzer cells declines, the internal electrical resistance, principally of the electrodes, increases and voltage required to produce the hydrogen increases. Therefore, the major cost implication in the production of hydrogen is in the use of electricity. The cost impacts are only associated with the quantity of power imported and the size of PCS. The next most influential costs are the high-temperature heat exchanger costs, which decrease with lower NHSS reactor temperature.

Figure 5-6 shows the result of the calculation of hydrogen selling price. As with the corresponding plots for SI and HyS, the upper curve is the effect of process plant costs only and the lower curve accounts for the NHSS cost variation with reactor outlet temperature. Step reductions in the total curve at 800°C and 750°C are due to the changes in the NHSS IHX material and/or configuration.

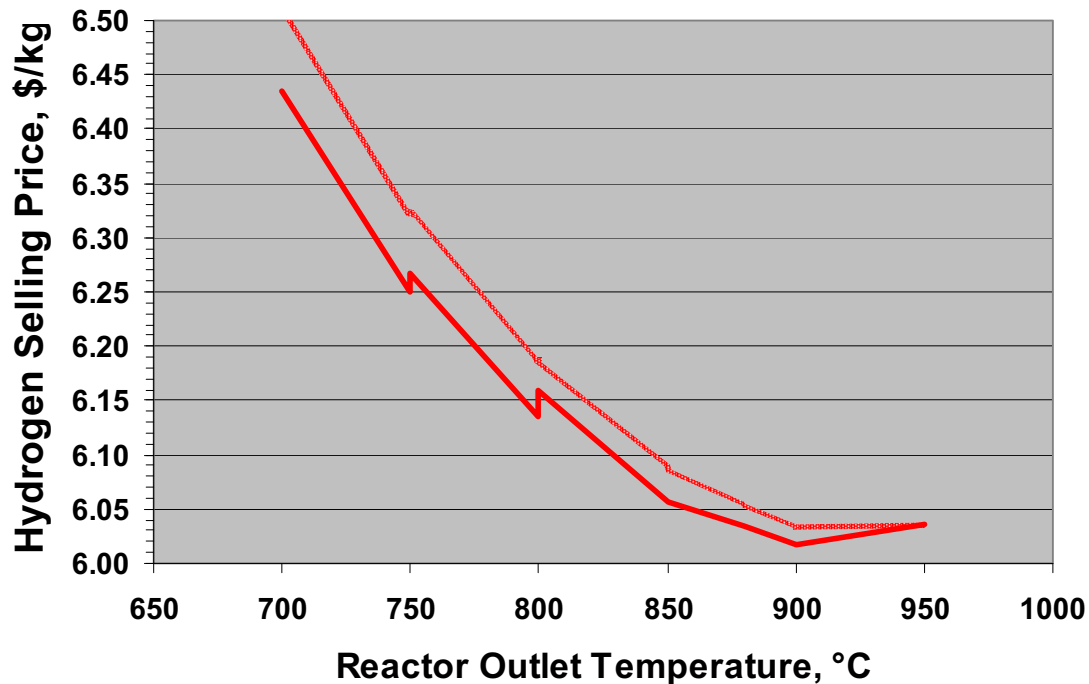


Figure 5-6: Influence of Reactor Outlet Temperature for HTSE

5.3.3 Combined Results

The process efficiencies as a function of ROT, as calculated in this evaluation for each of the three HPSs, is plotted in Figure 5-7. This efficiency is calculated as the heating value of the hydrogen produced divided by the sum of the nuclear, electric source and steam power inputs to the process section. Electric source power is the heat that would be required to generate the electricity consumed by the HPS at 33% conversion efficiency. Low pressure saturated steam input is in the reference designs for the sulfuric acid decomposition stage vacuum pumping in the SI and HyS designs.

Figure 5-8 shows the overall plant efficiencies for the same numerator divided by the sum of the reactor core heat, the source heat for HPS, NHSS, and BOP electric consumption and the steam heat input.

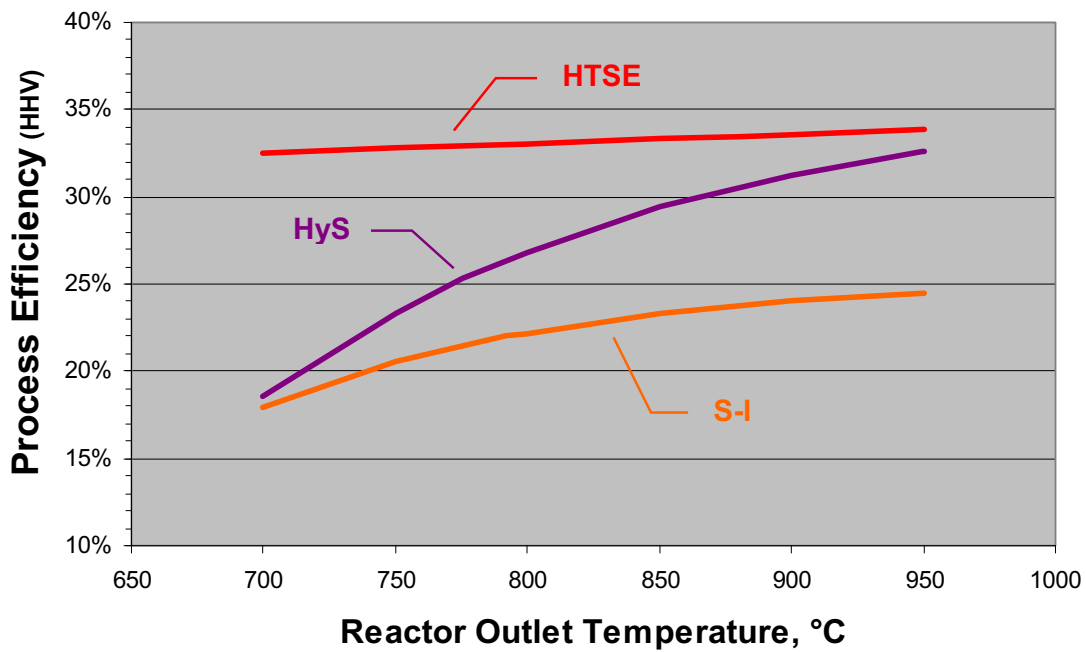


Figure 5-7: Influence of Reactor Outlet Temperature on Process Efficiency

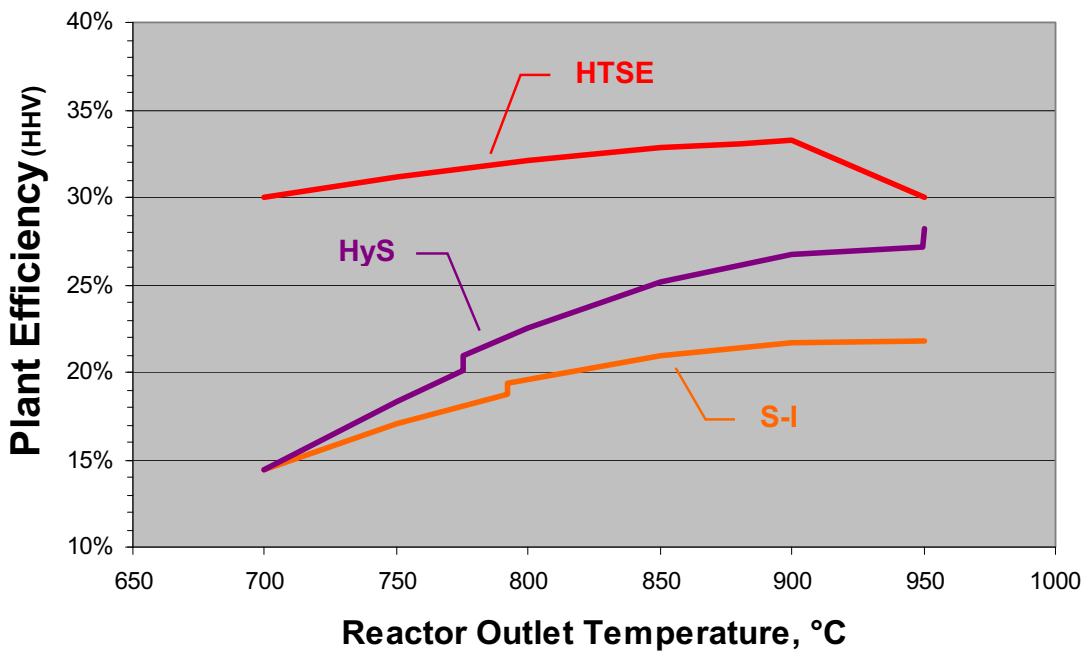


Figure 5-8: Influence of Reactor Outlet Temperature on Plant Overall Efficiency

The ultimate hydrogen cost is essentially calculated from the initial plant capital cost with consideration of the efficiencies shown in the preceding figures. Figure 5-9 reproduces the upper curves from the hydrogen cost curves from the analyses of the three HPS technologies (i.e., Figure 5-4, Figure 5-5 and Figure 5-6).

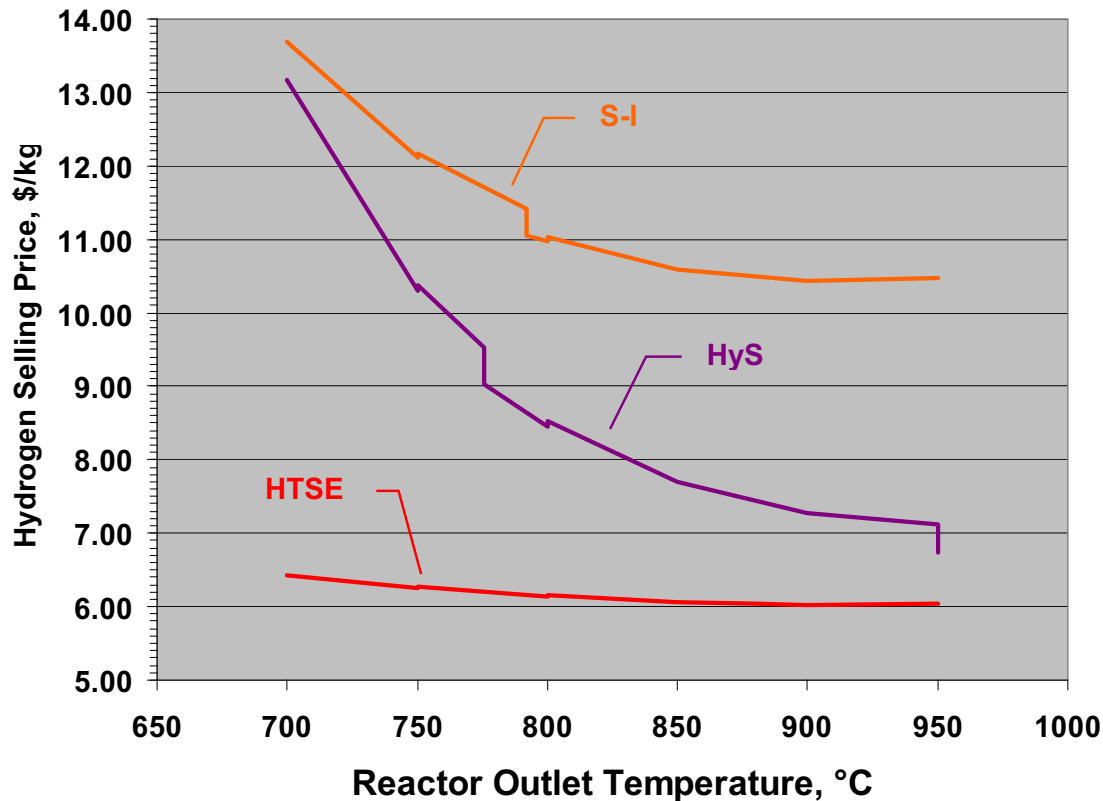


Figure 5-9: Hydrogen Selling Price as a Function of Reactor Outlet Temperature

It can be seen that HTSE has not only the lowest calculated hydrogen selling price, but also has the least sensitivity to NHSS reactor outlet temperature. The magnitude of sensitivity can be explained by the HTSE process cycle using the least amount of high-temperature heat among the three processes. At 950°C ROT, the reference HTSE HPS uses a small fraction of the heat from one reactor unit. As ROT declines, the fraction from the HTGR is less, and to provide the required heat for the electrolysis process, greater amounts of ohmic heating are utilized. Thus, as the temperature of heat from the NHSS goes down, the amount of heat per unit output of the HTSE process is even less. However, since the fraction of high-temperature heat in the reference 950°C case is so small, the influence on hydrogen selling price is slight. At or below a NHSS outlet temperature of about 850°C, the energy budget is such that no process heat is required.

Hybrid Sulfur has the most sensitivity to NHSS reactor outlet temperature at the 750°C end of the calculated range. This phenomenon is due to the limit on usable heat set by the pinch point in the Sulfuric Acid Decomposer. All heat below 522°C can only be used for electric generation. The same sensitivity is not shown by the Sulfur Iodine cycle because the NHSS heat

goes to both the Sulfuric Acid Decomposition section and to the HI section. Therefore, less heat is committed to the Acid Decomposer and consequently limited by the pinch.

A notable result is that, based on the mathematical model and assumptions of this evaluation, the hydrogen price with all factors considered is relatively flat as a function of reactor outlet temperature down to about 800-850°C for SI and HTSE. It should also be noted both HyS and SI show a marked increase in hydrogen selling price as the ROT decreases past 800°C, while HTSE shows only a modest increase. This trend would suggest that HTSE is a better match for an HTGR at lower temperatures than the other two technologies. However, this trend is misleading. Rather, the relatively modest increase in selling price is due to the fact that HTSE is increasingly importing inexpensive electricity for process use and is relying less and less on nuclear heat from the HTGR for process heat. In other words, HTSE technology is more appealing at lower temperatures because its process heat demands are being provided through other more economical energy sources.

6 TECHNOLOGY DEVELOPMENT

Hydrogen production development is organized into four separate process technology areas. These are the following, and for each the Technology Development status, needs, and plans are covered in Sections 6.1 through 6.4:

- Sulfuric Acid Decomposition, which is common to both Sulfur Iodine and Hybrid Sulfur hydrogen production systems;
- Sulfur Dioxide Electrolysis, the principal step in the Hybrid Sulfur thermo- electro-chemical water splitting;
- Bunsen Reaction and HI Decomposition, which are two steps in the Sulfur Iodine thermo-chemical water splitting, and;
- High Temperature Steam Electrolysis.

For each process or component area, the technology development needs and plans are addressed in two parts. First, the design of the technology area, as progressed to this point, is presented from the perspective of the functions and requirement of the process steps and in context of present design status and Design Data Needs (DDNs). Design status includes discussion of candidate designs, decisions already made, design options yet to be resolved and how they will be decided, and a numerical ranking of Design Readiness Level (DRL) at this point in the conceptual design.

The second part of Technology Development is the path forward. This consists of the assessment of present TRL, the Technology Development Road Map (TDRM), which is a graphic format outline showing present status and plans to advance the TRL rank and the Technology Maturation Plans. For each of the four process technology areas, the TRLs, TDRMs, and summary Maturation Plans are organized by subsystems in each of the technology areas. Within each subsystem only the Critical Systems, Structures, and Components (SSCs) are evaluated for TRL.

Critical Systems, Structures, and Components are those identified aspects or portions of the systems that must be developed prior to commercialization, are not commercially available or do not have proven industry experience.

Design Readiness Levels

DRLs are assigned to provide a semi-quantitative measure of the readiness of the design of critical SSCs for full-scale deployment. The term “semi-quantitative” is used because the DRL ratings are partially subjective. The fact that the levels are numbered is only a method to categorize the levels. DRLs provide the ability to compare the design readiness of any SSC relative to another SSC to assist in programmatic decisions.

Table 6-1 is a presentation of the guidance used to assign DRLs, and it is taken from the Westinghouse Report “NGNP and Hydrogen Production, Report on Design Readiness Levels and Design Technology Readiness Levels”^[Ref. 30].

Table 6-1: Design Readiness Level Generic Definitions

Rating Level	Definition
1	Design need or concept identified in white papers or feasibility study reports. Goal and scope defined. Typically part of Pre-Conceptual Design. In most instances, design need identification is indicative that a design concept is not presently known.
2	Initiate Conceptual Design. Establish functional & operational requirements and define design criteria. Identify alternative configurations and materials. Prepare scoping cost and schedule estimates. Establish top level requirements. Allocate requirements to SSCs.
3	Complete Conceptual Design. Complete trade studies, selection of alternatives, and select initial configuration and materials. Initial Overall Plant Design Specification (System Requirements Manual) and initial portions of Facility Design Descriptions (FDDs), and System Design Descriptions (SDDs) issued for facilities, major systems, structures, and components. (FDDs, SDDs, scoping calculations, drawings, and outline specifications. Block Flow Diagrams, Mass Balances, Process Flow Diagrams (PFDs) and Piping & Instrumentation Diagrams (P&IDs), one lines, Instrument & Control (I&C) diagrams, plant layout, Floor plans, General Arrangements, Systems Configurations, etc. are initiated) Perform Value Engineering and evaluate changes that can reduce cost. Preliminary Cost & Schedule Baseline Range. This rating is associated with a 15% completion of the overall design.
4	Initiate Preliminary Design. Perform preliminary safety and other analyses, complete additional trade studies, engineering analysis, preliminary calculations, preliminary performance specifications, and PFD and P&IDs. This rating is associated with a 25% completion of the overall design.
5	Complete Preliminary Design. Issue preliminary key design output documents. The major key documents are SDDs, calculations, drawings, and specifications, PFDs and P&IDs, one lines, I&C diagrams, plant layout, floor plans, typical sections, general arrangements, systems configurations, etc. When finalized, all key documents are placed under cost & schedule change control. Complete initial startup and operation planning. Final Cost & Schedule Performance Baseline established. All facilities, associated systems, structures, and components have been identified, sized, and integrated. This rating is associated with a 40% completion of overall design.
6	Initiate Final Design. Validate design selections, and safety and other engineering analyses. This rating is associated with a 50% completion of the overall design.
7	Continue Final Design. Prepare final FDDs, SDDs, calculations, drawings, and procurement and construction specifications. Develop operating manuals and operator training programs. Long Lead procurement initiated. This rating is associated with a 75% completion of the design.

Rating Level	Definition
8	Complete Final Design. Issue construction and procurement specifications and drawings for use. Complete final startup and operation documentation. This rating is associated with a 100% of the final design, but not including changes during construction and start-up.
9	Facilities, structures, systems, and components manufactured and/or constructed, inspected, tested, and ready for turnover to operations.
10	Facilities, structures, systems, and components successfully operated for one full cycle. As built drawings reviewed and approved.

Design Data Needs (DDNs)

DDNs are formally prepared descriptions of the needed data for design calculations and design decisions that are identified at the level of the SSCs.

The ideal sequence entails the design engineer writing a DDN telling what quantitative data results are needed to do the design. The DDN is related to technology readiness in that more than likely there are one or more DDNs written for a system or component that is not "ready" technologically. On the other hand, existence of a DDN does not necessarily mean something is not developed, just that required design data is missing.

The listings of DDNs for the hydrogen production systems are tabulated in Section 8.4.2. Complete DDNs include discussion of current status, assumptions, alternatives, detailed statements of the needs, schedules, and priorities. These have been prepared for the HyS hydrogen production system as part of the NGNP Preconceptual Design^[Ref. 31], but the DDNs need updating. A review of the listings for the DDNs in Section 8 shows that many of the needs are design-related rather than strictly addressing the technology. This reflects the focus thus far on the technology and anticipates the Conceptual Design phase ahead.

Design Tasks

The process of establishing DRLs, DDNs, and TRLs has resulted in initial lists of design tasks that should be addressed in the next phase of design for the three hydrogen processes – Hybrid Sulfur, Sulfur Iodine, and High Temperature Steam Electrolysis. These Design Tasks are tabulated in Section 8.4.3.

Technology Readiness Level

TRL ranks for the Critical SSCs of the hydrogen generation process are assigned according to the definitions in Table 6-2, which is revised from the NGNP Technical Readiness Plan^[Ref. 32]. Note the addition of a rating "U" for the situations where requirements are

undefined and technology readiness is unclear. This categorization is necessary for a few of the SSCs of the HPSs.

Table 6-2: Technology Readiness Level Generic Definition

Rating Level	Definition
U	Uncertain at this phase in design and development.
1	Basic principles observed and reported in white papers, industry literature, lab reports, etc. Scientific research without well-defined application.
2	Technology concept and application formulated. Issues related to performance identified. Issues related to technology concept have been identified. Paper studies indicate potentially viable system operation
3	Proof-of concept: Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory scale to identify/screen potential viability in anticipated service.
4	Technology or Component is tested at bench scale to demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties.
5	SSC demonstrated at experimental scale in relevant environment. Components have been defined, acceptable technologies identified and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection.
6	SSCs have been demonstrated at a pilot scale in a relevant environment.
7	SSCs integrated engineering scale demonstration in a relevant environment.
8	Integrated prototype of the SSC is demonstrated in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. Analyses, if used support extension of demonstration to all design conditions. Analysis methods verified and validated. Technology issues resolved pending qualification (for nuclear application, if required). Demonstrated readiness for application.
9	The project is in final configuration, tested and demonstrated in operational environment.
10	Commercial-scale demonstration is achieved. Technological risks minimized by multiple units built and running through several years of service cycles – Multiple Units

Distinctions between TRLs are generally a function of three factors. These are: 1) the scale of the technology demonstration; 2) the closeness of the design to prototype; and 3) the extent to which test conditions match the operating conditions in application. The demonstration that can advance the SSC from one to the next TRL needs to meet a specific quantitative test duration and satisfy criteria for acceptable stable operation.

In the following listings of current TRL rankings, a large number of supporting SSCs can be seen to be TRL-6. This is in contrast to the systems that are the focus of hydrogen process development. A ranking of TRL-6 denotes that there will be no new technology required for the hydrogen process, only the extension of the present technology to more extreme operational environments and maybe with new materials of construction. These technologies are clearly beyond experimental demonstration of feasibility (i.e., TRL-4) but no prototype has been tested in the operational environment (i.e., TRL-8). TRL-5, -6 and -7 are all demonstrations in relevant environments, and the gradation is on the scale and closeness to prototype. Striking the middle value of TRL-6 seems logical.

In several places in this section, specific hydrogen outputs, heat or power inputs, scale factors, and scale-up steps are quantified. These are all estimates based on the TDRMs developed here and on the present plans of the technology developers in the NHI Program who have been consulted. Far more progress in development and work on specific designs is required before these numbers can be confirmed. The ratings should be used only for general planning purposes and not as bases for design.

Where scale relative to the NGNP Demonstration or the NGNP commercial application is expressed, the reference plants are single nuclear reactor-powered units of 550 MW_{th} rating. The sizes of the HPS in the NGNP Demonstration are based on thermal input of 50 MW_{th} for the Sulfur Iodine and Hybrid Sulfur technologies and 5 MW_{th} for High Temperature Steam Electrolysis. The 50, 50, and 5 MW_{th} numbers were preliminarily judged to correspond to the scale of the minimum commercially viable hydrogen production train for each of the three technologies^[Ref. 33].

For each process concept, the Hydrogen Production Facility consists of the Hydrogen Production System and the Hydrogen Production Buildings and Structures. For discussion of technology development, the buildings and structures are assumed to be entirely commercially available or having proven industry experience. Therefore, the following technology assessment relates only to the Hydrogen Production Systems.

DRLs and TRLs of the Hydrogen Generation Processes

In the following sections, DRLs and TRLs are developed for the four technology areas. Table 6-3 summarizes the DRLs and TRLs for the three HPS overall systems where the system level is the minimum level of its respective constituent SSCs.

Table 6-3: Overall System DRLs and TRLs

	DRL	TRL
Sulfur Iodine Thermo-Chemical Water Splitting	1	2
Hybrid Sulfur Thermo- Electro-Chemical Water Splitting	1	2
High Temperature Steam Electrolysis	1	3

In this table, and in the tables of DRLs and TRLs for the critical SSCs that follow, the DRL levels are seen to be lower than the TRL levels, and in some cases much lower. The reason for this is the early developmental status of the nuclear hydrogen technologies. The emphasis of the DOE NHI Program has been technology development, and so there is substantial work on which to base TRL ratings. Designs have been prepared, but the format of the design work has been general. The tasks that comprise DRLs above DRL-2 are more formal and rigorous design steps, such as functions and requirements analysis and complete suites of system design documentation. These formal steps have not been done as of the initiation of this HPAS. For most systems, this study advances design work further toward attainment of DRL-2, but further progress into the Conceptual Design phase will be necessary for DRLs to begin to catch up with the TRLs.

Technology Development Roadmaps

The development plan consists of the Road Map, which shows the “whole picture,” and the Maturation Plan, which is a description of the Road Map. The Maturation Plan also includes the scope, schedule, and budget for the plan, as well as statements of the objectives of the various development steps in the Road Map.

6.1 SULFURIC ACID DECOMPOSITION

This section is shared by the SI thermo-chemical water splitting process and the HyS thermo-electro-chemical process. Sulfuric Acid Decomposition is described in detail in Sections 2 and 3.

The Sulfuric Acid Decomposition subsection is made up of the Sulfuric Acid Decomposer, the Reactor Product and Recycle Flash System, and the Vacuum Stripper System.

6.1.1 Functions and Operating Requirements

The Sulfuric Acid Decomposition section receives aqueous sulfuric acid at a concentration of 59% by weight. First, the acid is concentrated to 75% and then thermally decomposed into oxygen, sulfur dioxide, and water. The water is separated from the SO₂ and oxygen. The products are delivered to the subsequent sections of the respective HPS overall system (i.e., for SI or HyS). The water is delivered as liquid and the SO₂ and oxygen in the gas phase.

6.1.2 Development Status

6.1.2.1 Candidate Configurations

There are several concepts that have been proposed for the Acid Decomposer. In the most straight-forward concept, the heat source is flowing helium, which would flow across or along the outside of tubes containing the process fluids in a shell-in-tube configuration.

Another concept that is under study in the DOE NHI Program has the features of a compact heat exchanger of the plate-fin or “printed circuit” construction^{[Ref. 34][Ref. 35]}. A novel feature of one embodiment of this concept is the inclusion of platinum catalyst in the material of a “printed circuit” heat exchanger^[Ref. 36].

Two similar concepts consider a bayonet tube configuration with the process flow in the tube and helium on the shell side. One has the tubesheet at the top and one at the bottom. These are the Westinghouse Electric Company’s decomposer design^[Ref. 37] and the Sandia National Laboratory design^[Ref. 38].

Also, there are optional conventional technologies for acid concentration, such as using mechanically pumped vacuum or vapor compression. However, since they are conceptually well developed, there is no justification for further discussion of the choice of vacuum flash with the vacuum provided by steam air ejectors.

6.1.2.2 Decision Discriminators

A tentative choice was made for the SNL decomposer configuration for the SI ILS Experiment. The WEC configuration was proposed after that test was defined. In the TDRM, the final decision is in sequence after a number of experimental and analytical tasks.

The decision on configuration and materials for the Acid Decomposer will consider these factors:

- Corrosion resistance;
- High temperature operation, especially thermal expansion;
- Sealing and transition from ceramics to metals;
- Thermal performance: longitudinal and transverse temperature profiles in each tube and among tubes, recuperation, heat transfer rate;
- Ease of catalyst replacement, and;
- Hydraulic performance: need for gravity flow, even flow distribution between tubes, pressure drop, etc...

6.1.2.3 Reference Design for Hydrogen Plant Alternative Study

The Sulfuric Acid Decomposition processes and chosen design are discussed in Section 3.

6.1.2.4 DRLs

The Sulfuric Acid Decomposition section is at the preconceptual design stage. There are concept designs for the Decomposer tubes and catalyst and for the Concentrator. The Decomposer vessel and the complete interface with the helium heat source are not yet beyond concept definition. Table 6-4 lists the DRLs of the components of the Acid Decomposition section common to the SI and the HyS process systems.

Table 6-4: Sulfuric Acid Decomposition DRLs

	DRL
Acid Decomposition Section	1
Acid Decomposer (Decomposition Reactor)	1
Tube Array	2
Manifolds and Seals	2
Vessel	2
Catalyst	2
Helium Control Valves	1
Process Side Control Valves	1
Decomposer product handling equipment	1
Valves	1
Pumps	1
Coolers	1
Acid concentration vacuum column	1
Feed acid handling and concentrating equipment	1
Steam ejectors and vacuum pump	1
Instrumentation and Control	1
I&C System	1
Sensors, instruments	1

6.1.2.5 Down-Selection Tasks

Decisions will be made on the alternatives at the Conceptual Design stage. Note that in the TDRM, considerable additional testing and experimental development is charted ahead of

Conceptual Design. Considerable design work is also required before final selections can be considered. Testing in full thermal and hydraulic similitude will be needed to establish a basis for performance going into the Conceptual Design.

Additional decision discriminators will be the performance in testing and anticipated operational features, such as fill and drain procedure, leak detectability, access for catalyst removal, etc.

6.1.3 Sulfuric Acid Decomposition TRLs

In summary, the current TRLs for the critical SSCs of the Acid Decomposition section are evaluated as shown in Table 6-5. The critical SSCs other than the Acid Decomposer and the Helium Control Valves are generally established technology lacking only the choice of and verification of materials compatibility for the operational environment.

Table 6-5: Acid Decomposition Section TRLs

	TRL
Sulfuric Acid Decomposition Section	3
Acid Decomposer (decomposition reactor) [H ₂ SO ₄ → ½O ₂ + SO ₂ + H ₂ O] – including tubes, seals, manifolds and vessel	3
Tube Array	4
Manifolds and Seals	4
Vessel	4
Decomposer Catalyst	3
Decomposer product handling equipment	6
Acid concentration vacuum column	6
Feed acid handling and concentrating equipment	6
Steam ejectors and vacuum pump	6
Helium Control Valves	4
Sensors and Instruments	6

In Section 8.4.1 can be found the detailed rating sheets of the TRLs for the five SSCs in Table 6-5 that make up the Acid Decomposition Section.

6.1.4 Technology Development Plan

6.1.4.1 Overview and Road Map

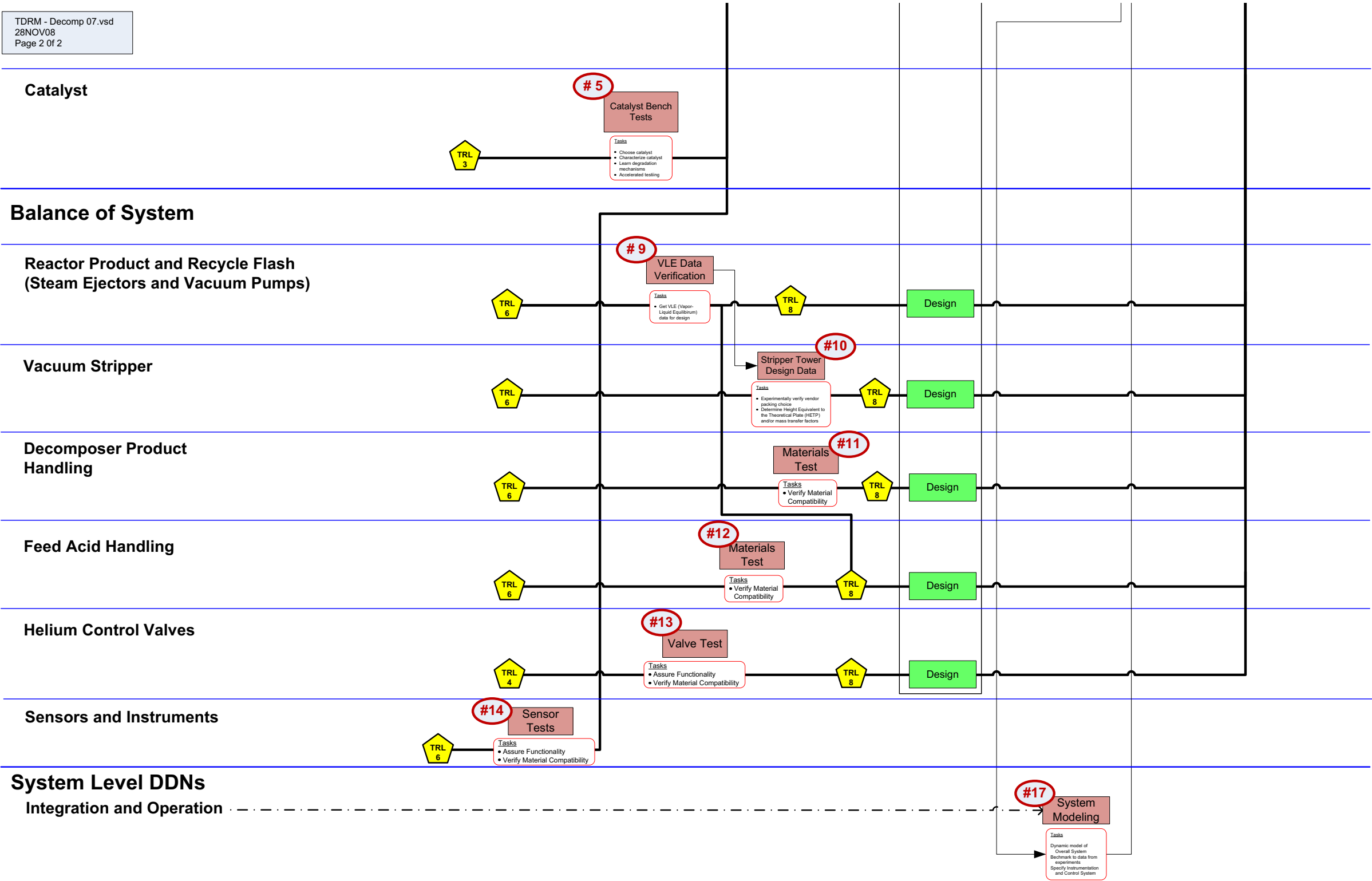
The Technology Development Road Map (TDRM) for the Sulfuric Acid Decomposition section, which is common to both the SI and HyS HPSs, is shown on the next pages.

Hydrogen Production System (HPS) Technology Development Road Map (TDRM) Process Technology #1: **Sulfuric Acid Decomposition**

Design Activity



Figure 6-1: Technology Development Roadmap for Sulfuric Acid Decomposition (Sheet 2 of 2)



6.1.4.2 Maturation Plans for Reference Design

6.1.4.2.1 Scope

The SI ILS Experiment is in progress. Successful operation of the Acid Decomposer in the SI ILS provides feasibility and functional demonstration and supports the computational modeling that has gone into the SI and HyS flow sheets. The SI ILS brings the Acid Decomposer to TRL-4.

Before a pilot test, further maturation of the technology will move along parallel tracks. One track is for materials compatibility verification and the second track concerns the decomposition: verification of the equilibrium thermodynamic model and characterization of reaction kinetics. The third track is determination of a workable Decomposer Catalyst. These tests are essential to prove the technology is feasible and functional, as well as to support analytical modeling. Thus, TRL 5 can be accomplished.

The pilot test and balance of system tests are in sequence ahead of Conceptual Design. The pilot test will be the first test in a fully relevant environment (e.g., convective tube heating). Because it is also to be a full-scale test of one tube, the step to test at experimental-scale is skipped. The two alternative decomposer designs can be tested at this stage. With the pilot test, the technology goes to TRL-6.

The balance of the Sulfuric Acid Decomposition section consists of the feed and recycle concentration equipment and the effluent handling equipment. Tests are also needed to advance their TRLs.

TRL-8 can be reached in two steps from the Conceptual Design: Engineering and Prototype Tests, both of which are multi-tube sections of a full-scale Acid Decomposer.

6.1.4.2.2 Specific Steps in the Road Map

Following are brief descriptions of the objectives of the nineteen tests shown with numbered ovals on the TDRM.

SI Integrated Laboratory Scale (ILS) Experiment (#1)

The SI ILS, which is in progress, is a test of the SNL Acid Decomposer on a small scale with heating provided by an electric furnace rather convective heating with helium. However, it is a significant test that will demonstrate feasibility and functionality. Test results will provide data to support further analytical modeling of the SI and HyS cycles. Particular results anticipated are effects of catalyst and process side flow distribution. For the SI process, but not HyS, this ILS will give initial data on time effects of iodine impurities on the decomposition process and on materials compatibility when operated for an extended period.

The completion of this test advances the Acid Decomposer to TRL-4, skipping TRL-3, because operation in the SI ILS accomplishes both proof of concept and demonstration of technical functionality.

Materials Testing (#2)

The SI ILS Experiment will validate the compatibility of the SiC tubes with the process fluids, which is to be expected from initial decomposer demonstration tests. Separate tests are needed for materials other than the SiC tubes. In particular, the seals between the SiC tubes and their manifolds or tubesheets need to be tested in anticipated pulse and cycle conditions. For the SI process the tests need to determine effects of iodine impurities on corrosion and seal life.

Thermal-Hydraulic Analysis (#3)

The alternative decomposer designs that are the most advanced, SNL and WEC as described in Section 6.1.2.1, have significantly different fluid follow patterns. This thermal-hydraulic analysis may be a discriminator in the choice of which design to carry forward to the pilot test. This task will require iteration with the Bench-scale Tests for Decomposer Catalyst Development to account for the effects of flow and temperature on the catalyst and the decomposition reaction.

Acid Decomposer Data Verification (#4)

Experimental confirmation of the equilibrium and kinetic model implicit in the simulations generated thus far are essential. Much of the modeling has involved extrapolations of data that need confirmation. Results will provide data to support further analytical modeling of the SI and HyS cycles.

Bench-scale Tests for Decomposer Catalyst Development (#5)

The Decomposer Catalyst requires development testing to assure reasonable performance stability and lifetime, since periodic replacement is expected. Chemical industry practice would dictate a lifetime of 20,000 hours, which often can be established by accelerated testing.

The characteristic of the Decomposer Catalyst, combined with thermodynamic analyses, determines whether the Decomposer design is set by limits on heat transfer or by the Decomposer Catalyst performance. This is essential input to the Conceptual Design. This task will require iteration with the Thermal-Hydraulic Analysis to account for the effects of flow and temperature on the Decomposer Catalyst and the decomposition reaction.

Catalyst bench testing will reveal the mechanisms and parameters of catalyst poisoning and degradation, and from those results one can initiate meaningful accelerated testing to support the overall HPS design.

The completion of this test will advance the Decomposer Catalyst to TRL-5, skipping TRL-4, because operation in the SI ILS demonstrates technical functionality in a relevant environment.

HyS Integrated Laboratory Scale Experiment (#6)

An ILS test is in the program plan for the HyS process development. According to present plans, the HyS ILS is to use the same or an improved Acid Decomposer based on the design of the SI ILS. The alternative WEC decomposer design needs to be considered for the Acid Decomposer in the HyS ILS, in which case the Conceptual Design would have the test results from each decomposer design to choose from.

Note that the HyS ILS will not advance the Decomposer technology to a higher level.

Technology Decision Point (#7)

The two alternative designs for the Decomposer, WEC and SNL, may need to be carried to this stage in development to discriminate sufficiently to make a final choice. The principal factors in the choice will be the feasibility and buildability. These factors will be determined by the testing of the materials of construction and the catalyst, and by the verified thermodynamic data. Other discriminators will be the relative technology readiness, economics of the cycle in application, and schedule and risk in the context of the overall program.

Pilot Test (#8)

The combined tests and analyses following the ILS Experiment will bring the Acid Decomposer to TRL-5. At this point in development, a decision can be made on the preferred concept, SNL or WEC, as described in Section 6.1.2.1, to carry forward.

In the Pilot Test, a full-scale-length, single-tube, convection-heated bayonet tube assembly will be tested at design conditions. The test assembly will also include a reference sealing configuration and replaceable catalyst to verify the function of these features. This will be the first test with helium convective heating, rather than furnace heating, of the Decomposer. Only in this configuration are the catalyst bed and wall temperature profiles correct in detail. Helium flow in this test can be in one end and out the other, in contrast to the Engineering Test for which the flow return to the same end as entry will be required.

Possibly this test, and the later Engineering and Prototype Tests, could be conducted at a sulfuric acid plant since sulfuric acid decomposition is nothing more than undoing what a sulfuric acid plant does. It would draw a continuous feed from the plant and put its effluent product back into their feed.

A nominal goal of 1000 hours of steady operation without degradation of performance exceeding 5% per 1000 hours would constitute success. Ideally, the testing would also include startup, shutdown, and accident transients to the degree confirmed at that design phase.

The test provides the thermal and hydraulic data needed for integration of the decomposer into the HPS of either SI or HyS. The single full-length tube will have been tested at relevant conditions and so this will advance the TRL of the Acid Decomposer to TRL-6.

Integration of this test with the HyS ILS should be considered for program efficiency.

VLE Data Verification (#9)

The design of the reactor product and recycle concentration system requires verification and refinement of the vapor-liquid equilibrium data.

Vacuum Stripper Tower Design Data (#10)

Determinations of mass transfer coefficients or Heights Equivalent to the Theoretical Plate (HETPs) are needed along with good VLE data in order to confidently design this tower and, for the HyS system, the SO₂ absorber.

A vendor would supply a suitable packing that will be tested to measure an HETP or mass transfer coefficient. It may be useful also to do small bench scale tests to determine whether and how much the mass transfer in this system of components and conditions deviates from that of similar known systems.

Decomposer Product Materials Test (#11)

The materials of construction of the decomposer product handling equipment need to be tested for compatibility. Because of the effects of material transport, simple immersion of material coupons will not be sufficient. A circulating test loop should be considered.

Feed Handling Materials Test (#12)

Testing of the materials of construction of the feed acid handling and concentrating equipment and the verified VLE data completes development to the TRL-8 level for the prototype application.

Valve Test (#13)

The valves that control the flow of high temperature helium in the NHSS Secondary Heat Transport System (SHTS) between either series or parallel PCHXs are part of the HPS. The number of valves is dependent on the process, either SI or HyS, and on the scale of eventual

application. These valves are not anticipated to be new technology, but they are critical SSCs because there is no recent industrial experience with such valves. The valves will need verification testing. These do not need to be full-scale valve tests, but they should be prototypic in form to the ultimate application, and therefore experience with smaller valves will not apply. Once the technology is validated at the pressures and temperatures of the NNGP application, the TRL will advance from a ranking of 4 to 8.

Sensor Tests (#14)

Thermocouples, pressure sensors, and other instruments need to be qualified for the operational environment they will experience. New technology is not expected to be required, and so prior to such tests the sensors would have been operated in relevant environments. Scale does not particularly apply to sensors, and so prior to testing they could be TRL-5, TRL-6 or TRL-7. The middle value is chosen arbitrarily. After successful testing, the sensors are TRL-8.

Decomposer Model (#15)

A computational model of the Conceptual Design unit in a system will be based on data from the pilot-scale testing. This computer model will provide a basis for design of the Engineering Test unit and confidence that the results of the Engineering Test will work in the NNGP Demonstration.

Engineering Test (#16)

In order to reach TRL-7, there needs to be a further scale-up and approach to prototype configuration. The test proposed is for a hexagonal matrix of 19 full-length tubes with helium heating. In such a configuration, the central 5 tubes would be tested in full-scale thermo-hydraulic conditions on the outside, and likewise for the process flow inside the tubes.

Note that this test precedes the Final Design and so will not necessarily include the prototypical tube seals, process side valves or instrumentation sensors. The test will provide design verification for these components.

The goal is 1500 hours of steady operation without degradation of performance exceeding 2% per 1000 hours

System Model (#17)

The input from the Acid Decomposer mathematical model will be used in the SI and HyS HPS models.

Prototype Test (#18)

This final test in the sequence of technology maturation would be the same configuration as the Engineering Test, but with the final design features including the prototype seals, valves, and instruments. The testing would cover the full operational environment and through the design cycles as determined by final system design. In addition, stable operation of less than 1% decline per 1000 hours for a time period of 2000 hours would be expected. This is full prototypic testing of a full-scale section of the Decomposer and constitutes advancement to TRL-8.

Sulfuric Acid Decomposition Section for S-I or HyS Development (#19)

The Sulfur Dioxide Electrolysis and the Bunsen Reaction and HI Decomposition TDRMs show system tests that would require a Sulfuric Acid Decomposition Section. These are discussed in Sections 6.2.4.2.2 and 6.3.4.2.2.

A SI Systems Engineering Test is in the Bunsen Reaction and HI Decomposition TDRM is an optional step before the NGNP. This test will have integrated a Sulfuric Acid Decomposition Section approximately 1/20th of the NGNP size. This would be a design derived from the Acid Decomposer Engineering Test.

An optional HyS Systems Engineering Test is shown in the Sulfur Dioxide Electrolysis TDRM before the NGNP, and that would have a Sulfuric Acid Decomposition Section of as yet undetermined size. This could be also a design derived from the Acid Decomposer Engineering Test.

Neither of these tests nor test articles is essential to the Sulfuric Acid Decomposition technology development, but their execution would support the other steps and as a minimum reduce risk in the final application. In addition, use of the Acid Decomposer developmental test article may be cost effective for the SO₂ supply needed for these other tests.

6.1.4.2.3 Schedule and Cost

The cost and schedule for the Sulfuric Acid Decomposition technology development that are developed in this study are summarized in Table 6-6. The cost and completion years are keyed to stages along the Road Map as indicated by the step numbers, which correlate to the numbers in red ovals on the TDRM.

Table 6-6: Cost and Schedule for the Sulfuric Acid Decomposition Technology Area

TRL Achievement	Step Numbers from TDRM	Completion
Up to completion of S-I ILS – TRL-2➔3	#1	--
Complete analysis, supporting data, materials testing, and catalyst choice & tests – TRL-4➔5	#2, #3, #4, #5, #6	1.5 \$M 2011
Pilot test of Decomposer – TRL- 5➔6	#7, #8, #14	10.3 \$M 2014
Engineering test of Decomposer – TRL-6➔7	#15, #16	22.0 \$M 2016
Prototype test of Decomposer – TRL-7➔8	#17, #18	27.0 \$M 2018
Balance of system design verification – TRL-x➔8	#9, #10, #11, #12, #13	4.9 \$M

6.2 SULFUR DIOXIDE ELECTROLYSIS

The HyS thermo- electro-chemical water splitting HPS design is discussed in Section 3.1. There are three major systems associated with the HyS HPS, and of these, the Sulfuric Acid Decomposition System is very similar to the SI Sulfuric Acid Decomposition System addressed in Section 6.1. The three systems marked with asterisks are those that are covered in Section 6.1 and are not discussed further here.

- Sulfuric Acid Decomposition System (SAD)
 - Acid Concentration System *
 - Acid Steam Preheater and Vacuum Stripping *
 - H₂SO₄ Decomposition and Acid Separation *
 - Anolyte Processing
 - SO₂ Recovery System
 - SO₂ Compression
- Electrolyzer System (ELE)
 - SO₂ Electrolysis Cells
 - Electrolyzer Internal Components
 - Electrolyzer Module Pressure Boundary
- Feed and Utility System (FUS)
 - Acid and Caustic Storage
 - Water Treatment
- Product Purification System (PPU)
 - H₂ Compression and Drying
 - H₂ Purification System
 - O₂ Purification System
- Instrumentation and Control System

Schematic flow diagrams of the HyS process are shown in Section 8.1.3.

6.2.1 Functions and Operating Requirements

The Sulfur Dioxide Electrolysis section of the HyS HPS accepts the output of the Acid Decomposer. It separates the sulfuric acid (H_2SO_4) and water for concentration and recycle from the sulfur dioxide (SO_2) and oxygen (O_2), and then in multi-cell Sulfur Dioxide Electrolyzers converts water and the SO_2 into H_2SO_4 and the hydrogen product.

6.2.2 Development Status

6.2.2.1 Candidate Concepts

The focus of the HyS technology development is the SO_2 Electrolyzer cell. Alternate configurations and materials have been proposed for the cells. The membrane-electrode assembly (MEA) consists of one of several choices of proton exchange membranes coated with alternative electrode layers.

6.2.2.2 Decision Discriminators

The early phase of HyS electrolysis cell development has consisted of experimental testing of various MEAs in different configurations within a systematic approach. The process going forward will be successive interaction between proposed configurations and experimental functions to iteratively arrive at an optimum electrolyzer sized for practical and economical application to the HyS HPS.

6.2.2.3 Reference Design for Hydrogen Alternative Study

The HyS process and design used as a reference for this Technology Development analysis is presented in Sections 2 and 3.

6.2.2.4 DRLs

Table 6-7 summarizes the DRL status of the SSCs in the Sulfur Dioxide Electrolysis section of the HyS HPS.

Table 6-7: Sulfur Dioxide Electrolysis Systems DRLs

	DRL
Electrolyzer System (ELE)	1
SO_2 Electrolysis Cells	2
Electrolyzer Internals	2

	DRL
Electrolyzer Module Pressure Boundary	1
SO ₂ portions of the Acid Decomposition System (SAD)	1
Anolyte Processing	1
SO ₂ Recovery System	1
SO ₂ Absorber	1
SO ₂ Compressor	1
Feed and Utility System (FUS)	1
Water Treatment System	1
Acid and Caustic Storage	1
Product Purification System (PPU)	1
H ₂ Compression and Drying	1
H ₂ Purification System	1
O ₂ Purification System	1

6.2.3 Sulfur Dioxide TRLs

In summary, the current TRLs for the Sulfur Dioxide Electrolysis technology area are evaluated in Table 6-8.

Table 6-8: Sulfur Dioxide Electrolysis TRLs

	TRL
Electrolyzer System (ELE)	2
SO ₂ Electrolysis Cells	3
Electrolyzer Internals	2
Electrolyzer Module Pressure Boundaries	5
SO ₂ portions of the Sulfuric Acid Decomposition System (SAD)	6
SO ₂ Absorber	6
Feed and Utility System (FUS)	--
Water Treatment System	U
Instrumentation and Control System – including sensors	6

In Section 8.4.1 may be found detailed rating sheets of the TRLs for the seven bottom-tier SSCs in Table 6-8 that are not rated TRL-8.

6.2.4 Technology Development Plan

6.2.4.1 Overview and Road Map

The Technology Development Road Map for Sulfur Dioxide Electrolysis is shown on Figure 6-2.

Figure 6-2: Technology Development Road Map for Sulfur Dioxide Electrolysis (Sheet 1 of 2)

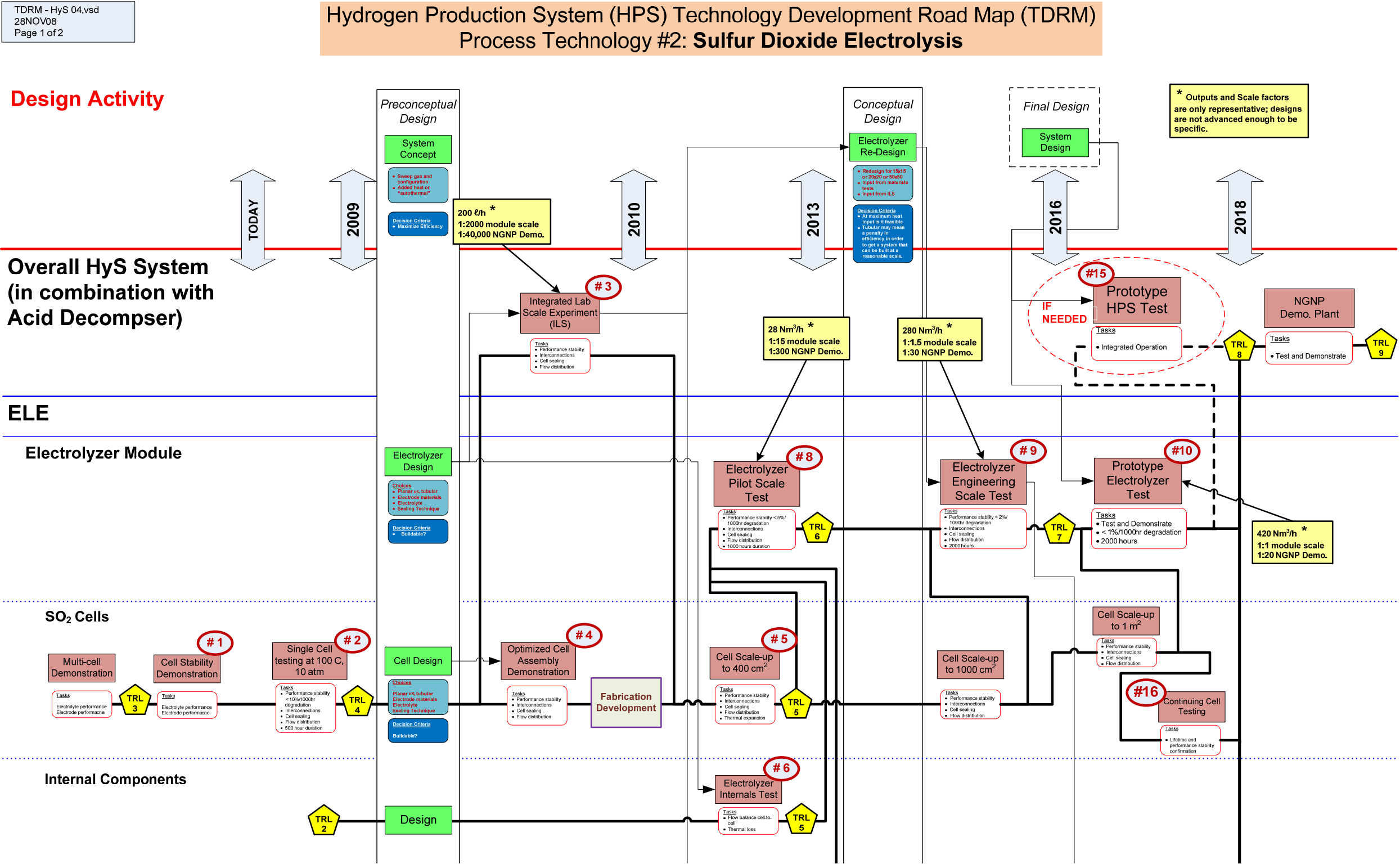
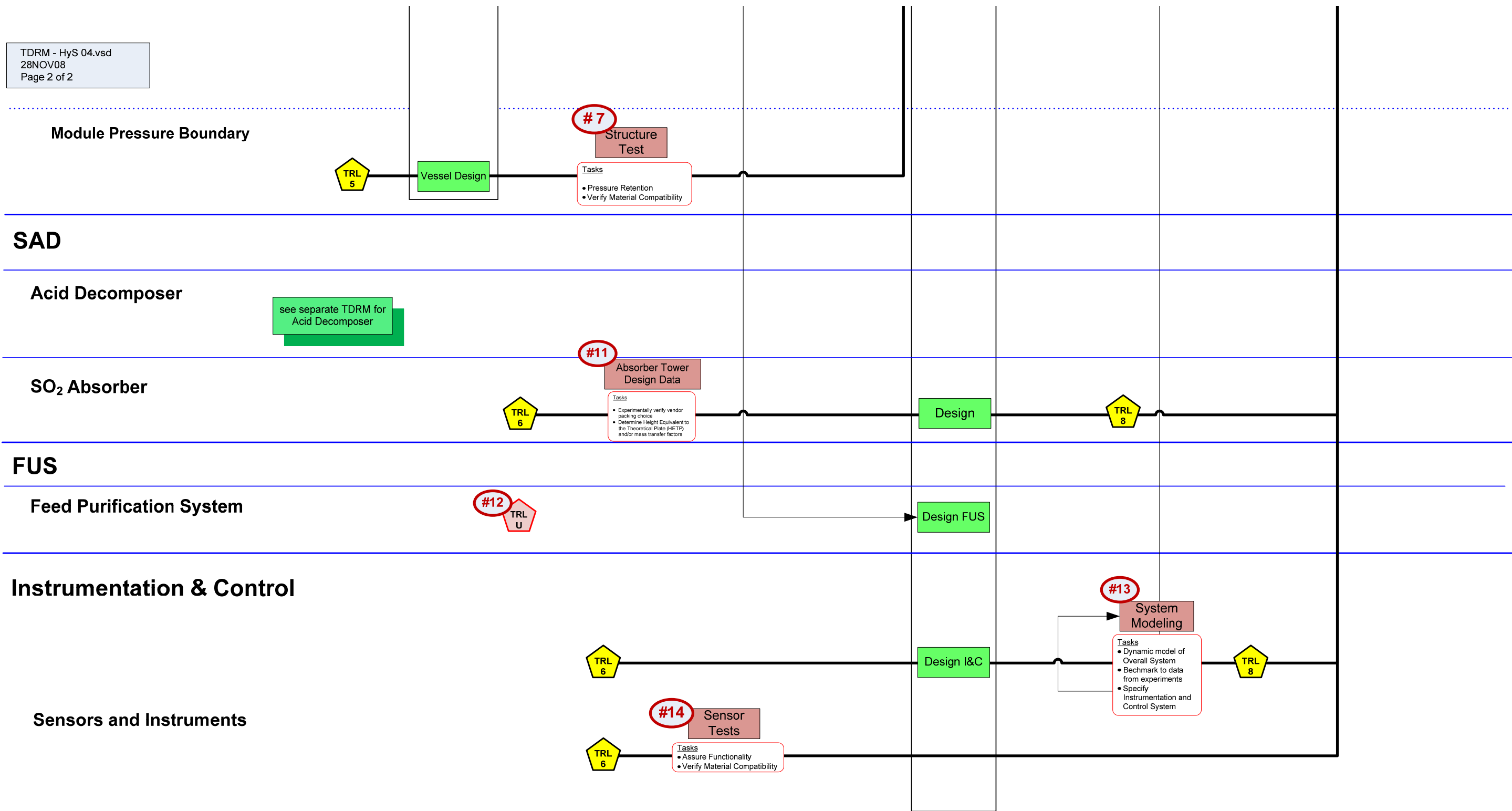


Figure 6-2: Technology Development Road Map for Sulfur Dioxide Electrolysis (Sheet 2 of 2)



6.2.4.2 Maturation Plans for Reference Design**6.2.4.2.1 Scope**

A ranking of TRL-8 for the technology requires the design and development of an SO₂ Electrolyzer Module that is scaled appropriately such that a reasonable number of the units can be combined with the Sulfuric Acid Decomposition section to make up the HyS HPS for an NNGP heat source.

From the individual SO₂ cells being tested today, there will be scale up in three steps: (1) from the present 160 cm² of cell demonstration to 400 cm², (2) from 400 cm² to 1000 cm² and (3) finally to one square meter. Cells would be assembled into SO₂ Electrolyzer Modules of progressively larger power input and hydrogen output. Although subject to further definition in the design process, the final SO₂ Electrolyzer Module for the NNGP Demonstration would be sized so that about 20 modules would comprise the HyS HPS. Since the NNGP commercial plant is to have as many as ten such trains in the HPS, the eventual NNGP commercial application would have about 200 of the finally developed SO₂ Electrolyzer Modules.

Scale-up proposed for planning purposes and shown in the TDRM is as follows:

	Module Basis	System Basis
ILS to Pilot	x 140	--
Pilot to Engineering	x 10	--
Engineering to System Prototype	x 1.5	--
System Prototype to NNGP Demonstration Plant	x 1	x 20
NNGP Demonstration Plant to NNGP Commercial Plant	--	x 10

In addition, demonstrations will be done on the SO₂ Recovery System, the Feed Purification System and the Instrumentation and Control system. These are conventional systems that can be assembled in prototype at sub-scale to bring them to TRL-8 in one step.

6.2.4.2.2 Specific Steps in the Road Map

The following are brief descriptions of the objectives of the sixteen tests shown with numbered ovals on the TDRM.

Cell Stability Demonstration (#1)

Basic issues of cell degradation, due for example to migration of constituents across cell membranes, will be resolved through interaction of design and experiment.

Single Cell testing at 100°C, 10 atm (#2)

Tests up to this point are in a laboratory environment. This test is at elevated temperature and at pressure, similar to the application. The stability demonstration and this test at relevant conditions accomplish TRL-4.

Integrated Lab Scale Experiment (#3)

This test will combine a small-scale Decomposition section to demonstrate the HyS cycle. As noted in Section 6.1.4.2.2, this could be combined with the Pilot Test of the Acid Decomposer.

Optimized Cell Assembly Demonstration (#4)

In parallel with the ILS and Preconceptual Design, the electrolysis cell design and materials will be reoptimized. This is an additional step in iteration of design and experiment.

Cell Scale-up to 400 cm² (#5)

The plan has electrolyzer cells scaled-up from the ILS size in two steps. Each step corresponds to the completion of the Preconceptual and Conceptual Design. Cell scale-up to 400 cm² plus the ILS operation constitute experimental demonstration and advance Sulfur Dioxide Electrolysis to TRL-5. Note that this scale-up follows a step of Fabrication Development, which will transition the overall R&D from laboratory orientation to manufacturing orientation. The Fabrication Development envisions significant participation by a commercial entity with some relevant experience.

Electrolyzer Module Internals Test (#6)

Following Preconceptual Design of the Electrolyzer Module Pressure Boundary, the Module Internal design will be tested. At this stage, all components of the Electrolyzer Module are TRL-5, including cells, internals, and vessel. This is because they are defined and demonstrated on experimental scale.

Structural Test (#7)

The design requirements of the vessel or pressure retaining exterior boundary for the SO₂ Electrolysis Cell are not finalized. However, there is a preferred concept of a pressurized module that qualifies for TRL-5 because it is defined and has been modeled analytically. It would be tested separately for pressure retention and material compatibility and then used in the Electrolyzer pilot-scale test.

Electrolyzer Pilot-scale Test (#8)

This is the first test of an electrolyzer with 400 cm² cells and the first test of the Module Pressure Boundary and module internals. For this test the nominal goals, which are subject to change as the R&D program proceeds along the Road Map, are as follows:

Table 6-9: Nominal Goals of Electrolyzer Pilot-Scale Test

Electrolyzer	
Avg. cell voltage, mV	700
Current Density, mA/cm ²	500
Cell Active Area, cm ²	400
HyS System	
Hydrogen output, l/h	28,000
Hydrogen output, kW _{th} (HHV)	70
Process heat input, kW _{th}	200
Process electrical input, kW _e	100
Time on line, hours	1000

Electrolyzer Engineering-Scale Test (#9)

This is a test of one electrolyzer with full-scale cells (i.e., 1000 cm²) following Conceptual Design. It will suffice as an engineering scale test since this is the final electrolyzer scale-up, although not yet prototypical. Testing will not necessarily be to the full range of transients, and so the test will advance the TRL from 6 to 7.

The nominal goals of this test are as follows:

Table 6-10: Nominal Goals of Electrolyzer Engineering-Scale Test

Electrolyzer	
Avg. cell voltage, mV	650
Current Density, mA/cm ²	500
Cell Active Area, cm ²	1000
HyS System	
Hydrogen output, l/h	280,000
Hydrogen output, kW _{th} (HHV)	1000
Process heat input, kW _{th}	2000
Process electrical input, kW _e	1000
Time on line, hours	1500

Prototype Electrolyzer Test (#10)

This test will also be of one electrolyzer. It will be the full-scale prototype resulting from Final Design with the cell scaled up in area from 1000 cm² to 1 m². The heat and power input

and the hydrogen output in this test will be only 1.5 times that of the Electrolyzer engineering-scale test.

It is anticipated that this test would be performed in the same facility as the Engineering Test. Tests will be in the operational environment and cover the appropriate number and duration of tests. This will accomplish TRL-8 for the Electrolyzer Module.

The goal of this test is 2000 hours of operation with production on the order of 420 Nm³ of hydrogen per hour and stability of less than 1% decline per 1000 hours.

SO₂ Absorber Demonstration Test (#11)

System feasibility and functionality can be assured from general industry experience, but design data is needed in the operating environment. Specifically, mass transfer in the SO₂ absorber column, the Heights Equivalent to the Theoretical Plate (HETPs) need to be experimentally determined. In order to be applied to the NNGP, sub-scale demonstration testing of the SO₂ Recovery System in the operational environment is expected. This is a jump from TRL-6 to TRL-8.

Feed Purification System Demonstration Test (#12)

There are a number of proven water purification processes that can provide ultra-pure water, but without requirements the scope of development of this SSC is uncertain.

System Modeling (#13)

Demonstration of integrated operation can be done by computer simulation given input of the performance of the discrete components in prototype or pilot testing in their operational environments. Results will be input to the final system design.

Sensor Tests (#14)

Thermocouples, pressure sensors, and other instruments need to be qualified for the operational environment they will experience. New technology is not expected to be required. It is presumed that the sensors would have been operated in relevant environments. Scale does not particularly apply to sensors, and so prior to testing they could be TRL-5, TRL-6 or TRL-7. The middle value is chosen arbitrarily. After successful testing, the sensors are TRL-8.

Prototype HPS Test (#15)

This test is intended to be an assembly of one or more of the Prototype Electrolyzers from the previous test with a scaled-down Acid Decomposer section. It is not clear that this test is needed. Separate testing of the Acid Decomposer and one Prototype Electrolyzer with transfer

of feed and products between them could be sufficient to assure TRL-8. Integrated operation would be demonstrated by analysis.

Continuing Cell Testing (#16)

As cell stack and system tests proceed, there is a need to accumulate lifetime data and quantify long-term degradation. One or more cell tests should continue after the cell scale-up to one square meter. The attainment of TRL levels elsewhere on the Road Map would be supported by the Continuing Cell Testing according to the criteria in Table 6-11.

Table 6-11: Duration and Maximum Rates Degradation for Cell Tests

TRL	Max. rate of degradation	Minimum test duration
4	20%/1000 hours	500 hours
5	10%/1000 hours	1000 hours
6	5%/1000 hours	2000 hours
7	2%/1000 hours	5000 hours
8	1%/1000 hours	10,000 hours

6.2.4.2.3 Schedule and Cost

The cost and schedule for the Sulfur Dioxide Electrolysis technology development are summarized in Table 6-12. The cost and completion years are keyed to stages along the Road Map as indicated by the step numbers (i.e., the numbers in red ovals on the TDRM).

Table 6-12: Cost and Schedule for the Sulfur Dioxide Electrolysis Technology Area

TRL Achievement	Step Numbers from TDRM	Cost Completion
Up to completion of cell demonstration at temperature and pressure – cells: TRL-3→4	#1, #2, #3, #4	3.0 \$M 2009
HyS ILS and optimized cell demonstration – cells: TRL-4→5	#5, #6	4.8 \$M 2010
Scale-up cells to 400 cm ² – TRL-4→5, and Electrolyzer Pilot Test – module: TRL-2→6	#7, #8	36.5 \$M 2013
Scale-up cells to 1000 cm ² and Engineering test of Electrolyzer – TRL-6→7	#9	59.0 \$M 2016
Scale-up cells to 1 m ² and Prototype test of Electrolyzer – TRL-7→8	#10	22.0 \$M 2018
(Prototype HPS Test)	(#15)	--
Balance of system design verification – TRL-x→8	#11, #12, #13, #14	2.9 \$M

6.2.4.3 Maturation Plans for Alternatives

Presently there are no plans for alternative HyS HPS designs. The Preconceptual Design phase could generate an alternate path in the development road map for the Sulfur Dioxide Electrolysis technologies.

6.3 BUNSEN REACTION AND HI DECOMPOSITION TECHNOLOGY AREA

The Bunsen Reaction and HI Decomposition technology area is part of the SI thermochemical water splitting process. Combined with the Sulfuric Acid Decomposition section, this area makes up the SI HPS. The SI HPS has been discussed in Sections 2 and 3. The Bunsen and HI Decomposition sections are comprised of the following systems and major components:

- Bunsen Reaction Section (Section 1 - reference version: Co-Current Reactor)
 - Bunsen Reactor [$I_2 + SO_2 + 2 H_2O \rightarrow H_2SO_4 + 2 HI$]
 - Reverse Bunsen Reactor
- HI Distillation Section (Section 3 - reference version: Reactive HI Distillation)
 - Reactive Still [$2 HI \rightarrow I_2 + H_2$]
 - Recuperators
 - Process Coupling Heat Exchanger
 - Power Recovery System
- Balance of SI Plant
 - Feed Purification
 - Product Purification
 - Instrumentation and Controls

6.3.1 Functions and Operating Requirements

The Bunsen Reaction section of the SI cycle ideally receives feed water, sulfur dioxide from the Acid Decomposer section and iodine from the HI Decomposition section, and produces sulfuric acid and hydroiodic acid. This is an exothermic reaction requiring cooling and is run at about 100°C. In actuality, the cycle flowsheets balance with significant water, H₂SO₄ and HI recirculation.

In the HI Decomposition section, HI is decomposed into I₂ and H₂ and these two separated. The reaction is endothermic, and so heat is added from the nuclear heat supply secondary helium circuit through a PCHX in order to maintain a temperature within the range of 300 to 400°C. The I₂ is recycled to the Bunsen Reaction section and the H₂ is delivered as product after purification.

6.3.2 Development Status

The three sections of the SI cycle have been demonstrated separately in the laboratory and in small-scale glass apparatus. Although there has been no final selection of the optimum alternatives from among various approaches, integrated systems have been assembled and tested. Testing of a complete system was reported in Japan several years ago^[Ref. 39] and the SI ILS Experiment is in progress under an International Nuclear Energy Research Initiative (I-NERI) as part of the NHI Program.

These experiments are running ahead of SI system design, which is only reaching a Preconceptual Design phase. This Hydrogen Plant Alternatives Study is an initial step in that Preconceptual Design.

6.3.2.1 Candidate Configurations

Each of the three sections of the SI cycle has two or more alternative candidate concepts. The Sulfuric Acid Decomposer alternatives are addressed in Section 6.1.2.1. The Bunsen Reaction section has the alternatives of a co-current reactor with separate phase separation or a counter current reactor with integral phase separation. The former has been conceptually considered and used in flowsheets developed in the U.S. The latter is the design of the Commissariat à l'Énergie Atomique (CEA), which was developed under I-NERI and has been selected for the SI ILS.

There are two HI Decomposition section concepts proposed. Distillation by extraction with phosphoric acid is the method chosen for the SI ILS based upon the recommendation of the CEA. Reactive distillation is proposed for the NGNP and eventual commercial application.

6.3.2.2 Decision Discriminators

In all cases of choices made thus far, the discrimination has been a trade-off of the minimum critical path to demonstration versus the estimated cycle efficiency and anticipated cost to commercially produce hydrogen.

6.3.2.3 Reference Design for Hydrogen Plant Alternative Study

The SI process and chosen design has been discussed in Sections 2 and 3.

6.3.2.4 DRLs

The SI HPS is at an early design stage with numerous issues related to design yet to be resolved. Preconceptual design is ahead for essentially all parts of the Bunsen Reaction and HI Decomposition Systems.

Table 6-13: Bunsen Reaction and HI Decomposition Systems DRLs

	DRL
Bunsen Reaction System	1
Bunsen Reactor	2
Contact Device	2
Seals	1
Vessel	1
Three-Phase Separator	1
HI Decomposition Systems	1
Reactive Still	1
Catalyst	1
Contact Device	1
Seals	1
Vessel	1

6.3.2.5 Down-Selection Tasks

While one SI flowsheet has been chosen for ultimate development, the conceptual design phase of the NNGP is still ahead. When that design phase is entered, it is recommended that alternatives be reviewed.

6.3.3 Sulfur Iodine TRLs

The three sections of the SI cycle have been demonstrated separately in the laboratory and in small-scale glass apparatus. However, the three sections tested do not have the same flow sheets as the reference designs for nuclear hydrogen production with the NNGP. The useful results from these tests are the basis for the SI ILS Experiment. For the Bunsen Reaction section, the concepts have been formulated and issues related to performance are identified. General proof-of-principle was demonstrated and critical functions proven. These put the Bunsen section at TRL-3.

The HI Decomposition section of the ILS, however, was a solvent extraction cycle and not the reference concept, which is reactive distillation. Therefore, the HI Decomposition section remains TRL-2.

In summary, the current TRLs for the Bunsen Reaction and HI Decomposition sections are evaluated as shown in Table 6-14.

Table 6-14: Bunsen Reaction and HI Decomposition Section TRLs

	TRL
Bunsen Reaction System	3
Bunsen Reactor -- including seals and vessel	3
Three-Phase Separator	3
HI Decomposition Systems	2
Reactive Still -- including catalyst, seals, and vessel	2
Process Coupling Heat Exchanger	5
Power Recovery System	6
Balance of SI Plant	6
Reactor Product Handling Equipment	6
Feed Purification	U
Product Purification	U
Helium Control Valves	4
Instrumentation and Controls -- including sensors	6

In Section 8.4.1 may be found detailed rating sheets of the TRLs for the ten SSCs in Table 6-14 that make up the Bunsen Reaction and HI Decomposition sections.

6.3.4 Technology Development Plan

6.3.4.1 Overview and Road Map

The Technology Development Road Map for the Bunsen Reaction and HI Decomposition is shown in Figure 6-3.

Hydrogen Production System (HPS) Technology Development Road Map (TDRM)

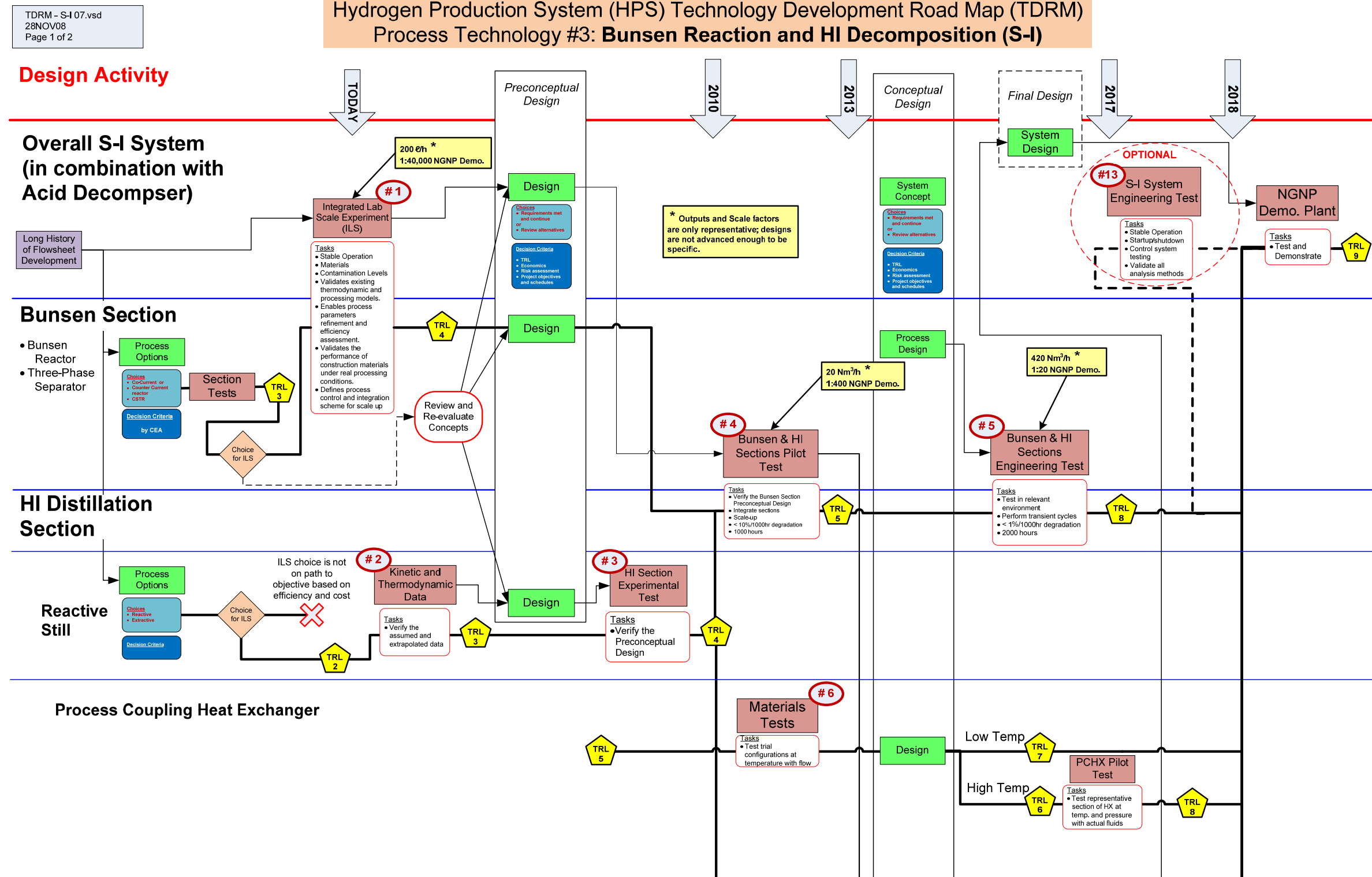
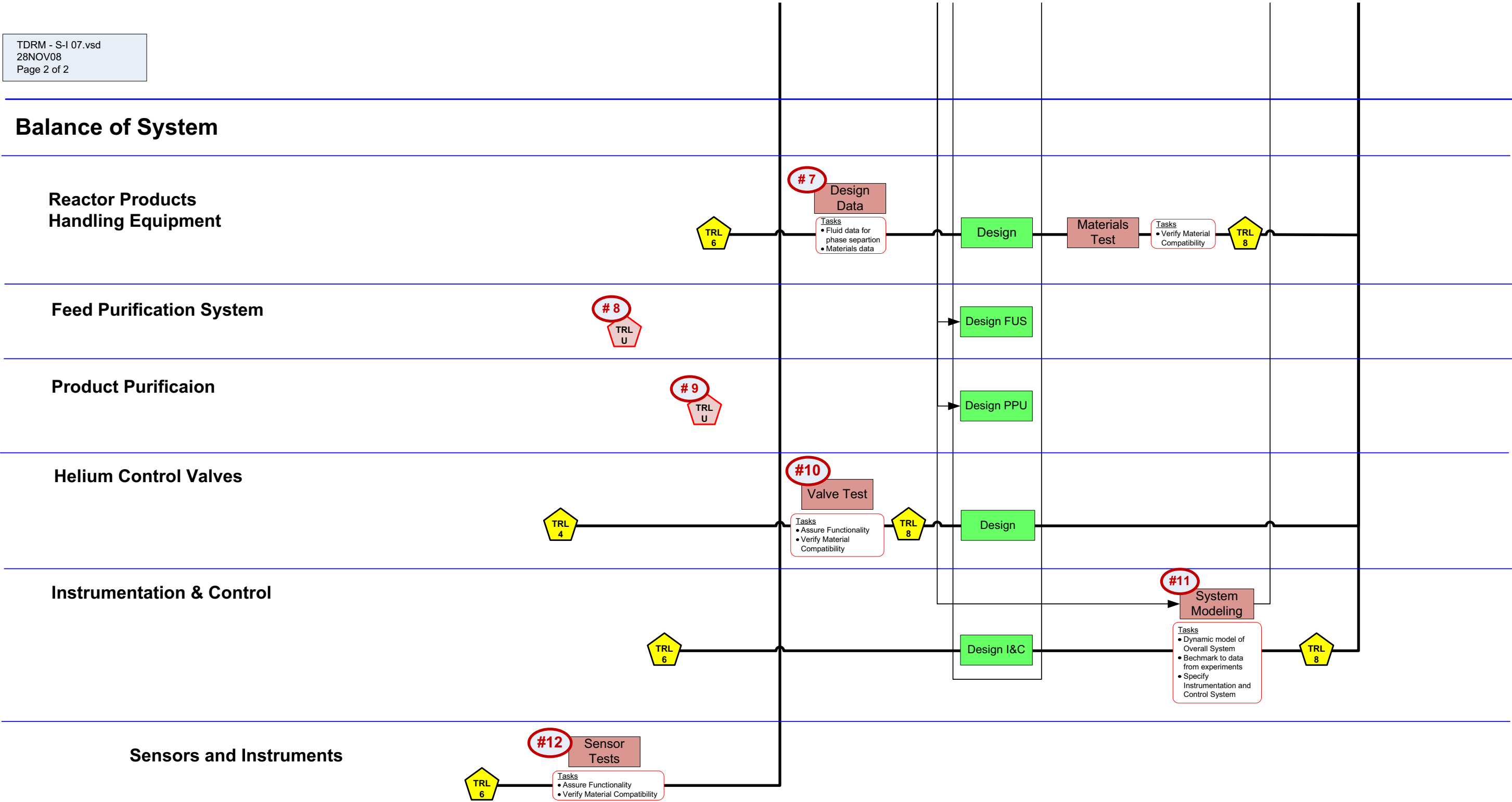


Figure 6-3: Technology Development Road Map for Bunsen Reaction and HI Decomposition (Sheet 2 of 2)



6.3.4.2 Maturation Plans for Reference Design

6.3.4.2.1 Scope

From today's status, the next step is for the reactive HI distillation concept to be brought up to the same level of proof of concept that the Bunsen Reaction section design will have reached at the end of the SI ILS Experiment. Following that will be the Preconceptual Design of a flowsheet and components that will meet the performance goals of the NGNP. The steps to TRL-8 will then be successive tests of scaled-up assemblies.

The Preconceptual Design will lead to experimental-scale tests of the Bunsen Reaction section and the HI Decomposition section separately to demonstrate progress in basic unit operations and to confirm the design. The two sections will then be combined for integrated operation into a pilot-scale test, the results of which will support Conceptual Design.

The next juncture on the Road Map is a Bunsen & HI Sections Engineering Scale Test. This test should bring these sections of the SI HPS to readiness for the NGNP Demonstration where they would then be combined with the Sulfuric Acid Decomposition section. However, if necessary, the next step could be a SI System Engineering Prototype Test including the Sulfuric Acid Decomposition Section.

Scale-up proposed for planning purposes and shown in the TDRM is approximately as follows:

• ILS to Pilot	x 100
• Pilot to Engineering	x 20
• Engineering to NGNP Demonstration Plant	x 20
• NGNP Demonstration Plant to NGNP Commercial Plant	x 10

6.3.4.2.2 Specific Steps in the Road Map

The following are brief descriptions of the objectives of the thirteen steps shown with numbered ovals on the TDRM.

SI ILS Experiment (#1)

This is a presently ongoing system test. The apparatus has advanced from glass laboratory assembly to metal and SiC in contact with the process fluids. A major distinction of this experiment is that the HI Distillation section is not of a design that appears to be feasible in a commercial application because of the low overall system efficiency. Therefore, this system test advances only the Bunsen section to TRL-4. The development skips TRL-3 since operation in the SI ILS accomplishes both proof of concept and demonstration of technical functionality.

Kinetic and Thermodynamic Data (#2)

In order to design the HI reactive distillation section, the reaction kinetic and thermodynamic data is required. At this point in development of the reactive distillation option, thermodynamic and mass transfer data have been approximated and/or extrapolated. The cycle requires work input, in the form of electric power, and the calculation of this is indeterminate without more reliable data. Gathering this data fulfills the TRL-3 criterion to prove analytical and experimental critical function and/or characteristic in the laboratory.

HI Section Experimental Test (#3)

Following Preconceptual Design, an experimental scale design verification test of the HI Decomposition section will advance it to TRL-4. It falls short of TRL-5 because without the Bunsen section the test is not in a relevant environment.

Bunsen & HI Sections Pilot Test (#4)

Before Preconceptual Design, the results of the SI ILS will be reviewed. Following Preconceptual Design, further maturation requires a test of the Bunsen section combined with the reactive distillation HI section. Separate tests would not be adequate because of the high interchange of I_2 and HI between the sections during operation. This test assembly would be equivalent in scale to an HPS producing about one half gram/second of hydrogen. This test will provide the data for SI HPS Conceptual Design, and the test size is the minimum that would provide confidence to proceed with the system design.

The goal of this test is 1000 hours of operation with production on the order of 20 Nm^3 of hydrogen per hour and stability of less than 10% decline per 1000 hours.

Bunsen & HI Sections Engineering Test (#5)

The design and experimental iterative process will continue according to the design resulting from the Conceptual Design. This test assembly would be equivalent in scale to an HPS producing about ten grams per second of hydrogen. The assembly will be tested in the full operating conditions at the required temperatures and pressures for dynamics, startup, shutdown, emergencies, etc. The test assembly would include designed seals, valves, and instrumentation sensors, and the testing would provide design verification for the Final Design exercise.

The goal of this test is 2000 hours of operation with production on the order of 420 Nm^3 of hydrogen per hour and stability of less than 1% decline per 1000 hours.

This completes the maturation of the Bunsen Reaction and HI Decomposition sections to TRL-8.

Process Coupling Heat Exchanger Tests (#6)

This heat exchanger is conventional and will require materials compatibility testing at the temperatures and pressures at which it will operate. If necessary, a pilot assembly of the PCHX would be tested at sub-scale but with appropriate similitude at its high temperature operational environment. Further definition of these tests requires the completion of design.

Bunsen Reactor Products Handling Equipment (#7)

Basic fluid data and materials compatibility data are needed for the various compositions of iodine and HI. No specific equipment handling technology development is intended. Materials' testing after the designs are established advances this technology to TRL-8.

Feed Purification System Demonstration Test (#8)

Design of the water purification system of the FUS needs to mitigate the effects of various contaminants on the Bunsen and HI decomposition reactions. Concern is with impurities dissolved in iodine that build up in the system or precipitate out at the liquid/liquid interface. Without requirements the scope of development of this SSC is uncertain.

Product Purification System Demonstration Test (#9)

The overall system design must assure that the hydrogen product purity requirements are realized. The concern is iodine presence in the hydrogen. In theory it could be removed, but this would have to be demonstrated convincingly before the hydrogen could be put into any pipeline. Without requirements the scope of development of this SSC is uncertain.

Valve Test (#10)

The valves that control the flow of high-temperature helium in the NHSS SHTS between either series or parallel PCHXs are part of the HPS. The number of valves is dependent on the process, either SI or HyS, and on the scale of eventual application. These valves are not anticipated to be new technology, but they are critical SSCs because there is no recent industrial experience with such valves. The valves will need verification testing. These do not need to be full-scale valve tests, but they should be prototypic in form to the ultimate application, and therefore experience with smaller valves will not apply. Once the technology is validated at the pressures and temperatures of the NGNP application, the TRL will advance from a ranking of 4 to 8.

System Modeling (#11)

Instrumentation and Control (I&C) requires design verification that can be accomplished by analysis. The model will use data from the Bunsen & HI Sections Pilot Scale Test. Since the HPS is made of discrete thermal-hydraulic components connected by piping, the demonstration

of integrated operation can be done by computer simulation given input of the performance of the discrete components in prototype or pilot testing in their operational environments. Results will be input to the final System Design.

A specific I&C concern is interface measurement and control of the liquid/liquid interface in the three phase separator and elsewhere in the system. There is a need to test available methods of interface determination and assess their effectiveness. If none were suitable, a new technology might have to be developed.

Completion of system modeling will constitute demonstration of the I&C System, and so the I&C System advances to TRL-8.

Sensor Tests (#12)

Thermocouples, pressure sensors, and other instruments need to be qualified for the operational environment they will experience. New technology is not expected to be required as the sensors would have been operated in relevant environments. Scale does not particularly apply to sensors, and so prior to testing they could be TRL-5, TRL-6 or TRL-7. The middle value is chosen arbitrarily. After successful testing the sensors are TRL-8.

SI System Engineering Prototype Test (#13)

This test is not considered useful to advance the technology because the separate testing of the Acid Decomposer and the combined Bunsen & HI Sections in the engineering scale could assure TRL-8. It is included as an option in the case that an integrated SI system HPS assembly is required. Depending on design work yet to be done, the test will be built for input power of about $2.5 \text{ MW}_{\text{th}}$, which is 1/20 of the minimum commercial scale and 1/200 of the ultimate commercial plant scale. This test assembly would be producing about 10 grams/second of hydrogen.

6.3.4.2.3 Schedule and Cost

The cost and schedule for the Bunsen Reaction and HI Decomposition technology development are summarized in Table 6-15. The cost and completion years are keyed to stages along the Road Map as indicated by the step numbers, which correlate to the numbers in red ovals on the TDRM.

Table 6-15: Cost and Schedule for the Bunsen Reaction and HI Decomposition Technology Area

TRL Achievement	Step Numbers from TDRM	Cost Completion
Up to completion of S-I ILS –Bunsen: TRL-2→4	#1	--
HI Section Experimental Test – HI: TRL-1→4	#2, #3	3.0 \$M 2010
Bunsen and HI Systems Pilot Test – TRL-4→5	#4	43.0 \$M 2013
Bunsen and HI Systems Engineering Test – TRL-5→8	#5, #6	58.0 \$M 2017
(Prototype HPS Test: Sulfuric Acid, Bunsen & HI Sections - optional)	(#13) Test is not needed, but .	(140.0 \$M) (15.0 \$M) 2018
	if done at scale of NGNP Demo	
	if done using duplicate of previous Engineering Test (or actual hardware)	
Balance of system design verification – TRL-x→8	#7, #8, #9, #10, #11, #12	8.1 \$M

6.3.4.2.4 Maturation Plans for Alternatives

Presently there are no plans for alternative SI HPS designs. Although, there will be a review of all design choices at the beginning of the Preconceptual Design phase. This review could generate an alternate path in the development road map for the Bunsen Reaction and HI Decomposition technologies.

6.4 HIGH TEMPERATURE STEAM ELECTROLYSIS

The HTSE process has been discussed in Sections 2 and 3. The overall HTSE system is divided into four major systems, as shown below, with the principal systems and major components itemized for each.

- Electrolyzer System (ELE)
 - Electrolyzer Modules
 - Solid Oxide Electrolysis (SOE) Cells
 - Other Electrolyzer Module Internals
 - Process Coupling Heat Exchangers

- Piping, Manifolds & Insulation
- Heat Recovery System (HRS)
 - Heat Exchangers
 - Recirculator
- Feed & Utility System (FUS)
 - Feed Purification Systems
 - Sweep Gas Turbine
- Product Purification System (PPU)

Process flow diagrams for the HTSE HPS are shown in Section 8.3.3.

6.4.1 Functions and Operating Requirements

The HTSE HPS accepts heat from the plant NHSS. Heat is provided to the PCHXs of the HTSE ELE system by the helium circuit of the NHSS SHTS. The HPS also takes electric power from the plant PCS and imports additional electric power from the offsite electric grid through the BOP.

The HPS gets process feed water from the BOP, the water is further purified for use in the HPS. The heat and electric energy converts the feed water into hydrogen and oxygen gas. The hydrogen is directly provided to a pipeline for export after drying, and the oxygen is vented to the atmosphere in the form of oxygen enriched air after drying. Wastewater streams are released to the environment after treatment.

Hydrogen production occurs in the ELE. Functions of the other major systems that comprise the HTSE HPS are implied from their names: Heat Recovery System, Feed & Utility System and Product Purification System.

Operating requirements are to meet project requirements with respect to safety, availability, product output, and environmental impact in accordance with the overall plant design. Therefore, cell and stack performance must be safe and meet the economic target of the project. Minimum requirements to accomplish this are:

- Oxygen-rich and hydrogen-rich environments must not communicate with one another;
- Cell area-specific resistance should be minimized;
- Cell current density should be maximized;
- Electrical potential between contiguous stack sections must be minimized;
- Flow distribution among cells, stacks of cells, and modules must be equalized;
- Sweep gas requirements should be minimized;
- Transfer adequate heat to the operating cells and maintain them at the required operating temperature;
- Maximize energy recuperation within practical engineering limits;

- Purify the feed water and sweep gas to the extent required by economical cell operation;
- Purify the products to the extent required by the customer;
- Treat waste streams to the extent required by applicable environmental regulations, and;
- Design the plant so that it can be operated in a safe manner and operate the plant in a safe manner in accordance with the design.

Further specific statements of functions and requirements of the HTSE HPS will result from the Conceptual Design.

6.4.2 Development Status

The most advanced concept for an HTSE HPS is the process described in Section 2. Although much work has been carried out in the design of bench-scale cells and stacks, significant work has yet to be done in the design of commercial scale cells, stacks, and modules. Future technology development must work to arrive at a practical initial concept. There are four areas for which HTSE electrolyzer issues must be addressed:

- Individual SOECs:
 - Maximize current density and minimize area specific resistance.
 - Seal the cells such that the hydrogen-rich side does not communicate with the oxygen-rich side in spite of differences in thermal expansion coefficient between cell components.
 - Avoid cell de-lamination in spite of differences in thermal expansion coefficient between cell components.
 - Optimize resistance to flow of the feed and sweep gases.
 - Minimize or eliminate the need for sweep gas.
- Stacks of cells:
 - Equalize the resistance to flow through the cells such that individual cells are neither flooded with nor starved of feed steam. This may be an issue of control of variability in the manufacture of cells.
 - Minimize the electric potential between contiguous sections of the stack.
 - Seal the edges of the stacks to the manifolds such that hydrogen-rich and oxygen-rich environments do not communicate.
 - Maintain electrical connectivity between the power supply and the cell stacks and between cells within the enclosure environment.
 - Maintain adequate mechanical force on the stack to hold the inter-cell seals within the enclosure environment.
- Enclosure of the stacks:
 - Optimize the operating pressure of the stacks. The higher the operating pressure, the lower product and sweep gas compression requirements. On the other hand, high operating pressures pose difficult sealing and safety issues.

- Maintain the required operating temperature of the stacks while minimizing heat losses
- System design
 - Low current density in the cells requires that very large cell area is required for a commercial installation. This, in turn, requires a large number of modules, each of which is a high pressure vessel operating at very high temperatures. There are 76 modules included in the preconceptual design.
 - The plant layout must be devised so as to minimize piping run length and pipe growth due to thermal expansion. A 1½% to 2% (2m/100m) growth from ambient to operating temperature is expected. Moreover, adequate access for repair and replacement of modules must also be provided.
 - Pressure drop in the feed lines must be limited to ensure adequate distribution among the modules.

6.4.2.1 Solid Oxide Electrolysis Cells

The SOECs have been developed to a “laboratory” or “bench scale” level and the electrolyzer stacks have been designed and tested to the degree necessary to demonstrate feasibility and functionality at low pressure. Commercial scale cell and stack concepts have received only very preliminary attention. Electrolyzer enclosure concepts and development of the overall process, including heat recuperation also have received little attention. All of these elements interact with one another and need to be part of the technology development effort.

Candidate Concepts

The SOEC’s are in the early stages of conceptual development using stacked individual planar cells with peripheral feed supply and product removal. An alternative is tubular cells^[Ref.40]. The tubular configuration appears to have inferior current and fluid flow access and an inherently lower packing density. However, the tubular design should be considered as a back-up to be revisited in the event difficulties with planar cells occur in the manufacturing, sealing, or module assemblies. Electrode materials and electrolyte materials have been chosen, but alternative materials continue to be considered.

Sealing concepts have been developed and tested in the partial stack tests. They will be further tested in the HTSE ILS. Sealing problems are connected with cell size and issues surrounding assembling cells into modules. Refinements are expected in the course of development.

The most significant issue is the size of the planar cell. The cells are now sized based upon a rectangular electrolyte 100 mm on a side. If physical limits – particularly differential thermal expansion – permit, the cells need to be scaled up to 500 mm on a side to approach commercial economic viability. This size has been selected for the design in Section 3 of this report.

6.4.2.2 Decision Discriminators

Decisions regarding the size and configuration of the cells include individual cell performance: primarily current density, area specific resistance and resistance to flow.

6.4.2.3 Reference Design for Hydrogen Alternative Study

HTSE process and design used as a reference for this Technology Development analysis has been presented in Section 3.

6.4.2.4 DRLs

The HTSE HPS is at an early design stage with numerous developmental issues yet to be resolved. The HTSE system design is based on the high temperature SOEC in development at INL. The Electrolyzer Unit general configuration and principal features have been selected from alternatives and materials chosen for further development work. Cost and requirements analyses are in progress as part of the initial phase of Conceptual Design. Therefore, the ELE System is considered DRL-2.

The remainder of the overall system is only at the preconceptual stage (i.e., DRL-1). A summary of the HTSE HPS DRLs is shown in Table 6-16.

Table 6-16: High Temperature Steam Electrolysis DRLs

	DRL
Overall HTSE HPS	1
ELE System (Electrolysis System)	1
Electrolyzer Module	1
SOE Cells	2
Internal Manifolds	2
Seals	2
Vessel	1
Sweep Gas Coupling Heat Exchanger	1
Helium control valves	1
Process Side Control Valves	1
Process Coupling Heat Exchanger	1
Helium control valves	1
Process Side Control Valves	1

	DRL
Piping and Manifolds	1
HRS System (Heat Recovery System)	1
Heat Exchangers	1
Feed Water Heaters	1
Process Boiler	1
Process Superheater	1
Recirculator	1
FUS System (Feed & Utility System)	1
Feed Purification System	1
Sweep Gas Turbine	1
Instrumentation and Control System	1
I&C System	1
Sensors, instruments	1

6.4.2.5 Down-Selection Tasks

While one electrolyzer concept has been chosen for development, the conceptual design phase of the NNGP is still ahead. When Conceptual Design begins, it is recommended that alternatives be reviewed. In practical terms that will be the down-selection for going forward to full-scale cell tests and then to a Pilot Test.

6.4.3 High Temperature Steam Electrolysis TRLs

In summary, the current TRLs for the HTSE HPS and its constituent systems are evaluated as shown in Table 6-17. In summary, the SOECs are the furthest advanced with the other systems lagging in development because of the low degree of design definition at this phase.

Table 6-17: High Temperature Steam Electrolysis TRLs

	TRL
Overall HTSE HPS	3
ELE System	3
Electrolyzer Module	3

	TRL
SOE Cells	3
Internal Manifolds	5
Seals	4
Sweep Gas Coupling Heat Exchanger	5
Process Coupling Heat Exchanger	5
Piping, Manifolds	U
HRS System	5
Heat Exchangers	5
FUS System	7
Feed Purification System	U
Sweep Gas Turbine	7
Helium Control Valves	4
Instrumentation & Controls -- including sensors	6

The HRS System Recirculator and the PPU System are ranked TRL-8. This is an indication that the technology is ready for the demonstration of the overall system, and therefore these SSCs are “critical.” These two systems do not need testing; only vendor confirmation as the design is detailed.

In Section 8.4.1 may be found detailed rating sheets of the TRLs for the SSCs in Table 6-17 that are the lowest constituent parts. Each sheet includes the summary basis for the rating and an outline of a plan for each SSC to get from the current level to the next level.

6.4.4 Technology Development Plan

6.4.4.1 Overview and Road Map

The Technology Development Road Map for HTSE is shown on Figure 6-4.

Figure 6-4: Technology Development Road Map for High Temperature Steam Electrolysis (Sheet 1 of 2)

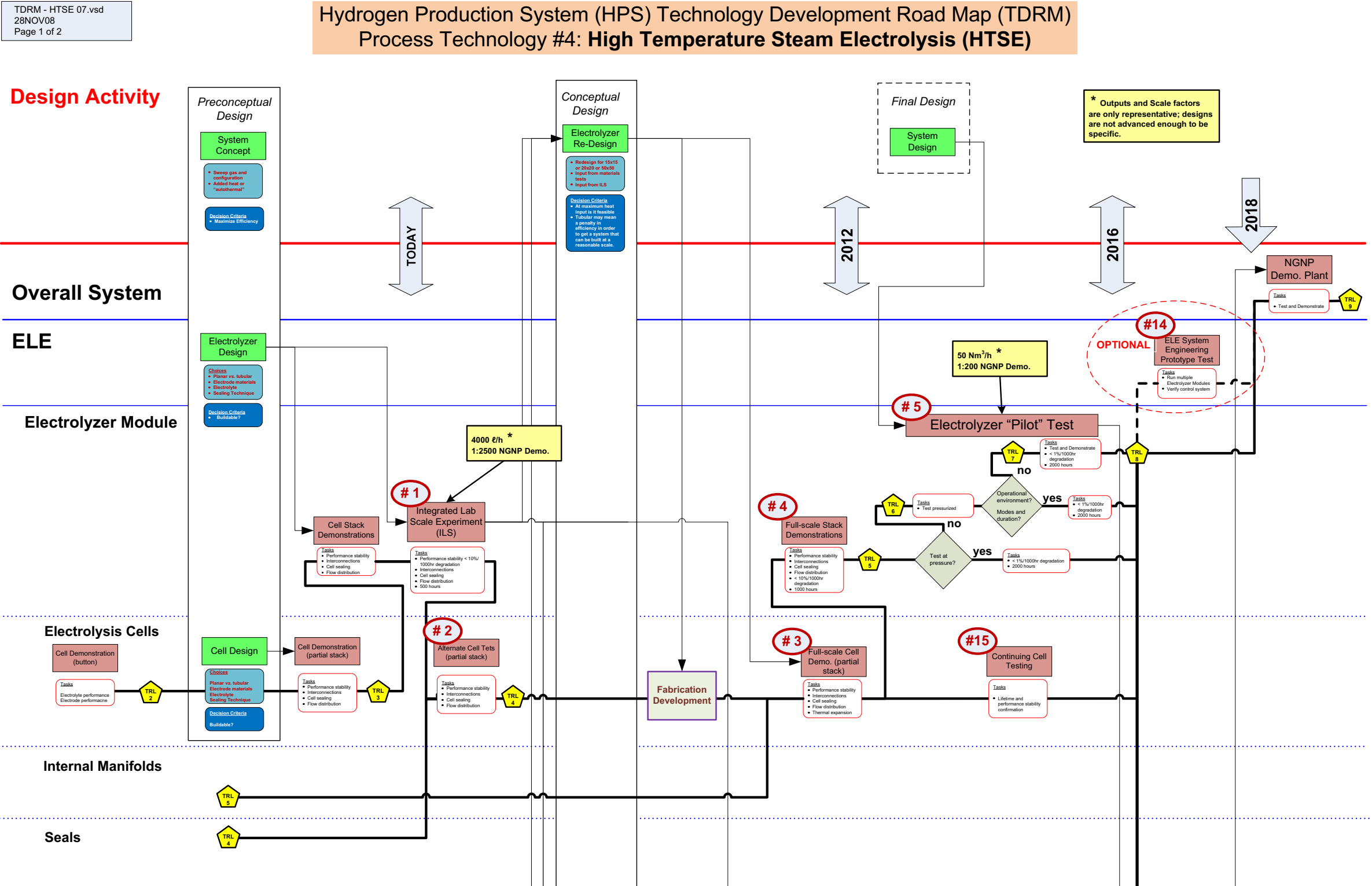
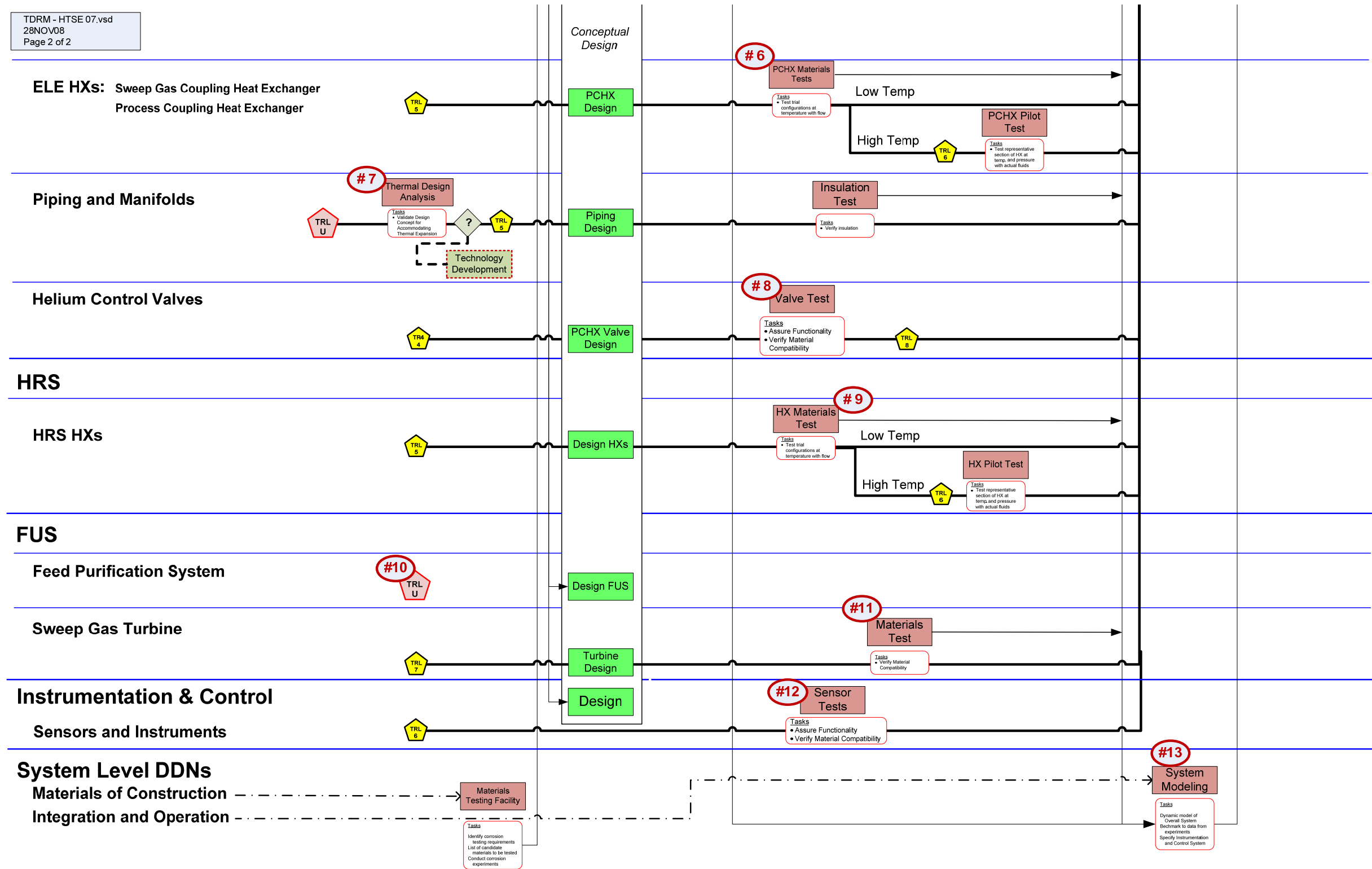


Figure 6-4: Technology Development Road Map for High Temperature Steam Electrolysis (Sheet 2 of 2)



6.4.4.2 Maturation Plans for Reference Design

6.4.4.2.1 Scope

The critical path through the TDRM toward maturation of the technologies pertaining to the HTSE HPS follows the following course.

The maturation plan can not be more precise because of the early stage of design and of the low TRLs today. The present phase is between preconceptual and conceptual design with supporting development at laboratory or bench scale. In those circumstances, design and development are in a chicken-or-the-egg relationship. Although we identify steps, mainly experiments and tests, to advance the technology, these can not be more definitely specified until the designs advance further. In some cases, whether the test is really necessary or if the technology is already nearly ready (i.e., TRL-6, -7 or -8) cannot be decided until after the design details are done.

The above describes the appropriate cycle of design and development, where initial concepts frame technical issues and produce DDNs. The technology is then developed to answer the need and the design moves to further detail. The continued design effort raises more technical uncertainties. More DDNs are written and through development testing technology moves ahead. This circuit is repeated numerous times maturing as it goes. In the current case of HTSE technology, the process is between preconceptual and conceptual design and at a low degree of technical maturity.

Note that the TDRM and maturation plans will need to be adjusted as new DDNs evolve as part of the conceptual and final designs.

Advance the Electrolyzer Module

The Materials Test Facility is in operation, and the ILS Experiment is running. The electrolyzers are presently at TRL-4. Their feasibility and functionality having been proved in earlier partial cell stack tests, but the specific issue of stable operation needs to be resolved in the ILS test.

The successful completion of the ILS Experiment will support the overall system conceptual design, which will include SOE cell and Electrolyzer Module re-design. At this point, the cell production will be re-engineered to meet the requirements of cell area scale-up, and a round of fabrication development tasks can be anticipated.

Scale-up proposed for planning purposes and shown in the TDRM is approximately as follows:

• ILS to Pilot	x 13
• Pilot to NNGP Demonstration Plant	x 200
• NNGP Demonstration Plant to NNGP Commercial Plant	x 10

This conceptual design will be followed by electrolyzer internal component tests for internal manifolds and connectors and cell stack tests of the new cell design. With completion of these tests, the Electrolyzer Module will attain TRL-5.

The next task is final design and testing of a prototypical Electrolyzer Module in operational conditions. In the Pilot Test of the unit, the TRL will advance to TRL-6, -7 and -8 as tasks identified are accomplished. Because in the ultimate application they are highly modular, testing of one full-scale Electrolyzer Module satisfies the scale requirement to reach TRL-8.

Advance the ELE Heat Exchangers

Two heat exchangers interface with the NHSS. These are the Process Coupling Heat Exchanger and the Sweep Gas Coupling Heat Exchanger. The former transfers heat from the SHTS helium to the HPS sweep gas (i.e., the electrolyzer anode input flow) and the latter transfers heat from the SHTS helium to HPS process feed (i.e., the electrolyzer cathode input flow).

As conceived thus far, these heat exchangers are not novel technology. Although, there is no significant similar experience at the temperatures and pressures of the superheating sections. Materials testing will advance these heat exchangers to TRL-6 or -8. The latter will be achieved if tested at operational conditions and at suitable scale. If only the former, then a separate pilot test is an alternative to assure TRL-8.

These heat exchangers have requirements for valves on the process side at the inlet and the outlet. In addition, there is a requirement for valves or other flow balancing components on the colder helium side to assure proper division of helium flow to the heat exchangers. These valves are not considered items requiring technology development based on the definition of the design at this stage. As system functional requirements are clarified and design proceeds, there could be DDNs for these valves that lead to development tasks on the TDRM.

Advance the ELE Piping and Manifolds

Piping and manifolds have a severe duty to accommodate significant differential thermal expansion because of the very high fluid temperatures. Piping very high temperature gas to several dozen cell modules will be an extremely difficult problem. Thermal expansion of the pipe is expected to be from 1 ½ to 2 %. Pipe runs will be on the order of 100+ meters. The growth that must be accommodated is therefore about 2 m. Absorbing this amount of expansion in very high temperature piping has not been done commercially and a design for this requirement is not at hand. It is not possible to say the technology has reached “proof-of-principle.”

Piping and manifolds on the process circuit will require thermal insulation to assure the efficiency of the overall system. The concept for this insulation needs to be determined, particularly when the insulation is integrated with the thermal expansion features. There would clearly be a trade-off between efficiency, internal insulation, external insulation, operating

temperature of the external surface and pipe material. If internal insulation is used, a concern is the fact that the lines carry steam and are subject to condensation as the vapor cools in the insulation. This is a design problem that needs to be addressed before the degree of technology development can be fully assessed.

When designed there is an insulation test for design verification of the resulting configuration and move it to TRL-8.

Advance the Heat Recovery System

The recuperative heat exchangers of the HRS System, like the ELE heat exchangers, will be operating at higher temperature and pressure than current-state-of-the-art. A materials test can advance these to TRL-8 directly, or a pilot test may be needed.

Advance the Feed & Utility System

The FUS System has two main parts. The Feed Purification System is likely to be critical to the stable operation of the cells. Results from the ILS Experiment will clarify the design requirements for this system.

The Sweep Gas Turbine is a standard turbomachine. Vendor design verification of compatibility of the materials of construction with air/oxygen mixture will give it TRL 8.

6.4.4.2.2 Specific Steps in the Road Map

The following are brief descriptions of the objectives of the fifteen tests shown with numbered ovals on the TDRM.

ILS Experiment (#1)

The ILS is a first assembly intended to demonstrate performance of the HTSE process in realistic conditions at or near temperatures needed for system feasibility^[Ref. 41]. Test objectives are closed-loop operation with good flow distribution and heat transport performance, stable operation for extended periods of operation or, if not, identification of degradation and/or failure mechanisms and results on materials compatibility testing.

Alternate Cell Testing (#2)

Following the HTSE ILS, there will be a new development activity in the main “Road.” It will entail testing of all ceramic, electrode-supported cells, which being metal-free may resolve some “poisoning” issues such as the suspected effect of displaced chromium. Cell designs to be considered are being developed for Solid Oxide Fuel Cells by Saint-Gobain, originally by Forschungszentrum Jülich, and NASA-Glenn Research Center. Accomplishment of this step will result in TRL-4.

Full-scale Cell Demonstration (#3)

Cells will be scaled-up in cross section in the Conceptual Design. Following that the re-designed cells will be tested. Long-term, stable operation will be the test objective.

Full-scale Stack Demonstration (#4)

A stack of the scaled-up cells will be tested. The goal of this test is 1000 hours of operation stability of less than 10% degradation per 1000 hours.

Combined with the demonstration of an Electrolyzer Module in the ILS, this will advance the technology to TRL-5.

Pilot Test (#5)

The purpose of the Pilot Test is to generate data needed to confirm or fine tune the design and to provide confidence to go on to the first application. The currently planned INL pilot test^[Ref. 42] may be this test, although the scope and scale of the test as presently planned appears to be less than what is proposed in the TDRM.

The HTSE Electrolyzer Pilot Test in reality would be most likely a series of tests with more-or-less the same test article design. The Pilot Test is intended to move the technology beyond TRL-5. It begins with the completion of the cell and cell stack tests of the SOEC re-designed for full sized cells, which are assumed for the purpose of the TDRM to be 500 mm x 500 mm in nominal area. The actual active cell surface area is approximately 2,300 cm².

To reach TRL-8, an SSC must be a prototype, being as close as possible to the form, fit, and function for final application. It also must be close to full scale, that is no less than approximately ¼ scale, and rigorously tested in its operational environments. Since feed purity is anticipated to be an issue influencing cell performance stability, the testing includes an appropriately sized water purification and deaeration system configured in the design for the NGNP Demonstration plant. It should also test variability of gas distribution by varying the flow of sweep gas and steam/hydrogen to this module.

The test article is to be prototypical of the Electrolyzer design progression to that stage based on the Conceptual Design of the component. It would ultimately be a complete modular unit of the form and size intended for final application. Although the initial tests in the series might use fewer than the design number of cells in the stacks or fewer stacks than the final arrangement. Therefore, the scale of the Pilot Test is 100%.

What then needs to be demonstrated in order to reach TRL-8 is sufficient performance in operational environments. Testing in the ILS will be testing of the 100 mm cells at temperature and flows but not at pressure. The Pilot Test article, since prototypical, includes the pressure vessel. Basic operation in the Pilot Test in full normal operating temperature, flows, and

pressure will accomplish TRL-6, because that will pass the “gate” of test at scale and in the relevant environment.

The goal of this test is 2000 hours of operation with production on the order of 50 Nm³ of hydrogen per hour and stability of less than 1% decline per 1000 hours.

ELE Heat Exchanger Tests (#6)

The preheaters, boilers, and superheaters of the HRS are anticipated to be multiple modular units of conventional configuration. However, the boilers and superheaters are being used at temperatures, pressures, and differential pressures that may challenge the present state-of-the-art. Therefore, in accord with chemical engineering industry practice, pilot tests will be done with actual fluids and at operational conditions.

If necessary, pilot assemblies would be tested at sub-scale. The issues are with the heat transfer equipment are material selections and thermal/mechanical properties.

Piping Thermal Design and Insulation Test (#7)

Accommodating differential thermal expansion is expected to be a significant design issue. Mechanical analysis, possibly supported by experiment, will be needed ahead of Conceptual Design. It is possible that technology development could be required for the expansion design, but this requirement is not demonstrated and is left off the TDRM at this phase until a specific DDN is prepared. Demonstration by analysis will suffice for TRL-5.

A section of the ELE Piping & Manifolds will be tested with flows at temperature to confirm the mathematical bases for pressure drop and thermal losses through the insulation in finally designed material and configuration.

Valve Test (#8)

This valve test is for the valves that control the flow of high-temperature helium in the NHSS SHTS between series and parallel PCHXs. These valves are not anticipated to be new technology, but they are critical SSCs because there is no recent industrial experience with such valves. The valves will need verification testing. These do not need to be full-scale valve tests, but they should be prototypic in form to the ultimate application, and therefore experience with smaller valves will not apply. Once the technology is validated at the pressures and temperatures of the NNGP application, the TRL will advance from level 4 to 8.

HRS Heat Exchanger Tests (#9)

These heat exchangers are conventional units but will require materials compatibility testing at the high temperatures and pressures and differential pressures at which they will

operate. If necessary, pilot assemblies would be tested at sub-scale. Further definition of these tests requires the completion of design.

FUS System Demonstration Test (#10)

Without requirements for feed water purity the scope of development of this SSC is uncertain. If necessary, air sweep gas pre-treatment requirements may be specified and subject to operational verification tests.

Sweep Gas Turbine Materials Test (#11)

This will be a vendor test to verify the compatibility with the application.

Sensor Tests (#12)

Thermocouples, pressure sensors, and other instruments need to be qualified for the operational environment they will experience. New technology is not expected to be required, as the sensors would have been operated in relevant environments. Scale does not particularly apply to sensors, and so prior to testing they could be TRL-5, TRL-6 or TRL-7. The middle value is chosen arbitrarily. After successful testing the sensors are TRL-8.

System Modeling (#13)

Since the HTSE HPS is made of discrete thermal-hydraulic components connected by piping, the demonstration of integrated operation can be done by computer simulation given input of the performance of the discrete components in prototype or pilot testing in their operational environments.

ELE System Demonstration Test (#14)

If separate, lower Level (subsystem) tests together with system computational modeling are not sufficient, this hardware assembly and test series will demonstrate the integrated operation of the ELE and HRS systems.

Continuing Cell Testing (#15)

As cell stack and system tests proceed, there is a need to accumulate lifetime data and quantify long-term degradation. One or more cell tests should continue after the Full Scale Cell Demonstration (#3). The attainment of TRL levels elsewhere on the Road Map would be supported by the Continuing Cell Testing according to the criteria in Table 6-11.

6.4.4.2.3 Schedule and Cost

The cost and schedule for the High Temperature Steam Electrolysis technology development are summarized in Table 6-18. The cost and completion years are keyed to stages along the Road Map as indicated by the step numbers (i.e., the numbers in red ovals on the TDRM).

Table 6-18: Cost and Schedule for the High Temperature Steam Electrolysis Technology Area

TRL Achievement	Step Numbers from TDRM	Cost Completion
Up to completion of ILS – TRL-3➔4	#1, #2	- -
Full-scale stack demonstration – TRL-4➔5	#3, #4	35.0 \$M 2012
Pilot Test – TRL-5➔8	#5	30.0 \$M 2016
(Prototype HPS Test)	(#14)	(50.0 \$M) 2018
Balance of system design verification – TRL-x➔8	#6, #7, #8, #9, #10, #11, #12, #13	13.8 \$M

6.4.4.3 Maturation Plans for Alternatives

Presently there are no plans for alternative HTSE HPS designs. However, there will be a review of all design choices in the conceptual design phase, which could generate an alternate path in the development road map.

7 CONCLUSIONS & RECOMMENDATIONS

7.1 SUMMARY OF FINDINGS

7.1.1 Major Findings

The best of the HTGR-based water-splitting processes is not projected to be competitive with SMR until the price of natural gas exceeds about 15\$/MMBtu plus a real escalation rate of 2%/yr, or there is an equivalent cost or tax associated with carbon collection and sequestration.

Operating risks of these technologies are very high in comparison with current hydrogen plants.

The HyS and HTSE hydrogen production processes are likely to be competitive with ambient temperature alkaline or PEM electrolysis, even considering the future cost goals associated with those technologies.

7.1.2 NGNP Application

For HTSE, there is a distinct disproportion between the amount of nuclear heat supplied by the HTGR and process heat used by the technology. There is significantly more heat produced by the HTGR than required by the process. Scaling up a HTSE process to match the nuclear heat would result in an unrealistically large hydrogen production rate. Coupling HTSE with an HTGR also presents formidable challenges with regard to thermal expansion of the process piping and thermal insulation within vessels and the electrolysis modules. From a commercial perspective, there is little incentive to incur the significant development costs and risks in developing HTSE for an HTGR when there are other more attractive alternatives for HTSE (e.g., a LWR). A key step in the SI process, HI reactive distillation, has not yet been proven in principle and operating risks and costs are likely to be very high. It too is an unlikely candidate for NGNP application. Although it also faces several challenges, the HyS process is the most likely candidate, at this time, for the earliest commercial-scale demonstration with NGNP, or to replace an industrial-scale SMR process.

7.1.3 Capital Cost

The capital costs of all three of these technologies are high in comparison to steam methane reforming plants. Current estimates for a ~150 MMSCFD steam methane-based hydrogen plant range around \$300 million.

The estimated costs of the hydrogen production plants developed for this study, excluding nuclear reactors, range from about three to ten times the cost of a comparably sized steam methane reforming plant. This is not surprising given the complexity of these plants, and the costly materials of construction. The cost of electrolyzer cells dominates the capital cost of both the HTSE and HyS technologies. Available cost estimates are indicative at best. The

authors utilized the best estimates available from the technology developers for capital costs associated with key components of these developing technologies. Otherwise, costs not provided by the technology developers are consistent in source and accuracy.

Total capital required to for a ~150 MMSCFD hydrogen production facility, including the HTGR reactors, is estimated to be \$5,973 million for SI, \$3,518 million for HyS, and \$2,252 million for HTSE. These are the costs of Nth-of-a-Kind plants and they do not include the development costs to proceed from the current state of the technologies to commercial-scale demonstrations, nor do they include the costs of the NNGP development and demonstration. In addition, if capital associated with the construction of new nuclear generation capacity for supply of imported electric power is included, the HyS and the HTSE process have about the same financing hurdle. The SI process, on the other hand, has the highest financial hurdle when considering both process plant capital costs and new nuclear generating capacity.

7.1.4 Cost of Hydrogen

Cost of production of hydrogen from these plants is largely dependent upon the capital charges and the cost of the nuclear heat. However, imported electric power is a significant cost contributor for the SI and HTSE processes.

Base case hydrogen production costs were calculated to be \$10.71/kg H₂ for SI, \$6.83/kg H₂ for HyS, and \$6.04/kg H₂ for HTSE. Hydrogen production costs were determined to be sensitive to capital cost, IRR, capacity factor, nuclear heat, and electricity costs. The HTSE hydrogen production cost was also sensitive to the electrolyzer replacement frequency.

7.1.5 Operating Risk

The operating risk – such as the potential for operating failure, loss of investment, and down-time – for all of these technologies is high. For HTSE, there is a serious potential for hot hydrogen and/or hot oxygen leakage. This type of event would result in a hydrogen flame with resulting loss of investment or operator injury, depending upon the design of the cell stacks.

Both Hybrid Sulfur and Sulfur Iodine plants handle large amounts of sulfuric acid as well as mixtures of hot steam, sulfur trioxide, sulfur dioxide, and oxygen. The potential for corrosion from these materials increases the risk of leakage.

The Sulfur Iodine process requires circulation of very large amounts of iodine and hydroiodic acid. The estimated inventory of the base case plant is 7,500 tonnes of iodine. The corrosive nature of these materials enhances the potential for leaks, spills, and increased maintenance costs.

7.1.6 Technology Development

Insufficient design has been carried out on the major components of these technologies to have assurance either that all the major component engineering and design issues have been discovered or that some of the major issues identified here can be resolved.

Materials of construction, including auxiliary materials such as seals, gaskets, and linings, will be a major development issue. Development of these materials is not included in the R&D program yet and may present a limiting factor for progressing the technologies and affect cost and schedule.

Current plans for technology development are for demonstrations larger than is typically required by industry. Since each technology will operate in a modular fashion or with multiple process trains, smaller demonstrations may be sufficient to demonstrate viability. Additionally, viability of the processes may be demonstrated with a non-nuclear heat source.

The technology readiness level for each of these technologies is currently low. This is the case because although some critical systems, structures, and components of each technology have advanced beyond the early stages of development, others have not. For example, the functionality of the bayonet tube reactor in the sulfuric acid decomposition section has been tested at bench scale. However, a catalyst with a reasonable commercial life has not.

7.1.7 Technology Risk

Risk as used here means the likelihood of not achieving a commercial, economically viable process design, including all critical components, in a ten year period. The risk assessed is the likelihood of missing the economic and schedule parameters set forth in this study by a significant margin due to technology development challenges.

By a careful analysis of the challenges faced by each technology, they fall into five major categories:

- **Fundamental (F)** limitations: These are clear limits set by the laws of physics, chemistry, and thermodynamics. It is evident that no amount of research or engineering will overcome these.
- **Possible (P)** fundamental limitations: These are limits that may be fundamental, but that could be circumvented by an alternative design.
- **Obscure (O)** path to success: These are issues for which little consideration has yet been given.
- **Difficult (D)** but relatively clear path forward: Some consideration has been given to these issues and the path forward is reasonably clear, but could still raise challenges to schedule and cost.
- **Straightforward (S)** path to success. These issues are treated in the body of the report, but are not dealt with here.

Some engineering judgment is involved in these rankings and some disagreement between honest judges is to be expected. The tables below list the major technical issues and categorize them according to the above scheme of five major categories (F, P, O, D or S). The initial letter of each category is used as a designator in the tables.

Table 7-1: Major HTSE Technology Challenges

A.	Uses proportionately little high temperature process heat	F
B.	High temperature heat added between cell stack and heat recuperation	F
C.	Thermal expansion in the delivery piping and pipe insulation	P
D.	Thermal insulation of electrolyzer modules	P
E.	Reliably sealing the cells from hydrogen, steam, air, and oxygen leaks	P→O
F.	Rapid deactivation of the cells	O→D
G.	Cell scale-up	P

- A. Very little of the energy required to electrolyze steam into oxygen and hydrogen can be supplied as process heat using the HTSE technology. At best only 15% of the total energy to split water would be added as process heat. The rest is added as electrical energy. Consider the process heat as a fraction of the total heat used for both process heat and electrical generation, the fraction is only about 7%. This means that if a 550MW_{th} HTGR were used exclusively for process heat, the plant capacity would be about 900 MMSCFD of hydrogen and the amount of imported electricity would be 3,000 MW_e/h. The bench scale laboratory work that has been carried out thus far has been using the thermal neutral point as the benchmark case. Consequently, process heat is required only to compensate for thermal losses. The thermal requirement of the process is generated by ohmic losses in the cells.
- B. Process heat must be added between the cell stack and the recuperation equipment. This results in several very challenging engineering problems including distributing very hot steam and air to many cell stacks, limiting heat losses from the pipe and stacks, designing for thermal expansion of the distribution piping, designing for thermal expansion of the stacks and of tension bars meant to maintain pressure on the inter-cell seals, penetrating a pressure boundary at very high temperatures and pressures with large electrical cables, and maintaining the integrity of electrical connections in a very hot and possibly oxidizing environment. Recognizing these issues, the technology development team has developed a recuperator integrated into the cell stack. Combined with operation at the thermal neutral point, this is an elegant approach. However, this approach practically precludes using any appreciable amount of nuclear process heat from a HTGR.
- C. Thermal expansion of the delivery pipe is a more difficult issue than it at first appears. The fact that the piping must operate at very high temperatures and possibly pressures will require that it be very heavy wall pipe. This will reduce its flexibility considerably thereby increasing the stress on critical fittings (e.g., elbows) during expansion of the piping. Expansion loops will be required to

compensate for about two meters of expansion. The length of these loops will add appreciably to the length, pressure drop, and heat losses from the piping. From discussions with piping experts, it is not clear that a feasible solution is available. It is unclear at this time how this expanding piping will be insulated such that the insulation will accommodate or expand with the piping.

- D. Per the study's design, the operating temperature and pressure of the electrolyzer modules are 870°C and 56 bar, respectively. For the modules, the insulating properties of any internal insulation will be an order of magnitude lower than we expected due to the high operating pressure. Up to about 40 bar, the thermal conductivity of gases are affected only very slightly by pressure. As pressure rises above this level, however, the thermal conductivity increases very rapidly. The thermal conductivity of the insulation is entirely dependent upon the conductivity of the gas in the insulation. For internal insulation, this will be air and oxygen. For air and oxygen above 40 bar, the dependence of thermal conductivity on pressure changes dramatically and becomes quite strong. Although the effect on the Prandtl number is negligible, the effect on conductivity, and therefore presumably also on viscosity, is large. For gas trapped in the insulation, conductivity and not Prandtl number is important: heat transmission is mostly by conduction, not convection. The net effect is that the insulation becomes largely ineffective.
- E. The sealing issues inherent in the current design are described above. A cell stack design that does not require enclosure by a pressure vessel may mitigate some of the problems, but it raises additional issues. Such a stack design would be able to operate only at low pressure. This would require much larger equipment as well as expensive compression of low pressure hydrogen to pipeline pressures.
- F. Current active cell life is extremely short by commercial standards. The causes of de-activation are as yet unknown. This may be a problem related to dissolved ions in the feed water or may be inherent to the cell design itself. If the current Ceramtec cell design is indeed inherently life limiting, alternative cell designs such as the all ceramic NASA cells may need to be considered. It should be noted, however, that the NASA cells are at a much earlier stage of development. Therefore, if the Ceramtec design is deemed not to be viable because of cell longevity, there is the implication that the technology readiness will need to be downgraded further.
- G. Cell scale-up is an issue for both HTSE and HyS. In the case of SO₂ electrolysis cells, there are similar commercial cells operating in chlor-alkali and in water electrolysis service. There is a reasonable chance, therefore, that this electrolysis technology can be successfully scaled to commercial size. For HTSE cells, on the other hand, operating conditions are far more demanding. Although solid oxide fuel cells have been developed and tested at a reasonable scale, there are significant differences between fuel cells and electrolysis cells that call into question the possibility of developing electrolysis cells at a scale large enough to make a nuclear

heated installation practical. Differential thermal expansion at high temperatures may establish a physical limit to the cell size.

The cell deactivation and scale-up may be resolved in a timely fashion for the NGNP project. The disproportionate process heat requirement and the difficulty of applying process heat to this technology, or the need to operate at low pressures and compress the products, reduce the incentive for using this as an NGNP application. The risk of reaching commercial status in time for commercial deployment with NGNP is high due to several key technical challenges: the thermal expansion issues associated with the electrolyzer modules' structure, distribution piping and cell stacks; the thermal insulation of the electrolyzer modules; and the sealing of the cells.

Table 7-2: Major Hybrid Sulfur Technology Challenges

A.	65% of the NHSS can be used for sulfuric acid decomposition.	F
B.	Decomposer tolerance to contaminants	P→O
C.	Metal to ceramic transition in the sulfuric acid decomposer	D→S
D.	Decomposition catalyst	D
E.	Thermal and hydraulic design of the decomposer	D→S
F.	Sulfur leakage through cell membranes	D
G.	Cell tolerance to contaminants	O
H.	Shunt currents	O

- A. Thermal analysis of the sulfuric acid decomposition shows that there is a heat recovery limitation associated with the bayonet reactor and the shape of the enthalpy versus temperature curve. In essence, the minimum process temperature at which heat can be used is 500°C. This means that the minimum temperature of helium leaving the sulfuric acid decomposer must be about 520 to 550°C. The remainder of the nuclear heat must be used in processes that use lower temperature heat. If the nuclear reactor return temperature is around 350°C, a significant portion of the nuclear heat cannot therefore be used in the process. Steam can be raised and power generated with this heat, but this would be high-cost power because of the scale of the reactor and generation plant.
- B. All of these technologies use liquid water as a feedstock. No matter how well the water is purified, there will be dissolved ions in it. The products are all gaseous and therefore these ions will be left in the system. After extended operation these will have an effect on the cells and decomposer. Those effects have not been identified or quantified.
- C. The sulfuric acid decomposer will most likely use silicon carbide heat transfer surfaces because of its resistance to both corrosion and loss of strength at high temperatures. The pressure boundary will, however, be metallic. At some point, regardless of the design, there must be a transition between silicon carbide and metal. This will be in the form of a seal or some kind of brazing or welding. Potential solutions for this are available, but further investigation is required.

- D. Decomposition catalyst now being used is costly and has a limited lifetime. A commercially viable catalyst must be developed. Although catalyst development is never straightforward, several avenues of approach have been suggested and the experts are hopeful that a catalyst can be developed in a timely fashion.
- E. Initial studies have been made of the thermal and hydraulic characteristics of the decomposer under ideal conditions. These must be extended to include reaction kinetics and realistic estimates of heat transfer rates, pressure drops, and the like.
- F. Current SO₂ electrolysis cell operation in some tests has shown a significant amount of sulfur formation on the hydrogen side of the proton exchange membrane (PEM). This indicates that one or more sulfur species are migrating through the membrane. Until now the approach has been to try different membrane materials to reduce this effect. Recent progress at SRNL has demonstrated cell operation for relatively short durations (i.e., 50 hours) without sulfur build-up or noticeable cell degradation, and longer term testing is planned. This may ultimately be successful, but it may be fruitful to work at better understanding the fundamentals of the problem.
- G. See paragraph “B” above.
- H. Distributing electrolyte flow to many cells in parallel while they are connected in series electrically presents the opportunity for current to flow through the electrolyte and short circuit the cells. This shunt current can become a serious problem with large cell stacks. The use of only a portion of the nuclear energy as process heat is a handicap for this technology, but it does not appear to render it economically uncompetitive with the other technologies. Lack of tolerance to contaminants and shunt currents may be potential roadblocks to this technology, but insufficient knowledge is available to make that judgment now. The risk of HyS reaching commercial status in time for NNGP is now high. If the contaminant and shunt current issues can be laid to rest promptly, the risk is deemed to be moderate.

Table 7-3: Major Sulfur Iodine Technology Challenges

A.	Decomposer tolerance to contaminants	P→O
B.	Process tolerance to contaminants	O
C.	Metal to ceramic transition in the sulfuric acid decomposer	D→S
D.	Decomposition catalyst	D
E.	Thermal and hydraulic design of the decomposer	D→S
F.	Large inventory of iodine and hydroiodic acid (7500 tonnes @ \$20,000 per tonne)	F
G.	Large circulation rate of iodine and hydroiodic acid	F
H.	Hydroiodic acid decomposition	O
I.	Materials of construction (Tantalum raw material costs \$40+ per pound)	D

- A. See item “B” under the HyS Challenges.
- B. See item “B” under the HyS Challenges.
- C. See item “C” under the HyS Challenges.
- D. See item “D” under the HyS Challenges.
- E. See item “E” under the HyS Challenges.
- F. The iodine inventory necessary to produce commercial quantities of hydrogen is large and costly. This is also a theoretical limit. It cannot be substantially reduced by further investigation. The inventory for one plant represents about 25% of the current worldwide annual production. It would cost \$150 million at today’s prices.
- G. The iodine circulation rate between the Bunsen reaction section and HI decomposition is about three tons or one cubic meter per second. This makes any intermediate storage between the units impractical. Operating upsets in one unit will be immediately propagated to the others rendering operations difficult.
- H. Most work to date on hydroiodic acid decomposition in the Nuclear Hydrogen Initiative has focused on an extractive distillation method. This method has been judged to be technically and economically infeasible. The alternative technology, reactive distillation has not been proven in principal. Moreover, design of the reactive distillation column will involve incorporating a catalytic section and handling two liquid phases. These are complex process engineering techniques that are difficult to reduce to practice. No effort has as yet been applied to design this on an industrial scale.
- I. For the most part, materials of construction for the SI process can be carbon steel lined with polytetrafluoroethylene (PTFE or Teflon®). Surfaces used for heat transfer cannot use this material because of its insulating qualities. Surfaces subject to erosion or with penetrations such as distillation tray or packing supports may not

use this material due to the possibility of lining failure and catastrophic corrosion. The only identified substitutes are tantalum or tantalum alloys. The cost of these materials will increase the capital cost of this plant unacceptably. Moreover, it is uncertain whether tantalum is available or can be fabricated in the quantities and forms required. Developing alternative materials is a time-consuming process and almost certainly cannot be accomplished in the required time frame.

The combination of the effects of large iodine inventory and circulation rates, the contaminant tolerance issue and the lack of economic materials of construction make the risk of reaching commercial status for NNGP high.

7.1.8 Schedule

The development schedules presented by the technology developers all indicated that the required work could be completed within about ten years. These estimates are based upon the assumption that the work will proceed in an orderly fashion without major roadblocks. This analysis shows, however, that there is a significant likelihood of major delays and detours in the development path for all of these technologies.

There is significant risk that none of the technologies can demonstrate commercial viability within ten years. Of the three technologies, the HyS process poses the least risks of achieving commercial status as a HTGR application. Schedule risk can be reduced by focusing on a single technology on which to concentrate resources. Further, initiating design will identify development needs earlier, allowing more time to investigate other options and still meet project deadlines.

7.1.9 Budget

The research and development budgets presented are those proposed by the technology developers researched for this study. Like the schedules, they are based upon an orderly progression of work following the current view of the remaining technology issues. If a development issue arises that clearly will have significant cost implications, such as the need to develop new materials, a decision will have to be made to continue with a larger budget or abandon the effort. With the current state of knowledge, the budgets are the best that can be produced. What is not included is the engineering effort recommended by this study to accompany the development effort. A first estimate for the engineering effort is that it can be covered by increasing each of the R&D budgets by 10%.

7.2 CONCLUSION

There is significant risk that none of the technologies can demonstrate commercial viability within ten years. Schedule risk can be reduced by focusing on a single technology on which to concentrate resources. Further, initiating design will identify development needs earlier, allowing more time to investigate other options and still meet project deadlines. Of the

three technologies, the HyS process poses the least risk of achieving commercial status as a HTGR application.

TRLs, sensitivity analysis, and the estimation of \$/kg H₂ costs are important only if a technology is fundamentally viable. All of these metrics assume a timely solution to the engineering problems. The overriding consideration in selecting a candidate technology should be the risk posed by unknowns and unresolved issues. Both HTSE and SI at this point pose risks that are significantly greater than those presented by HyS. If a single technology path is chosen for coupling with a HTGR, HyS is the most suitable candidate based on this study's findings.

The SI process was eliminated due to cost, the need for large quantities of exotic materials (i.e., tantalum and iodine), complexity, and technical risk due to lack of fundamental data and adequate design concepts.

HTSE was eliminated primarily due to the lack of proportion between the nuclear heat supply source and the need for process heat. However, HTSE also has serious technical challenges with regard to thermal expansion and thermal insulation. In contrast with both the SI and HyS processes, the HTSE technology using HTGR process heat requires extraordinary amounts of both equipment and piping that operate at both extremely high temperature and very high pressure. These problems are amenable for very short piping runs and for equipment where the pressure envelope can be maintained at a low temperature, but this is not the case for HTSE. In the author's view, HTSE technology and HTGR technology, as they have been developed to date, are not a good match. From a commercial perspective, there would be little point in facing the enormous development costs and risks identified herein by developing a large centralized HTSE system for the sake of supplying only a small portion of the energy required for splitting water as heat. This is especially so since a much less challenging, and perhaps even less costly, solution is available by using electricity alone. All these issues are extraneous to two basic issues having to do with the cell itself: the brief useful life of cells tested thus far and the scaling up of cells to a reasonable size. These challenges also pose significant technical risks.

Commercial enterprises would typically have made a selection by this stage of development, although they typically would not assume the financial risk associated with the identified technology challenges. Further, they commonly prove viability with smaller demonstrations. Demonstrating the hydrogen process at a smaller scale and with a non-nuclear heat source is judged to be as viable as a large demonstration coupled to the NGNP. A benefit of this approach is the ability to test severe transients for the hydrogen process independent of operating limits of a prototype reactor.

7.3 RECOMMENDATIONS

- Work should be carried out with electrolytic cell and fuel cell manufacturers to overcome the most serious technical challenges associated HyS cells and stacks (i.e., sulfur deposition and shunt currents).

- Serious design efforts developing alternatives should be started as soon as possible on major components such as helium control valves, SOEC stacks and enclosures, HyS electrolytic cells and enclosures, sulfuric acid decomposers, and Bunsen reactors and hydroiodic acid decomposition reactors.
- Added attention should be given to the interface components between the NHSS and the process plant. This includes not only the IHX but also high-temperature gas circulators, helium flow control valves, insulation, and features to accommodate thermal expansion.
- Consideration should be given to demonstrating the hydrogen process with a smaller, non-nuclear heat source to allow acceleration of testing, provide cost savings, and improve test flexibility.

8 APPENDICES

8.1 HYBRID SULFUR ELECTROLYSIS

8.1.1 Simulation Diagrams



Hybrid Sulfur Cycle Flowsheet

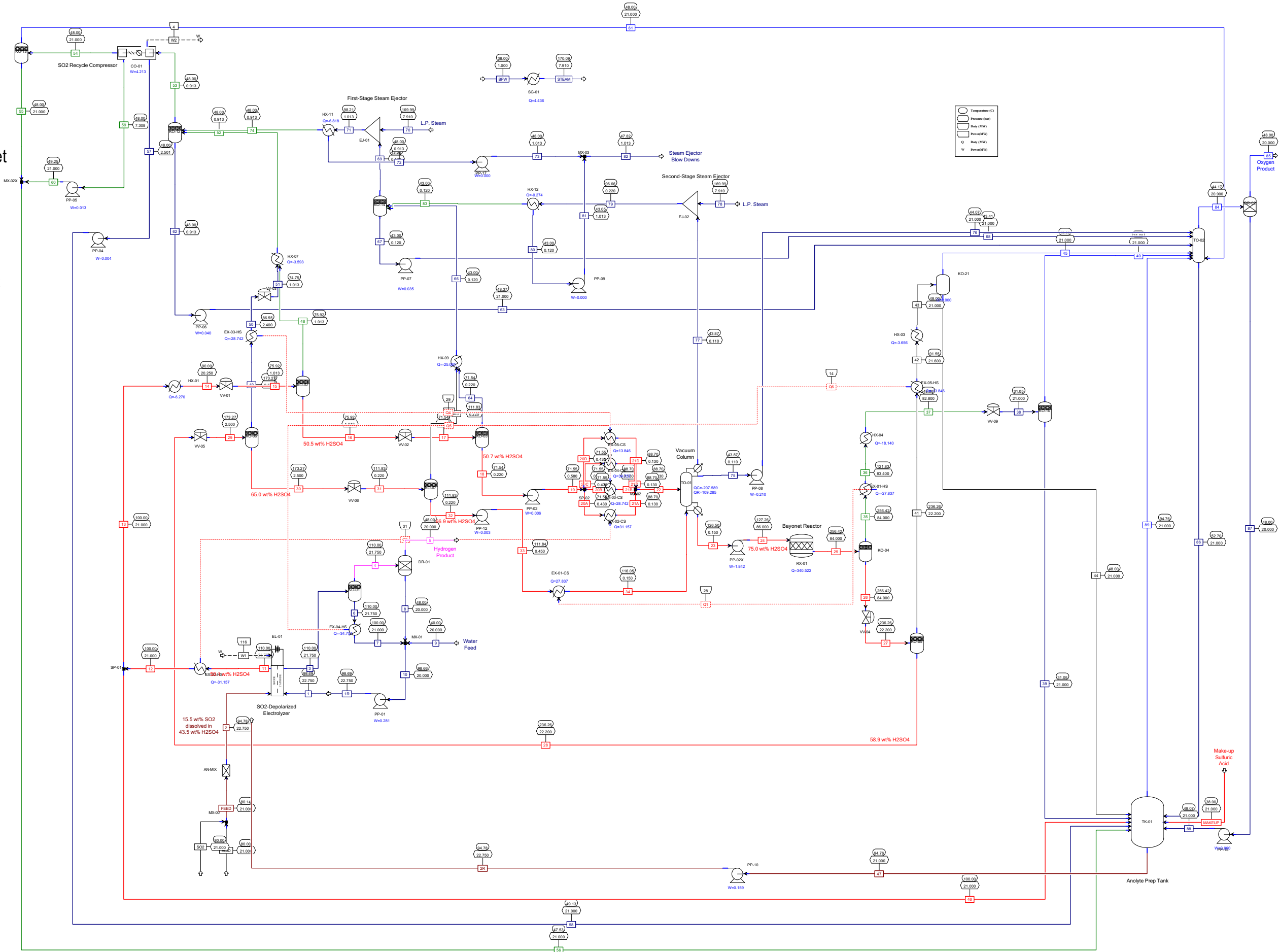
Maximilian B. Gorensek
July 25, 2008 version

PEM Electrolyzer at 110°C, 21 bar,
40% conversion, 50% acid product

Bayonet Decomposition Reactor at
870°C peak process temperature,
86-bar pressure, 75% acid feed

Vacuum Column at 0.11 bar using
2-stage steam ejector, 44°C
condenser

Steam Ejector condensate blow-
downs with make-up acid added
to Anolyte Prep Tank



8.1.2 Mass and Energy Balances

	1	1R	2	2R	3	4	5	6	7	8	9	10	11	12	13	14	15
	EL-01		EL-01		KO-01	DR-01		EX-04-HS	MX-01	MX-01	MX-01	PP-01	EX-02-HS	SP-01	HX-01	VV-01	KO-02
	LIQUID	PP-01	AN-MIX	PP-10	EL-01	KO-01	DR-01	KO-01	EX-04-HS	DR-01		MX-01	EL-01	EX-02-HS	SP-01	HX-01	VV-01
		LIQUID	LIQUID	LIQUID	MIXED	VAPOR	VAPOR	LIQUID	MIXED	LIQUID	LIQUID	MIXED	LIQUID	LIQUID	LIQUID	LIQUID	MIXED
Substream: MIXED																	
Mole Flow kmol/sec																	
H2O	46.678	46.678	31.363	31.363	45.678	0.072	-	45.605	45.605	0.072	1.000	46.678	31.363	31.363	6.431	6.431	6.431
H2SO4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.000
H2	0.014	0.014	-	-	1.014	1.000	1.000	0.014	0.014	-	-	0.014	-	-	-	-	-
O2	-	-	0.003	0.003	-	-	-	-	-	-	-	-	0.003	0.003	0.001	0.001	0.001
SO2	-	-	2.500	2.500	-	-	-	-	-	-	-	-	1.500	1.500	0.308	0.308	0.308
SO3	-	-	3.884	3.884	-	-	-	-	-	-	-	-	4.884	4.884	1.001	1.001	1.001
Mole Frac																	
H2O	1.000	1.000	0.831	0.831	0.978	0.068	-	1.000	1.000	1.000	1.000	1.000	0.831	0.831	0.831	0.831	0.831
H2SO4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.000
H2	0.000	0.000	-	-	0.022	0.932	1.000	0.000	0.000	-	-	0.000	-	-	-	-	-
O2	-	-	0.000	0.000	-	-	-	-	-	-	-	-	0.000	0.000	0.000	0.000	0.000
SO2	-	-	0.066	0.066	-	-	-	-	-	-	-	-	0.040	0.040	0.040	0.040	0.040
SO3	-	-	0.103	0.103	-	-	-	-	-	-	-	-	0.129	0.129	0.129	0.129	0.129
Mass Frac																	
H2O	1.000	1.000	0.545	0.545	0.998	0.393	-	1.000	1.000	1.000	1.000	1.000	0.537	0.537	0.537	0.537	0.537
H2SO4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.000
H2	0.000	0.000	-	-	0.002	0.607	1.000	0.000	0.000	-	-	0.000	-	-	-	-	-
O2	-	-	0.000	0.000	-	-	-	-	-	-	-	-	0.000	0.000	0.000	0.000	0.000
SO2	-	-	0.155	0.155	-	-	-	-	-	-	-	-	0.091	0.091	0.091	0.091	0.091
SO3	-	-	0.300	0.300	-	-	-	-	-	-	-	-	0.372	0.372	0.372	0.372	0.372
Total Flow kmol/sec	46.691	46.691	37.750	37.751	46.691	1.072	1.000	45.619	45.619	0.072	1.000	46.691	37.750	37.750	7.741	7.741	7.741
Total Flow kg/sec	840.942	840.942	1,036.254	1,036.255	824.943	3.321	2.016	821.622	821.622	1.305	18.015	840.942	1,052.253	1,052.253	215.762	215.762	215.762
Total Flow cum/sec	0.876	0.876	0.779	0.779	2.451	1.588	1.353	0.863	0.858	0.001	0.018	0.878	0.774	0.771	0.158	0.158	9.800
Temperature C	98.689	98.689	94.779	94.779	110.000	110.000	48.000	110.000	100.000	48.000	40.000	98.661	110.000	100.000	100.000	90.000	75.925
Pressure bar	22.750	22.750	22.750	22.750	21.750	21.750	20.000	21.750	21.000	20.000	20.000	20.000	21.750	21.000	21.000	20.250	1.013
Vapor Frac	-	-	-	-	0.023	1.000	1.000	-	0.000	-	-	0.000	-	-	-	-	0.044
Liquid Frac	1.000	1.000	1.000	1.000	0.977	-	-	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.956
Solid Frac	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Enthalpy J/kmol	-2.803E+08	-2.803E+08	-3.146E+08	-3.146E+08	-2.734E+08	-1.383E+07	6.963E+05	-2.795E+08	-2.802E+08	-2.843E+08	-2.849E+08	-2.804E+08	-3.201E+08	-3.210E+08	-3.210E+08	-3.218E+08	-3.218E+08
Enthalpy J/kg	-1.557E+07	-1.557E+07	-1.146E+07	-1.146E+07	-1.547E+07	-4.467E+06	3.454E+05	-1.552E+07	-1.556E+07	-1.578E+07	-1.581E+07	-1.557E+07	-1.149E+07	-1.152E+07	-1.152E+07	-1.154E+07	-1.154E+07
Enthalpy Watt	-1.309E+10	-1.309E+10	-1.188E+10	-1.188E+10	-1.276E+10	-1.483E+07	6.963E+05	-1.275E+10	-1.278E+10	-2.059E+07	-2.849E+08	-1.309E+10	-1.209E+10	-1.212E+10	-2.485E+09	-2.491E+09	-2.491E+09
Entropy J/kmol-K	8.657E+04	1.099E+03	7.598E+04	7.598E+04	8.949E+04	1.164E+05	1.080E+05	8.880E+04	8.684E+04	7.541E+04	7.358E+04	8.651E+04	7.467E+04	7.247E+04	7.247E+04	7.020E+04	7.263E+04
Entropy J/kg-K	4.807E+03	6.101E+01	2.768E+03	2.768E+03	5.065E+03	3.759E+04	5.356E+04	4.931E+03	4.822E+03	4.186E+03	4.084E+03	4.803E+03	2.679E+03	2.600E+03	2.600E+03	2.518E+03	2.606E+03
Density kmol/cum	53.301	53.301	48.434	48.434	19.051	0.676	0.739	52.836	53.166	54.940	55.123	53.177	48.789	48.952	48.952	49.055	0.790
Density kg/cum	959.985	959.985	1,329.517	1,329.517	336.587	2.092	1.490	951.609	957.551	989.768	993.062	957.744	1,359.930	1,364.485	1,364.485	1,367.362	22.017
Average Mol Wt	18.011	18.011	27.450	27.450	17.668	3.096	2.016	18.011	18.011	18.015	18.015	18.011	27.874	27.874	27.874	27.874	27.874
Liq Vol 60F cum/sec	0.843	0.843	0.908	0.908	0.879	0.055	0.054	0.824	0.824	0.001	0.018	0.843	0.908	0.908	0.186	0.186	0.186
*** VAPOR PHASE ***																	
Density kg/cum					2.092	2.092	1.490		1.879			1.796					1.978
MUMX N-sec/sqm					0.000	0.000	0.000		0.000			0.000					0.000
KMX Watt/m-K					0.192	0.192	0.189		0.194			0.193					0.013
*** LIQUID PHASE ***																	
Density kg/cum	959.985	959.985	1,329.517	1,329.517	951.609			951.609	958.982	989.768	993.062	959.909	1,359.930	1,364.485	1,364.485	1,367.362	1,363.587
MUMX N-sec/sqm	0.000	0.000	0.001	0.001	0.000			0.000	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.001	0.001
KMX Watt/m-K	0.675	0.675	0.222	0.222	0.680			0.680	0.676	0.635	0.626	0.675	0.200	0.214	0.214	0.227	0.262
SIGMAMX N/m	0.058	0.058	0.052	0.052	0.056			0.056	0.058	0.068	0.070	0.058	0.049	0.051	0.051	0.053	0.057
*** LIQUID_1 PHASE *																	
Density kg/cum														1,364.485	1,364.485		
MUMX N-sec/sqm														0.001	0.001		
KMX Watt/m-K														0.214	0.214		
SIGMAMX N/m														0.051	0.051		
*** LIQUID_2 PHASE *																	
Density kg/cum																	
MUMX N-sec/sqm																	
KMX Watt/m-K																	
SIGMAMX N/m																	

	16	17	18	19	20A	20B	20C	20D	21A	21B	21C	21D	22	23	24	25	26
	VV-02	KO-03	PP-02	SP-02	EX-02-CS	EX-03-CS	EX-04-CS	EX-05-CS	MX-02	MX-02	MX-02	MX-02	TO-01	PP-02X	RX-01	KO-04	VV-04
	KO-02	VV-02	KO-03	PP-02	SP-02	SP-02	SP-02	SP-02	EX-02-CS	EX-03-CS	EX-04-CS	EX-05-CS	MX-02	TO-01	PP-02X	RX-01	KO-04
	LIQUID	MIXED	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	MIXED	MIXED	MIXED	MIXED	MIXED	LIQUID	LIQUID	MIXED	LIQUID
Substream: MIXED																	
Mole Flow	kmol/sec																
H2O	6.373	6.373	6.331	6.331	1.818	1.677	2.028	0.808	1.818	1.677	2.028	0.808	6.331	5.830	5.830	5.830	5.334
H2SO4	-	0.000	-	-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.501	0.008
SO2	0.026	0.026	0.003	0.003	0.001	0.001	0.001	0.000	0.001	0.001	0.001	0.000	0.003	0.000	0.000	1.001	0.225
SO3	1.001	1.001	1.001	1.001	0.288	0.265	0.321	0.128	0.288	0.265	0.321	0.128	1.001	2.071	2.071	1.070	1.070
Mole Frac																	
H2O	0.861	0.861	0.863	0.863	0.863	0.863	0.863	0.863	0.863	0.863	0.863	0.863	0.863	0.738	0.738	0.694	0.804
H2SO4	-	0.000	-	-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.060	0.001
SO2	0.004	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.119	0.034
SO3	0.135	0.135	0.137	0.137	0.137	0.137	0.137	0.137	0.137	0.137	0.137	0.137	0.137	0.262	0.262	0.127	0.161
Mass Frac																	
H2O	0.584	0.584	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.587	0.388	0.388	0.388	0.489
H2SO4	-	0.000	-	-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.059	0.001
SO2	0.009	0.009	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.237	0.074
SO3	0.408	0.408	0.412	0.412	0.412	0.412	0.412	0.412	0.412	0.412	0.412	0.412	0.412	0.612	0.612	0.316	0.436
Total Flow	kmol/sec																
Total Flow	kg/sec																
Total Flow	cum/sec																
Temperature	C																
Pressure	bar																
Vapor Frac	-	0.009	-	-	-	-	-	-	0.296	0.296	0.296	0.295	0.296	-	-	0.210	-
Liquid Frac	1.000	0.991	1.000	1.000	1.000	1.000	1.000	1.000	0.704	0.704	0.704	0.705	0.704	1.000	1.000	0.790	1.000
Solid Frac	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Enthalpy	J/kmol																
Enthalpy	J/kg																
Enthalpy	Watt																
Entropy	J/kmol-K																
Entropy	J/kg-K																
Density	kmol/cum																
Density	kg/cum																
Average Mol Wt																	
Liq Vol 60F	cum/sec																
*** VAPOR PHASE ***																	
Density	kg/cum																
MUMX	N-sec/sqm																
KMX	Watt/m-K																
*** LIQUID PHASE ***																	
Density	kg/cum																
MUMX	N-sec/sqm																
KMX	Watt/m-K																
SIGMAMX	N/m																
*** LIQUID_1 PHASE *																	
Density	kg/cum																
MUMX	N-sec/sqm																
KMX	Watt/m-K																
SIGMAMX	N/m																
*** LIQUID_2 PHASE *																	
Density	kg/cum																
MUMX	N-sec/sqm																
KMX	Watt/m-K																
SIGMAMX	N/m																
Density	kg/cum																
MUMX	N-sec/sqm																
KMX	Watt/m-K																
SIGMAMX	N/m																

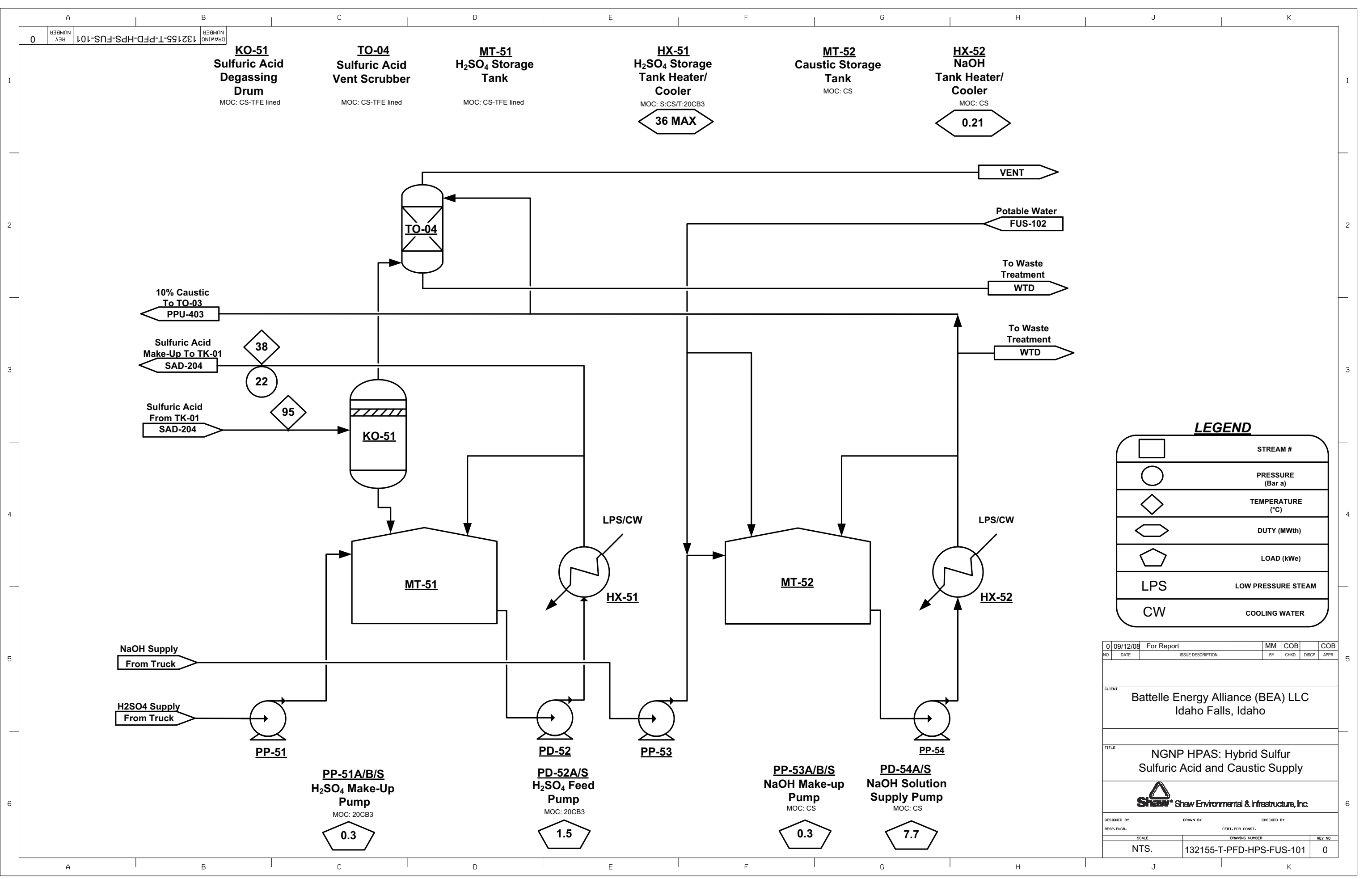
	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	
	KO-05	VV-05	KO-06	VV-06	KO-07	PP-12	EX-01-CS	TO-01	EX-01-HS	HX-04	VV-09	KO-10	TK-01	TO-02	EX-05-HS	HX-03	KO-21	
	VV-04	KO-05	VV-05	KO-06	VV-06	KO-07	PP-12	EX-01-CS	KO-04	EX-01-HS	HX-04	VV-09	KO-10	KO-10	KO-05	EX-05-HS	HX-03	
	MIXED	LIQUID	MIXED	LIQUID	MIXED	LIQUID	LIQUID	MIXED	VAPOR	MIXED	MIXED	MIXED	LIQUID	VAPOR	VAPOR	MIXED	MIXED	
Substream: MIXED																		
Mole Flow	kmol/sec																	
H2O	5.334	5.075	5.075	4.418	4.418	3.850	3.850	3.850	0.495	0.495	0.495	0.495	0.494	0.002	0.260	0.260	0.260	
H2SO4	0.000	-	0.000	-	0.000	-	-	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
O2	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.493	0.493	0.493	0.493	0.000	0.492	0.008	0.008	0.008	
SO2	0.225	0.049	0.049	0.001	0.001	0.000	0.000	0.000	0.776	0.776	0.776	0.776	0.617	0.159	0.176	0.176	0.176	
SO3	1.070	1.070	1.070	1.070	1.070	1.070	1.070	1.070	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	
Mole Frac																		
H2O	0.804	0.819	0.819	0.805	0.805	0.783	0.783	0.783	0.281	0.281	0.281	0.281	0.444	0.003	0.585	0.585	0.585	
H2SO4	0.000	-	0.000	-	0.000	-	-	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
O2	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.279	0.279	0.279	0.279	0.000	0.754	0.018	0.018	0.018	
SO2	0.034	0.008	0.008	0.000	0.000	0.000	0.000	0.000	0.440	0.440	0.440	0.440	0.555	0.243	0.397	0.397	0.397	
SO3	0.161	0.173	0.173	0.195	0.195	0.217	0.217	0.217	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	
Mass Frac																		
H2O	0.489	0.507	0.507	0.481	0.481	0.447	0.447	0.447	0.120	0.120	0.120	0.120	0.184	0.001	0.289	0.289	0.289	
H2SO4	0.000	-	0.000	-	0.000	-	-	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
O2	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.212	0.212	0.212	0.212	0.000	0.607	0.016	0.016	0.016	
SO2	0.074	0.018	0.018	0.000	0.000	0.000	0.000	0.000	0.668	0.668	0.668	0.668	0.816	0.392	0.696	0.696	0.696	
SO3	0.436	0.475	0.475	0.518	0.518	0.553	0.553	0.553	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	
Total Flow	kmol/sec	6.638	6.194	6.194	5.489	5.489	4.920	4.920	1.764	1.764	1.764	1.764	1.111	0.653	0.444	0.444	0.444	
Total Flow	kg/sec	196.462	180.240	180.240	165.310	165.310	155.014	155.014	74.402	74.402	74.402	74.402	48.443	25.959	16.222	16.222	16.222	
Total Flow	cum/sec	0.935	0.150	10.435	0.124	82.681	0.104	0.104	115.550	0.818	0.372	0.207	0.782	0.032	0.749	0.785	0.027	
Temperature	C	236.256	236.256	173.269	173.269	111.829	111.829	111.837	256.420	121.832	48.000	31.046	31.046	31.046	236.256	91.549	48.000	
Pressure	bar	22.200	22.200	2.500	2.500	0.220	0.220	0.450	84.000	83.400	82.800	21.000	21.000	21.000	22.200	21.600	21.000	
Vapor Frac		0.067	-	0.114	-	0.104	-	0.109	1.000	0.689	0.329	0.370	-	1.000	1.000	0.279	0.029	
Liquid Frac		0.933	1.000	0.886	1.000	0.896	1.000	0.891	-	0.311	0.671	0.630	1.000	-	-	0.721	0.971	
Solid Frac		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Enthalpy	J/kmol	-3.169E+08	-3.216E+08	-3.216E+08	-3.319E+08	-3.319E+08	-3.427E+08	-3.427E+08	-3.370E+08	-1.924E+08	-2.081E+08	-2.184E+08	-2.184E+08	-3.037E+08	-7.319E+07	-2.526E+08	-2.838E+08	-2.920E+08
Enthalpy	J/kg	-1.071E+07	-1.105E+07	-1.105E+07	-1.102E+07	-1.102E+07	-1.088E+07	-1.088E+07	-1.070E+07	-4.560E+06	-4.934E+06	-5.178E+06	-5.178E+06	-6.967E+06	-1.841E+06	-6.915E+06	-7.769E+06	-7.994E+06
Enthalpy	Watt	-2.104E+09	-1.992E+09	-1.992E+09	-1.822E+09	-1.822E+09	-1.686E+09	-1.686E+09	-1.658E+09	-3.393E+08	-3.671E+08	-3.853E+08	-3.853E+08	-3.375E+08	-4.778E+07	-1.122E+08	-1.260E+08	-1.297E+08
Entropy	J/kmol-K	9.085E+04	8.262E+04	8.818E+04	7.392E+04	7.892E+04	6.372E+04	6.373E+04	7.915E+04	2.007E+05	-8.966E+08	-4.573E+09	-1.156E+09	-1.835E+09	1.900E+05	2.056E+05	-1.953E+09	-3.987E+09
Entropy	J/kg-K	3.070E+03	2.839E+03	3.030E+03	2.454E+03	2.620E+03	2.022E+03	2.023E+03	2.512E+03	4.758E+03	-2.126E+07	-1.084E+08	-2.740E+07	-4.209E+07	4.778E+03	5.629E+03	-5.347E+07	-1.091E+08
Density	kmol/cum	7.096	41.197	0.594	44.286	0.066	47.255	47.255	0.043	2.158	4.739	8.520	2.257	34.211	0.871	0.566	2.922	16.640
Density	kg/cum	210.015	1,198.837	17.273	1,333.843	1.999	1,488.949	1,488.936	1.342	91.011	199.887	359.387	95.192	1,491.537	34.653	20.661	106.761	607.873
Average Mol Wt		29.597	29.100	29.100	30.119	30.119	31.509	31.509	31.509	42.180	42.180	42.180	42.180	43.598	39.766	36.531	36.531	36.531
Liq Vol 60F	cum/sec	0.166	0.152	0.152	0.137	0.137	0.127	0.127	0.127	0.077	0.077	0.077	0.077	0.042	0.035	0.015	0.015	0.015
*** VAPOR PHASE ***																		
Density	kg/cum	20.661		1.448		0.125		0.084	91.011	164.587	124.966	34.653		34.653	20.661	51.565	37.050	
MUMX	N-sec/sqm	0.000		0.000		0.000		0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	
KMX	Watt/m-K	0.030		0.030		0.025		0.026	0.031	0.020	0.024	0.021		0.021	0.030	0.014	0.019	
*** LIQUID PHASE ***																		
Density	kg/cum	1,198.837	1,198.837	1,333.843	1,333.843	1,488.949	1,488.949	1,488.936	1,516.999		1,166.862	1,478.625	1,491.537	1,491.537		1,182.248	1,368.791	
MUMX	N-sec/sqm	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000									
KMX	Watt/m-K	0.083	0.083	0.116	0.116	0.182	0.182	0.182	0.171									
SIGMAMX	N/m	0.024	0.024	0.036	0.036	0.047	0.047	0.047	0.045									
*** LIQUID_1 PHASE *																		
Density	kg/cum	1,198.837		1,333.843						1,098.942	1,120.586	1,125.947	1,125.947			1,099.996	1,116.116	
MUMX	N-sec/sqm	0.000		0.000						0.000	0.001	0.001	0.001			0.000	0.001	
KMX	Watt/m-K	0.083		0.116						0.217	0.305	0.326	0.326			0.260	0.312	
SIGMAMX	N/m	0.024		0.036						0.047	0.063	0.067	0.067			0.054	0.063	
*** LIQUID_2 PHASE *																		
Density	kg/cum		1,198.837		1,333.843					1,442.451	1,594.468	1,639.101	1,639.101			1,491.299	1,586.333	
MUMX	N-sec/sqm		0.000		0.000					0.000	0.000	0.000	0.000			0.000	0.000	
KMX	Watt/m-K		0.083		0.116					0.142	0.184	0.195	0.195			0.160	0.185	
SIGMAMX	N/m		0.024		0.036					0.019	0.024	0.026	0.026			0.021	0.024	

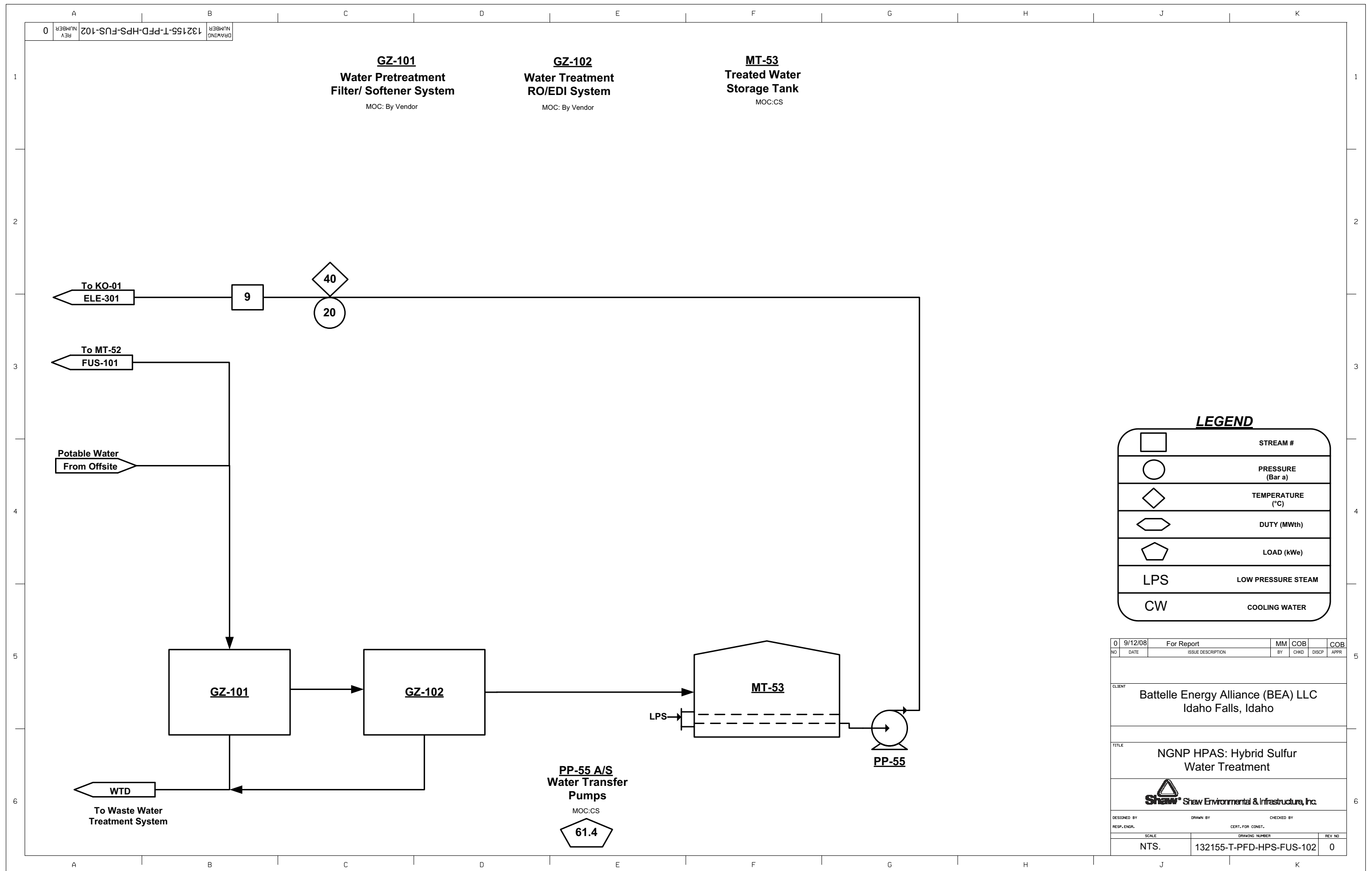
	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
	TK-01	TO-02	TK-01	PP-10	HX-07	EX-03-HS	VV-03	HX-07	KO-12	CO-01	KO-13	MX-02X	TK-01	PP-04	TK-01	PP-05	MX-02X
	KO-21	KO-21	SP-01	TK-01	KO-02	KO-06	EX-03-HS	VV-03	HX-07	KO-12	CO-01	KO-13	MX-02X	CO-01	PP-04	CO-01	PP-05
	LIQUID	VAPOR	LIQUID	LIQUID	VAPOR	VAPOR	MIXED	MIXED	MIXED	VAPOR	MIXED	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID
Substream: MIXED																	
Mole Flow kmol/sec																	
H2O	0.260	0.000	24.932	31.363	0.058	0.657	0.657	0.657	0.715	0.049	0.003	0.003	0.016	0.032	0.032	0.013	0.013
H2SO4	-	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-	-	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.000	0.008	0.002	0.003	0.001	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000
SO2	0.171	0.005	1.192	2.500	0.281	0.048	0.048	0.048	0.330	0.347	0.231	0.231	0.345	0.001	0.001	0.114	0.114
SO3	0.000	0.000	3.883	3.884	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-	-	-
Mole Frac																	
H2O	0.603	0.007	0.831	0.831	0.172	0.931	0.931	0.931	0.684	0.123	0.014	0.014	0.046	0.972	0.972	0.104	0.104
H2SO4	-	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-	-	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.000	0.614	0.000	0.000	0.002	0.000	0.000	0.000	0.001	0.002	0.003	0.000	0.000	0.000	0.000	0.000	0.000
SO2	0.397	0.379	0.040	0.066	0.827	0.068	0.068	0.068	0.315	0.875	0.983	0.986	0.954	0.028	0.028	0.896	0.896
SO3	0.000	0.000	0.129	0.103	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-	-	-
Mass Frac																	
H2O	0.299	0.003	0.537	0.545	0.055	0.793	0.793	0.793	0.379	0.038	0.004	0.004	0.013	0.907	0.907	0.032	0.032
H2SO4	-	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-	-	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.000	0.446	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.001	0.002	0.000	0.000	0.000	0.000	0.000	0.000
SO2	0.701	0.551	0.091	0.155	0.944	0.207	0.207	0.207	0.621	0.961	0.995	0.996	0.987	0.093	0.093	0.968	0.968
SO3	0.000	0.000	0.372	0.300	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-	-	-
Total Flow kmol/sec	0.431	0.013	30.010	37.751	0.340	0.705	0.705	0.705	1.046	0.396	0.235	0.234	0.362	0.033	0.033	0.128	0.128
Total Flow kg/sec	15.657	0.565	836.491	1,036.255	19.095	14.930	14.930	14.930	34.026	23.112	14.898	14.845	22.420	0.639	0.639	7.575	7.575
Total Flow cum/sec	0.011	0.015	0.613	0.779	9.656	10.311	0.717	2.095	10.694	11.457	0.011	0.009	0.014	0.001	0.001	0.005	0.005
Temperature C	48.000	48.000	100.000	94.757	75.925	173.269	86.549	74.751	48.000	48.000	48.000	48.000	47.530	48.000	49.134	48.000	49.253
Pressure bar	21.000	21.000	21.000	21.000	1.013	2.500	2.400	1.013	0.913	0.913	21.000	21.000	21.000	2.501	21.000	7.308	21.000
Vapor Frac	-	1.000	-	-	1.000	1.000	0.082	0.105	0.353	1.000	0.005	-	-	-	-	-	-
Liquid Frac	1.000	-	1.000	1.000	-	-	0.918	0.895	0.647	-	0.995	1.000	1.000	1.000	1.000	1.000	1.000
Solid Frac	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Enthalpy J/kmol	-2.973E+08	-1.140E+08	-3.210E+08	-3.146E+08	-2.851E+08	-2.408E+08	-2.815E+08	-2.815E+08	-2.861E+08	-2.889E+08	-3.172E+08	-3.181E+08	-3.167E+08	-2.853E+08	-2.852E+08	-3.141E+08	-3.140E+08
Enthalpy J/kg	-8.189E+06	-2.588E+06	-1.152E+07	-1.146E+07	-5.082E+06	-1.137E+07	-1.330E+07	-1.330E+07	-8.793E+06	-4.952E+06	-5.007E+06	-5.015E+06	-5.110E+06	-1.478E+07	-1.478E+07	-5.300E+06	-5.298E+06
Enthalpy Watt	-1.282E+09	-1.462E+06	-9.632E+09	-1.188E+10	-9.704E+07	-1.698E+08	-1.986E+08	-1.986E+08	-2.992E+08	-1.144E+08	-7.459E+07	-7.445E+07	-1.146E+08	-9.450E+06	-9.447E+06	-4.014E+07	-4.013E+07
Entropy J/kmol-K	-4.105E+09	1.974E+05	7.247E+04	7.598E+04	2.442E+05	1.992E+05	9.674E+04	9.736E+04	1.355E+05	2.446E+05	1.412E+05	1.409E+05	1.383E+05	7.691E+04	7.691E+04	1.344E+05	1.344E+05
Entropy J/kg-K	-1.131E+08	4.480E+03	2.600E+03	2.768E+03	4.352E+03	9.407E+03	4.570E+03	4.599E+03	4.164E+03	4.193E+03	2.229E+03	2.221E+03	2.233E+03	3.985E+03	3.985E+03	2.268E+03	2.268E+03
Density kmol/cum	37.700	0.841	48.952	48.431	0.035	0.068	0.984	0.337	0.098	0.035	22.340	25.522	26.010	53.340	53.356	26.873	26.862
Density kg/cum	1,368.791	37.050	1,364.485	1,329.441	1.978	1.448	20.831	7.126	3.182	2.017	1,415.080	1,618.841	1,611.614	1,029.509	1,029.816	1,592.824	1,592.200
Average Mol Wt	36.307	44.060	27.874	27.450	56.107	21.171	21.171	21.171	32.542	58.347	63.343	63.430	61.962	19.301	19.301	59.272	59.272
Liq Vol 60F cum/sec	0.014	0.001	0.722	0.908	0.016	0.014	0.014	0.014	0.031	0.019	0.012	0.012	0.019	0.001	0.001	0.006	0.006
*** VAPOR PHASE ***																	
Density kg/cum		37.050			1.978	1.448	4.270	1.650	2.017	2.017	38.733						
MUMX N-sec/sqm		0.000			0.000	0.000	0.000	0.000	0.000	0.000	0.000						
KMX Watt/m-K		0.019			0.013	0.030	0.015	0.015	0.012	0.012	0.018						
*** LIQUID PHASE ***																	
Density kg/cum	1,368.791		1,364.485	1,329.441			979.979	981.134	1,003.725		1,618.841	1,618.841	1,611.614	1,029.509	1,029.816	1,592.824	1,592.200
MUMX N-sec/sqm			0.001	0.001			0.000	0.000	0.001		0.000	0.000	0.000	0.001	0.001	0.000	0.000
KMX Watt/m-K			0.214	0.222			0.543	0.600	0.542		0.182	0.182	0.183	0.444	0.444	0.184	0.183
SIGMAMX N/m			0.051	0.052			0.060	0.063	0.068		0.018	0.018	0.020	0.067	0.067	0.023	0.022
*** LIQUID_1 PHASE *																	
Density kg/cum	1,116.116		1,364.485				979.979	981.134			1,618.841			1,029.509		1,592.824	
MUMX N-sec/sqm	0.001		0.001				0.000	0.000			0.000			0.001		0.000	
KMX Watt/m-K	0.312		0.214				0.543	0.600			0.182			0.444		0.184	
SIGMAMX N/m	0.063		0.051				0.060	0.063			0.018			0.067		0.023	
*** LIQUID_2 PHASE *																	
Density kg/cum	1,586.333			1,329.441													
MUMX N-sec/sqm	0.000			0.001													
KMX Watt/m-K	0.185			0.222													
SIGMAMX N/m	0.024			0.052													

	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77
	TO-02	PP-06	TO-02	HX-09	HX-09	KO-14	PP-07	TO-02	EJ-01	EJ-01	HX-11	PP-17	MX-03	KO-12	PP-08	TO-02	EJ-02
	KO-13	KO-12	PP-06	KO-03	KO-07	HX-09	KO-14	PP-07	KO-14		EJ-01	HX-11	PP-17	HX-11	TO-01	PP-08	TO-01
	VAPOR	LIQUID	LIQUID	VAPOR	VAPOR	MIXED	LIQUID	LIQUID	VAPOR	MIXED	VAPOR	LIQUID	LIQUID	VAPOR	LIQUID	LIQUID	VAPOR
Substream: MIXED																	
Mole Flow	kmol/sec																
H2O	0.000	0.670	0.670	0.041	0.568	0.609	0.547	0.547	0.064	0.089	0.154	0.151	0.151	0.003	4.348	4.348	0.004
H2SO4	-	-	-	0.000	0.000	0.000	-	-	0.000	-	-	-	-	-	0.000	-	0.000
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SO2	0.000	0.006	0.006	0.024	0.001	0.025	0.000	0.000	0.025	-	0.025	0.001	0.001	0.024	0.002	0.002	0.001
SO3	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-	0.000	-	0.000
Mole Frac																	
H2O	0.001	0.990	0.990	0.637	0.998	0.961	0.999	0.999	0.721	1.000	0.860	0.990	0.990	0.123	1.000	1.000	0.823
H2SO4	-	-	-	0.000	0.000	0.000	-	-	0.000	-	-	-	-	-	0.000	-	0.000
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.573	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SO2	0.426	0.010	0.010	0.363	0.002	0.039	0.001	0.001	0.279	-	0.140	0.010	0.010	0.877	0.000	0.000	0.177
SO3	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-	0.000	-	0.000
Mass Frac																	
H2O	0.000	0.967	0.967	0.331	0.994	0.874	0.998	0.998	0.420	1.000	0.634	0.967	0.967	0.038	0.998	0.998	0.566
H2SO4	-	-	-	0.000	0.000	0.000	-	-	0.000	-	-	-	-	-	0.000	-	0.000
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.402	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SO2	0.598	0.033	0.033	0.669	0.006	0.126	0.002	0.002	0.580	-	0.366	0.033	0.033	0.962	0.002	0.002	0.434
SO3	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-	0.000	-	0.000
Total Flow	kmol/sec																
Total Flow	kg/sec																
Total Flow	cum/sec																
Temperature	C																
Pressure	bar																
Vapor Frac	1.000																
Liquid Frac	-																
Solid Frac	-																
Enthalpy	J/kmol																
Enthalpy	J/kg																
Enthalpy	Watt																
Entropy	J/kmol-K																
Entropy	J/kg-K																
Density	kmol/cum																
Density	kg/cum																
Average Mol Wt																	
Liq Vol 60F	cum/sec																
*** VAPOR PHASE ***																	
Density	kg/cum																
MUMX	N-sec/sqm																
KMX	Watt/m-K																
*** LIQUID PHASE ***																	
Density	kg/cum																
MUMX	N-sec/sqm																
KMX	Watt/m-K																
SIGMAMX	N/m																
*** LIQUID_1 PHASE *																	
Density	kg/cum																
MUMX	N-sec/sqm																
KMX	Watt/m-K																
SIGMAMX	N/m																
*** LIQUID_2 PHASE *																	
Density	kg/cum																
MUMX	N-sec/sqm																
KMX	Watt/m-K																
SIGMAMX	N/m																

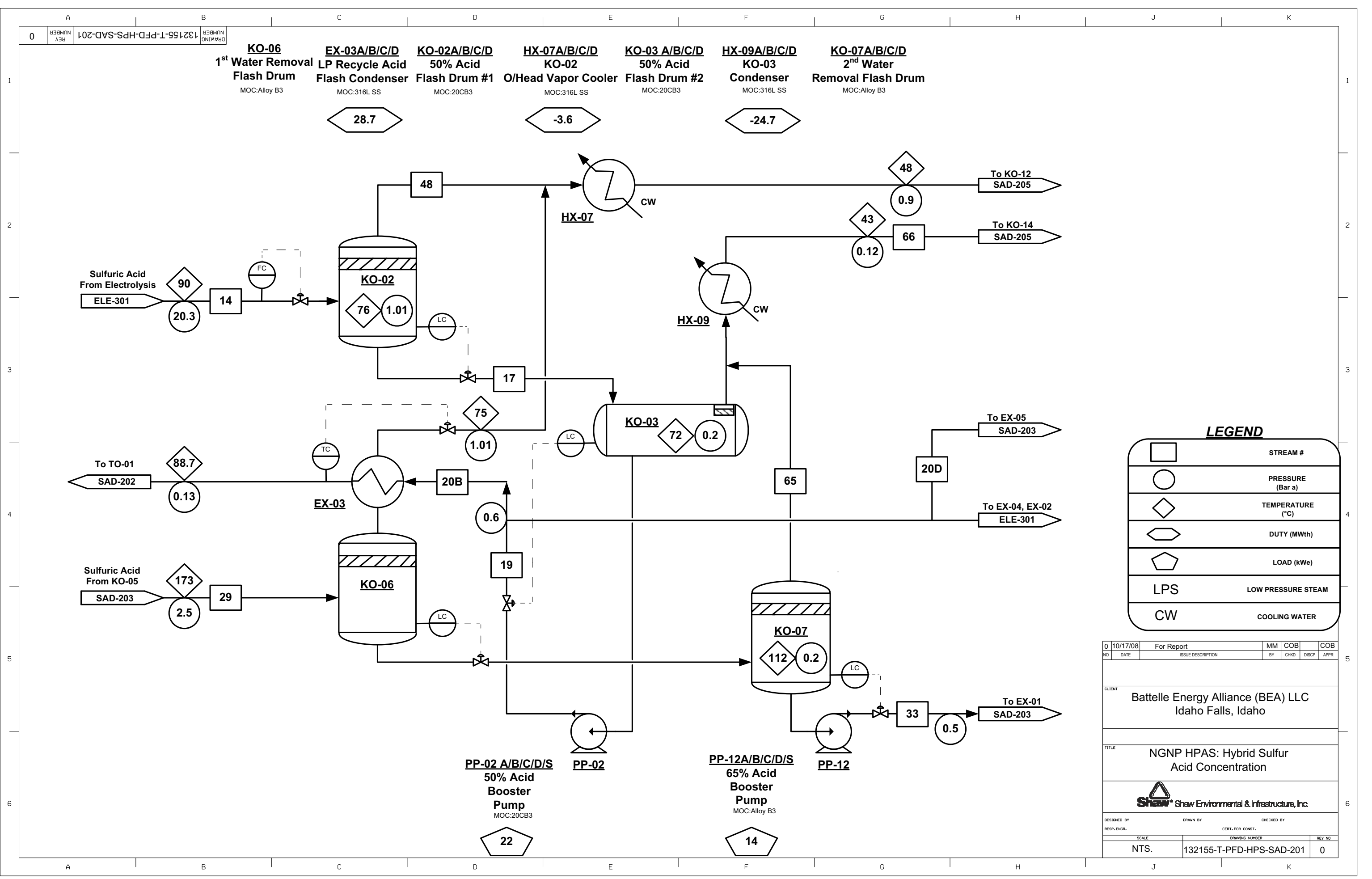
	78	79	80	81	82	83	84	85	86	87	88	89	ACID	BFW	FEED	MAKEUP	SO2
	EJ-02	HX-12	PP-09	MX-03		KO-14	DR-02		TK-01	PP-15	TK-01	TO-02	MX-00	SG-01	AN-MIX	TK-01	MX-00
	MIXED	VAPOR	LIQUID	LIQUID	LIQUID	VAPOR	VAPOR	VAPOR	LIQUID	LIQUID	LIQUID	VAPOR	LIQUID	LIQUID	LIQUID	LIQUID	MIXED
Substream: MIXED																	
Mole Flow kmol/sec																	
H2O	0.004	0.008	0.006	0.006	0.157	0.002	0.003	-	5.564	0.003	0.003	0.000	31.363	0.094	31.363	0.063	-
H2SO4	-	-	-	-	-	-	0.000	-	0.000	-	-	0.000	-	-	-	-	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	-	0.000	0.000	0.000	0.000	0.000	0.501	0.501	0.002	-	-	0.002	-	-	0.003	-	0.003
SO2	-	0.001	0.000	0.000	0.001	0.001	0.001	-	0.179	0.001	0.001	0.007	-	-	2.500	-	2.500
SO3	-	-	-	-	-	-	0.000	-	0.000	-	-	0.000	3.884	-	3.884	0.001	-
Mole Frac																	
H2O	1.000	0.911	0.999	0.999	0.991	0.721	0.005	-	0.968	0.780	0.780	0.029	0.890	1.000	0.831	0.977	-
H2SO4	-	-	-	-	-	-	0.000	-	0.000	-	-	0.000	-	-	-	-	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	-	0.000	0.000	0.000	0.000	0.000	0.993	1.000	0.000	-	-	0.189	-	-	0.000	-	0.001
SO2	-	0.089	0.001	0.001	0.009	0.279	0.001	-	0.031	0.220	0.220	0.783	-	-	0.066	-	0.999
SO3	-	-	-	-	-	-	0.000	-	0.000	-	-	0.000	0.110	-	0.103	0.023	-
Mass Frac																	
H2O	1.000	0.743	0.998	0.998	0.968	0.420	0.003	-	0.897	0.500	0.500	0.009	0.645	1.000	0.545	0.906	-
H2SO4	-	-	-	-	-	-	0.000	-	0.000	-	-	0.000	-	-	-	-	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	-	0.000	0.000	0.000	0.000	0.000	0.994	1.000	0.000	-	-	0.106	-	-	0.000	-	0.001
SO2	-	0.257	0.002	0.002	0.032	0.580	0.003	-	0.103	0.500	0.500	0.884	-	-	0.155	-	0.999
SO3	-	-	-	-	-	-	0.000	-	0.000	-	-	0.000	0.355	-	0.300	0.094	-
Total Flow kmol/sec	0.004	0.009	0.006	0.006	0.158	0.003	0.504	0.501	5.745	0.003	0.003	0.009	35.247	0.094	37.750	0.064	2.503
Total Flow kg/sec	0.078	0.192	0.108	0.108	2.913	0.085	16.119	16.023	111.789	0.096	0.096	0.526	875.996	1.689	1,036.254	1.247	160.257
Total Flow cum/sec	0.019	1.214	0.000	0.000	0.003	0.601	0.631	0.664	0.108	0.000	0.000	0.012	0.670	0.002	0.779	0.001	0.140
Temperature C	169.987	96.656	43.000	43.054	47.824	43.000	44.168	48.000	52.700	48.000	48.075	94.757	80.000	38.000	80.137	38.000	80.000
Pressure bar	7.910	0.220	0.120	1.013	1.013	0.120	20.900	20.000	21.000	20.000	21.000	21.000	21.000	1.000	21.000	21.000	21.000
Vapor Frac	1.000	1.000	-	-	-	1.000	1.000	1.000	-	-	-	1.000	-	-	-	-	0.013
Liquid Frac	0.000	-	1.000	1.000	1.000	-	-	-	1.000	1.000	1.000	-	1.000	1.000	1.000	1.000	0.987
Solid Frac	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Enthalpy J/kmol	-2.377E+08	-2.444E+08	-2.847E+08	-2.847E+08	-2.847E+08	-2.568E+08	-1.309E+06	5.381E+05	-2.849E+08	-2.916E+08	-2.916E+08	-2.380E+08	-3.158E+08	-2.850E+08	-3.158E+08	-2.922E+08	-3.161E+08
Enthalpy J/kg	-1.320E+07	-1.106E+07	-1.578E+07	-1.578E+07	-1.544E+07	-8.313E+06	-4.094E+04	1.682E+04	-1.464E+07	-1.036E+07	-1.036E+07	-4.196E+06	-1.271E+07	-1.582E+07	-1.151E+07	-1.504E+07	-4.938E+06
Enthalpy Watt	-1.035E+06	-2.129E+06	-1.696E+06	-1.696E+06	-4.497E+07	-7.061E+05	-6.599E+05	2.694E+05	-1.637E+09	-9.929E+05	-9.929E+05	-2.208E+06	-1.113E+10	-2.673E+07	-1.192E+10	-1.876E+07	-7.913E+08
Entropy J/kmol-K	1.842E+05	2.143E+05	7.432E+04	7.425E+04	7.588E+04	2.253E+05	1.814E+05	1.822E+05	7.825E+04	-1.683E+09	-1.673E+09	2.191E+05	6.828E+04	7.311E+04	7.193E+04	7.071E+04	1.581E+05
Entropy J/kg-K	1.022E+04	9.696E+03	4.118E+03	4.114E+03	4.115E+03	7.297E+03	5.673E+03	5.693E+03	4.021E+03	-5.980E+07	-5.946E+07	3.864E+03	2.747E+03	4.058E+03	2.620E+03	3.640E+03	2.470E+03
Density kmol/cum	0.227	0.007	54.986	54.987	54.411	0.005	0.799	0.754	53.050	43.956	43.956	0.782	52.582	55.118	48.491	55.307	17.888
Density kg/cum	4.083	0.159	992.327	992.345	1,003.353	0.141	25.533	24.116	1,032.256	1,236.797	1,236.801	44.343	1,306.794	992.969	1,331.084	1,074.310	1,145.289
Average Mol Wt	18.015	22.101	18.047	18.047	18.440	30.884	31.973	31.999	19.458	28.137	28.137	56.703	24.853	18.015	27.450	19.424	64.027
Liq Vol 60F cum/sec	0.000	0.000	0.000	0.000	0.003	0.000	0.027	0.027	0.110	0.000	0.000	0.000	0.774	0.002	0.908	0.001	0.134
*** VAPOR PHASE ***																	
Density kg/cum	4.083	0.159				0.141	25.533	24.116				44.343					52.922
MUMX N-sec/sqm	0.000	0.000				0.000	0.000	0.000				0.000					0.000
KMX Watt/m-K	0.031	0.023				0.016	0.028	0.028				0.015					0.013
*** LIQUID PHASE ***																	
Density kg/cum	897.535		992.327	992.345	1,003.353				1,032.256	1,236.797	1,240.576		1,306.794	992.969	1,331.084	1,074.310	1,568.635
MUMX N-sec/sqm	0.000		0.001	0.001	0.001				0.001		0.001		0.001	0.001	0.001	0.001	0.000
KMX Watt/m-K	0.681		0.622	0.622	0.544				0.424		0.246		0.274	0.623	0.241	0.492	0.161
SIGMAMX N/m	0.044		0.069	0.069	0.068				0.066		0.057		0.058	0.070	0.055	0.069	0.012
*** LIQUID_1 PHASE *																	
Density kg/cum			992.327	992.345	1,003.353					1,115.964							
MUMX N-sec/sqm			0.001	0.001	0.001					0.001							
KMX Watt/m-K			0.622	0.622	0.544					0.314							
SIGMAMX N/m			0.069	0.069	0.068					0.063							
*** LIQUID_2 PHASE *																	
Density kg/cum										1,586.376							
MUMX N-sec/sqm										0.000							
KMX Watt/m-K										0.185							
SIGMAMX N/m										0.024							

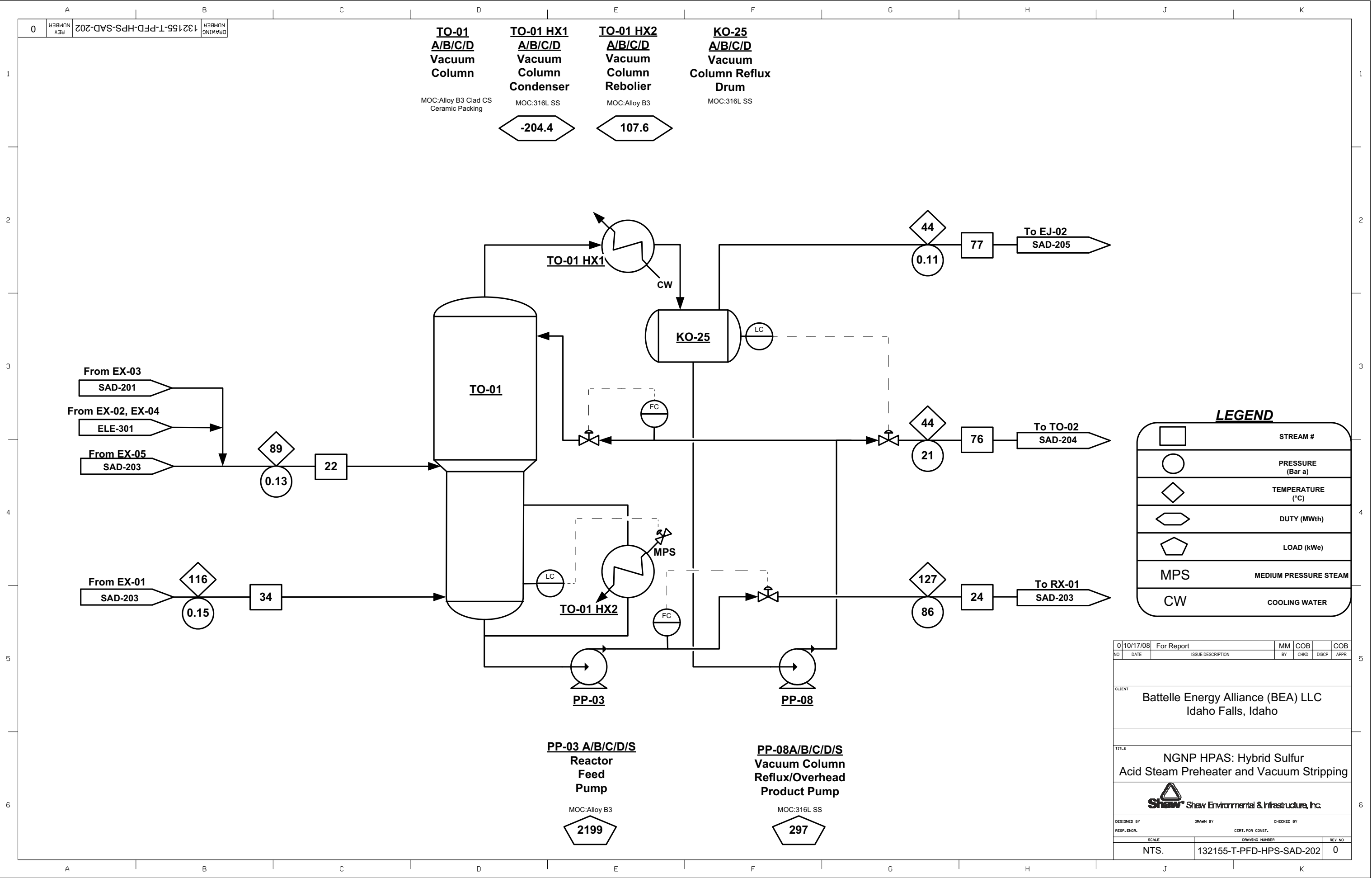
8.1.3 Process Flow Diagrams

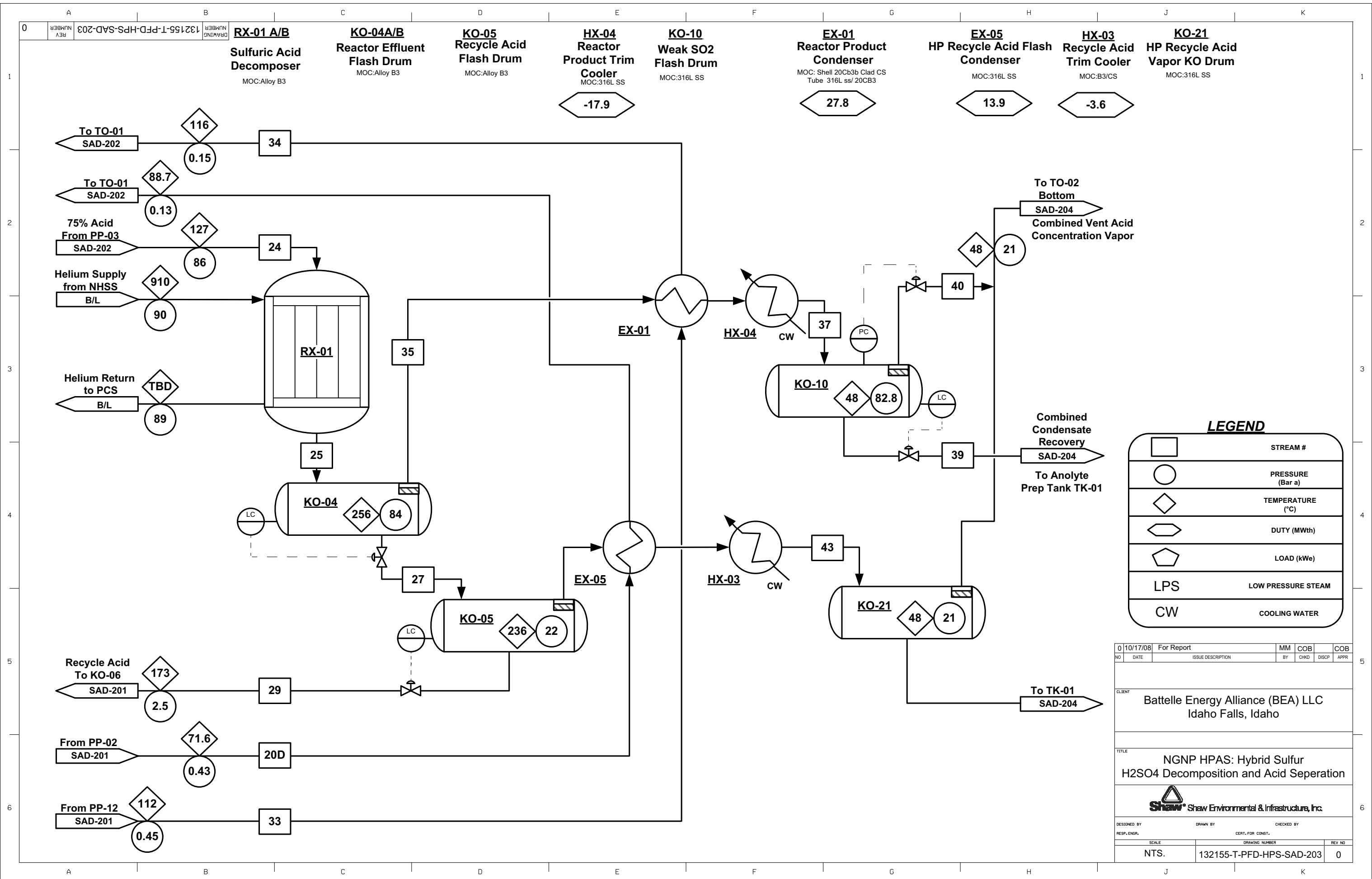




0	9/12/08	For Report	MM	COB		COB
NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISC	APPR
CLIENT Battelle Energy Alliance (BEA) LLC Idaho Falls, Idaho						
TITLE NGNP HPAS: Hybrid Sulfur Water Treatment						
 Shaw Shaw Environmental & Infrastructure, Inc.						
DESIGNED BY RESP. ENGR.		DRAWN BY		CHECKED BY		
		CERT. FOR CONST.				
SCALE		DRAWING NUMBER			REV NO	
NTS.		132155-T-PFD-HPS-FUS-102			0	

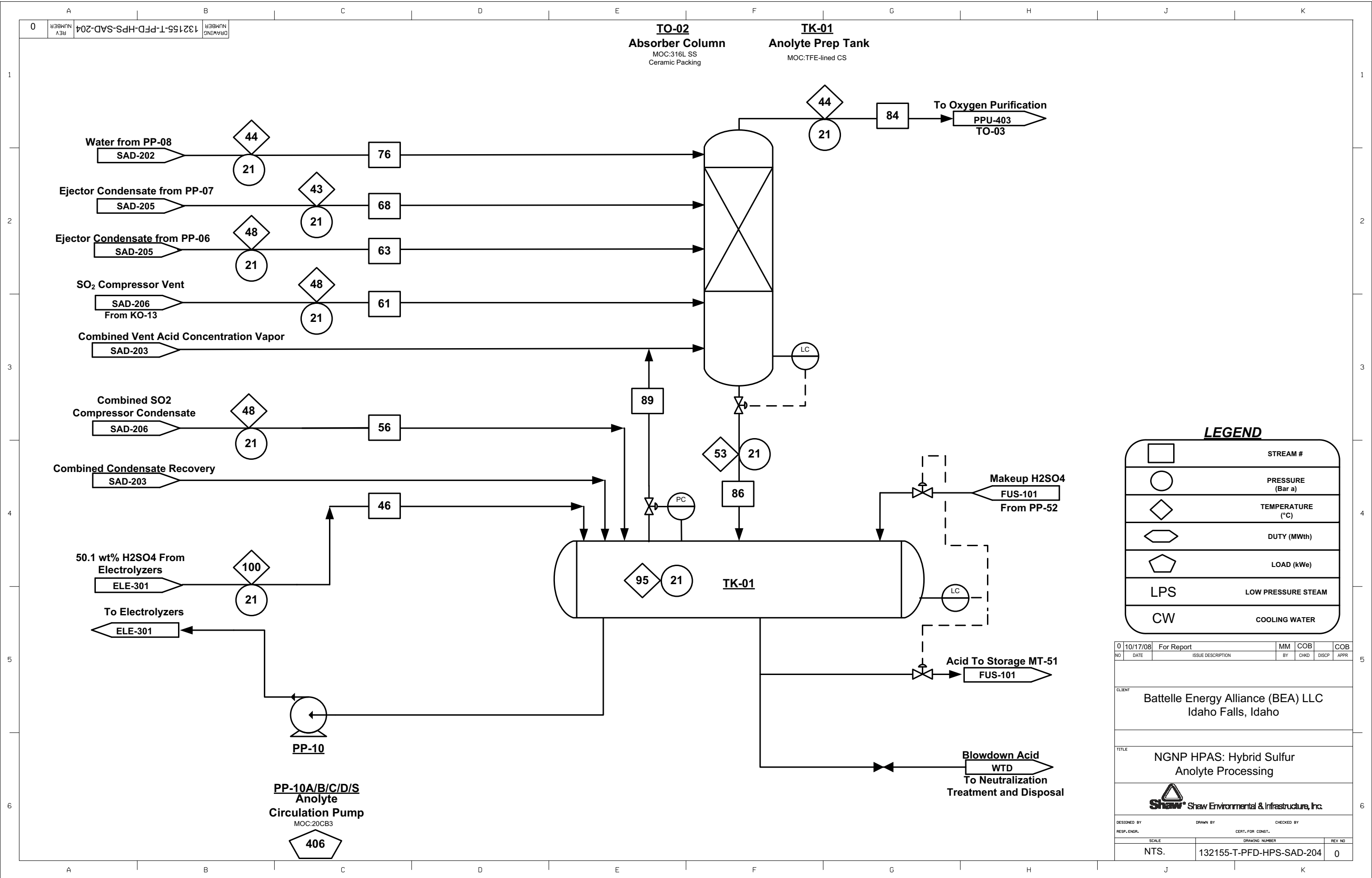


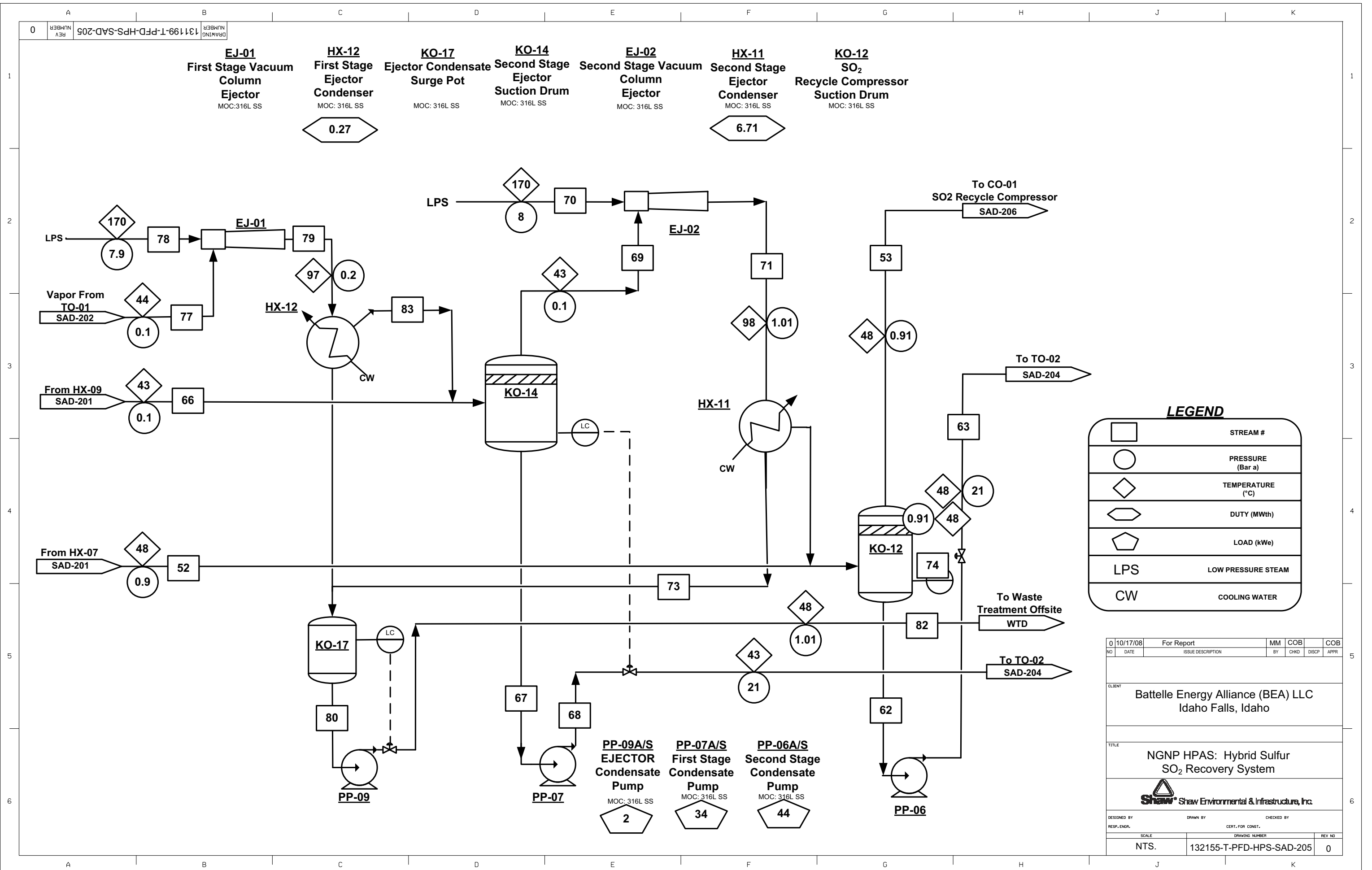


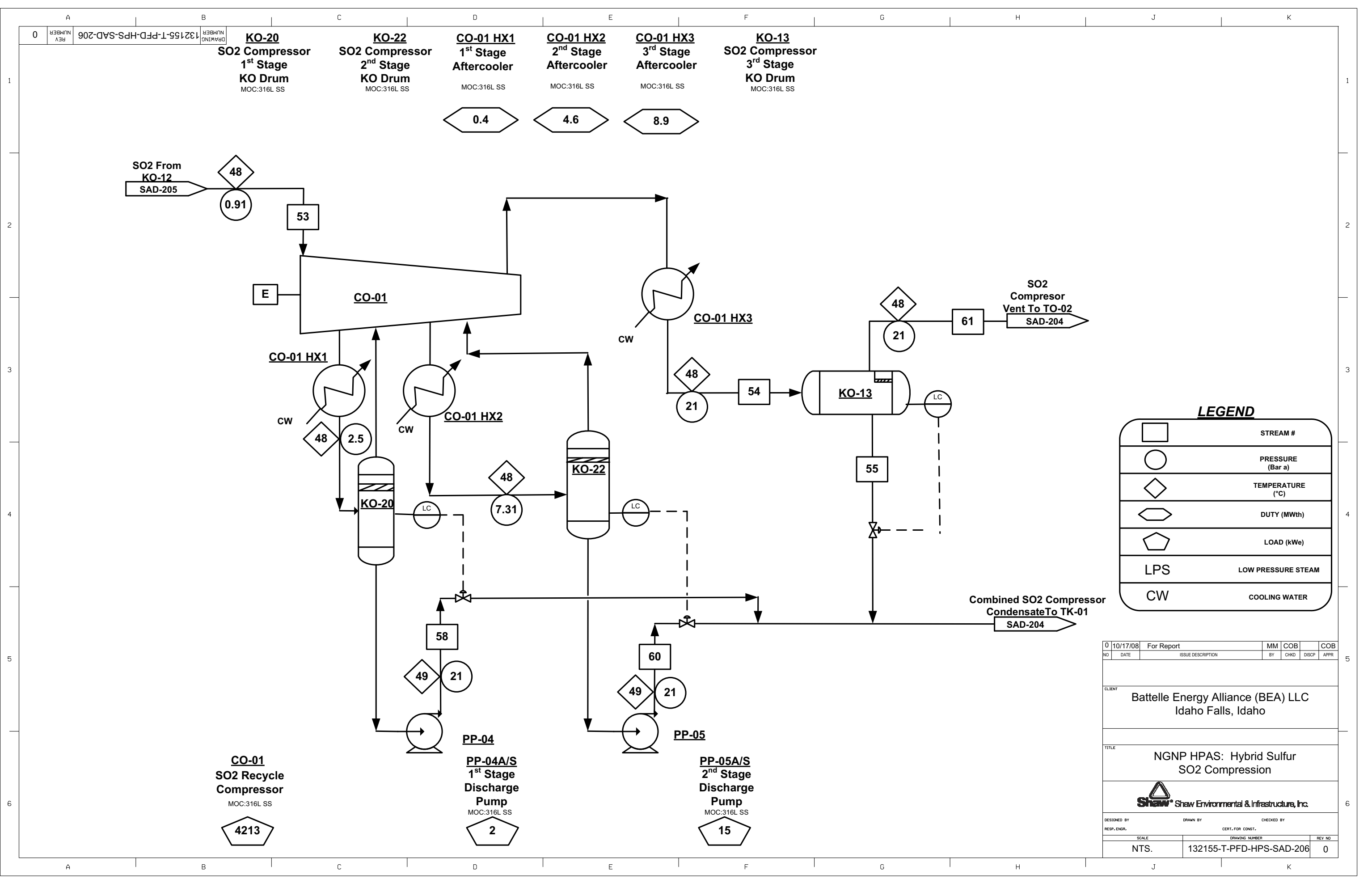


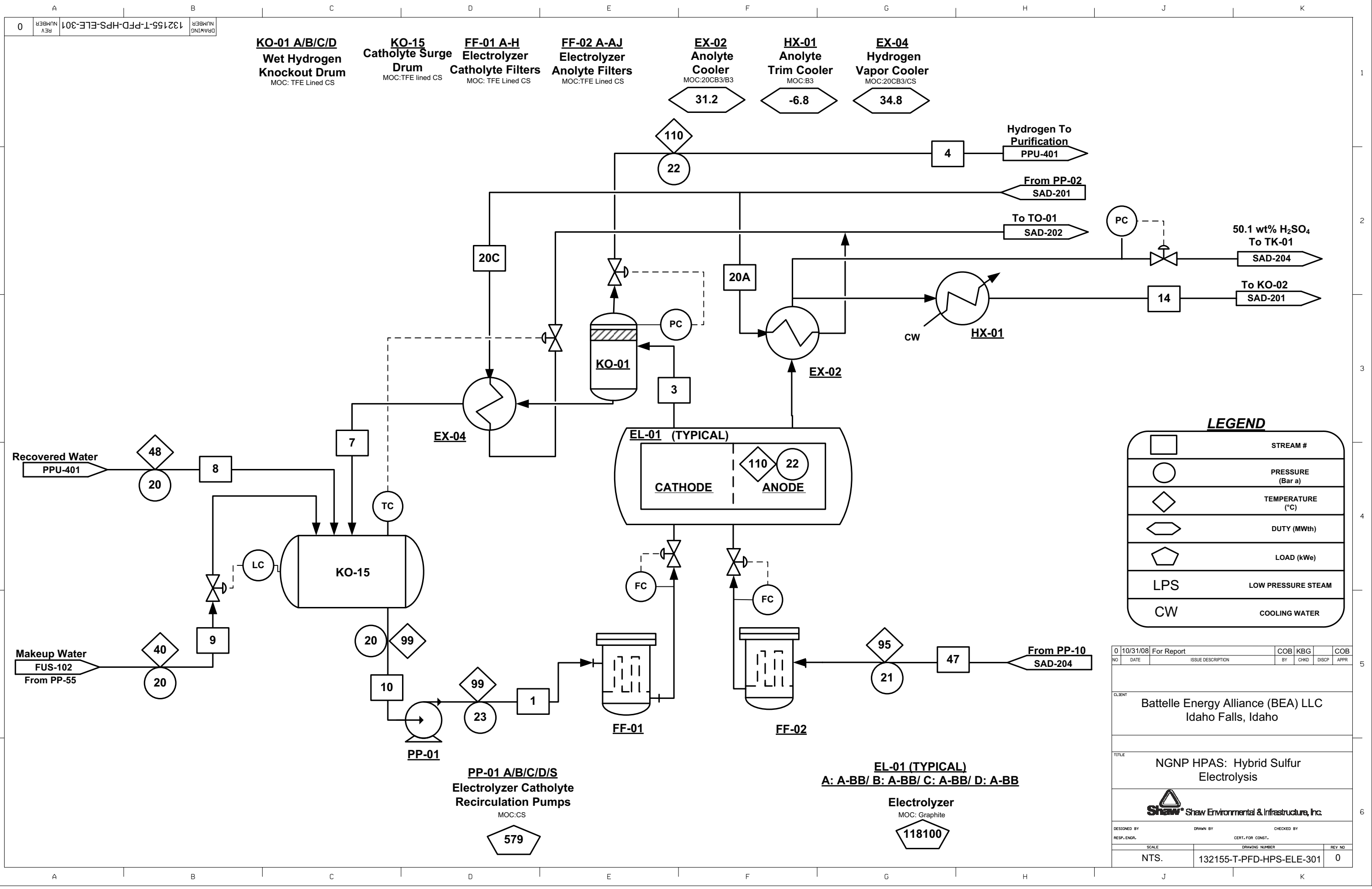
LEGEND	
	STREAM #
	PRESSURE (Bar a)
	TEMPERATURE (°C)
	DUTY (MWth)
	LOAD (kWe)
LPS	LOW PRESSURE STEAM
CW	COOLING WATER

0	10/17/08	For Report	MM	COB	COB
NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISCP
CLIENT					
Battelle Energy Alliance (BEA) LLC Idaho Falls, Idaho					
TITLE					
NGNP HPAS: Hybrid Sulfur H2SO4 Decomposition and Acid Separation					
Shaw Environmental & Infrastructure, Inc.					
DESIGNED BY		DRAWN BY		CHECKED BY	
RESP. ENGR.		CERT. FOR CONST.		REV NO	
SCALE		DRAWING NUMBER		REV NO	
NTS.		132155-T-PFD-HPS-SAD-203		0	

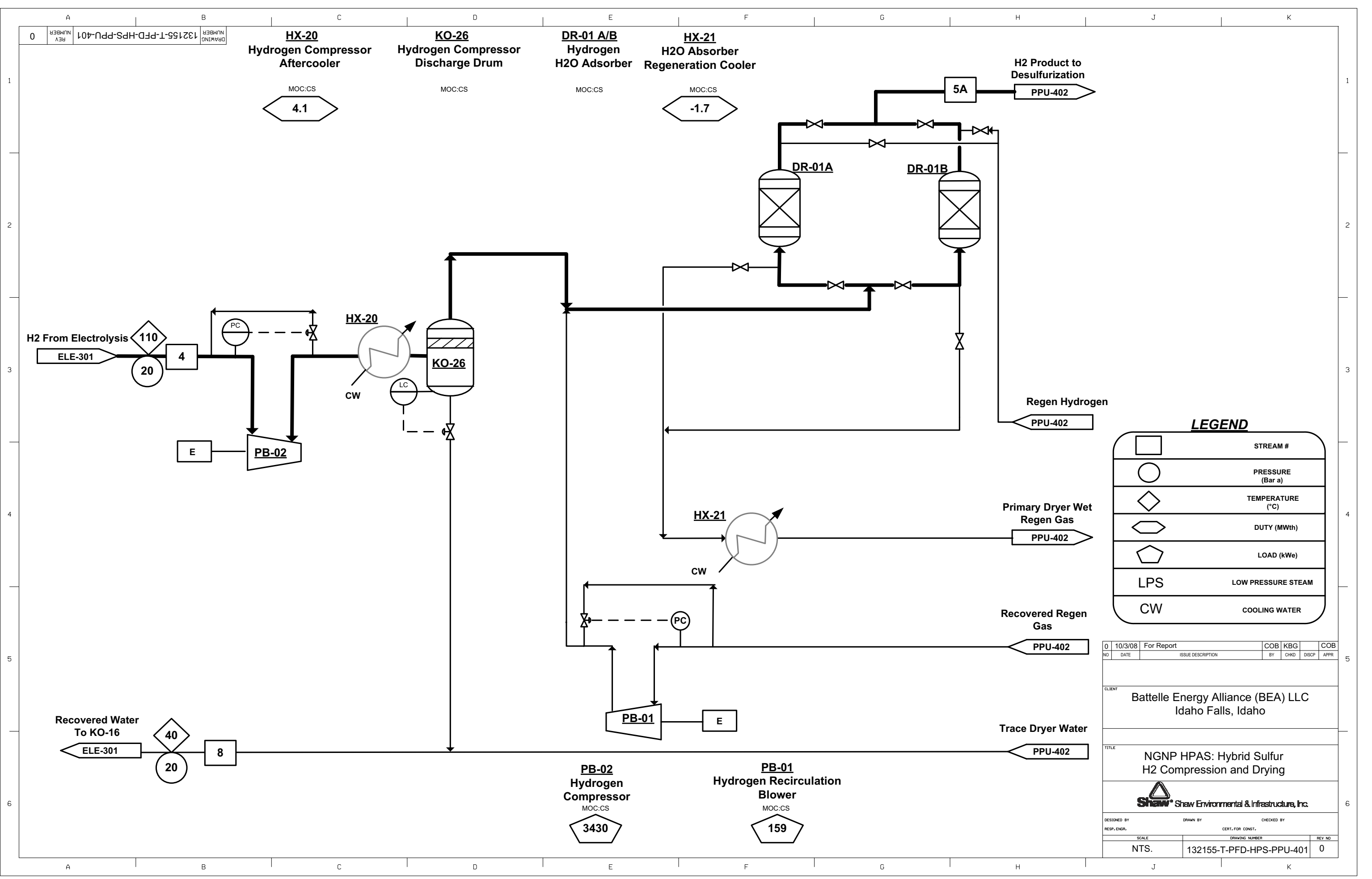




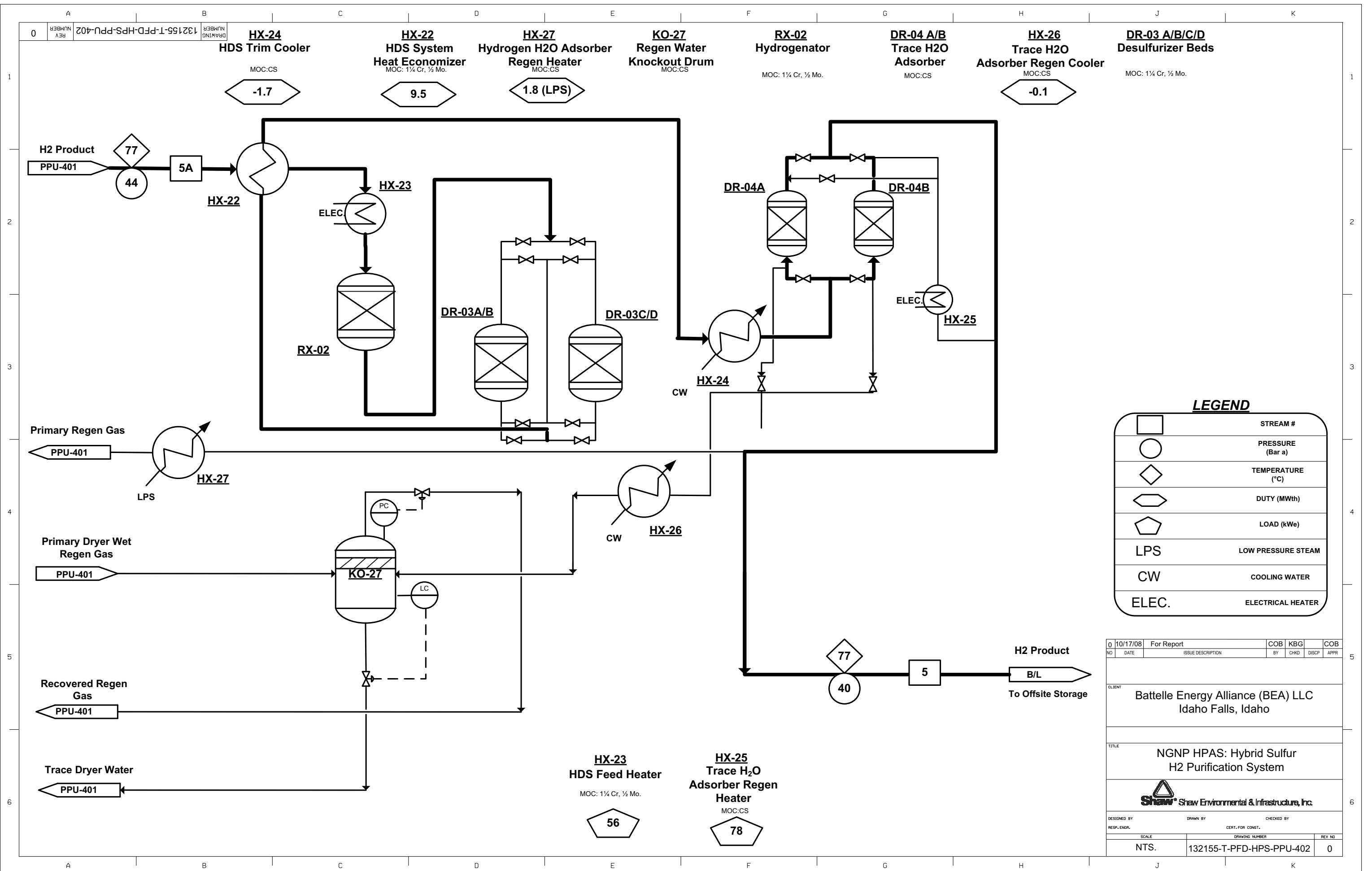


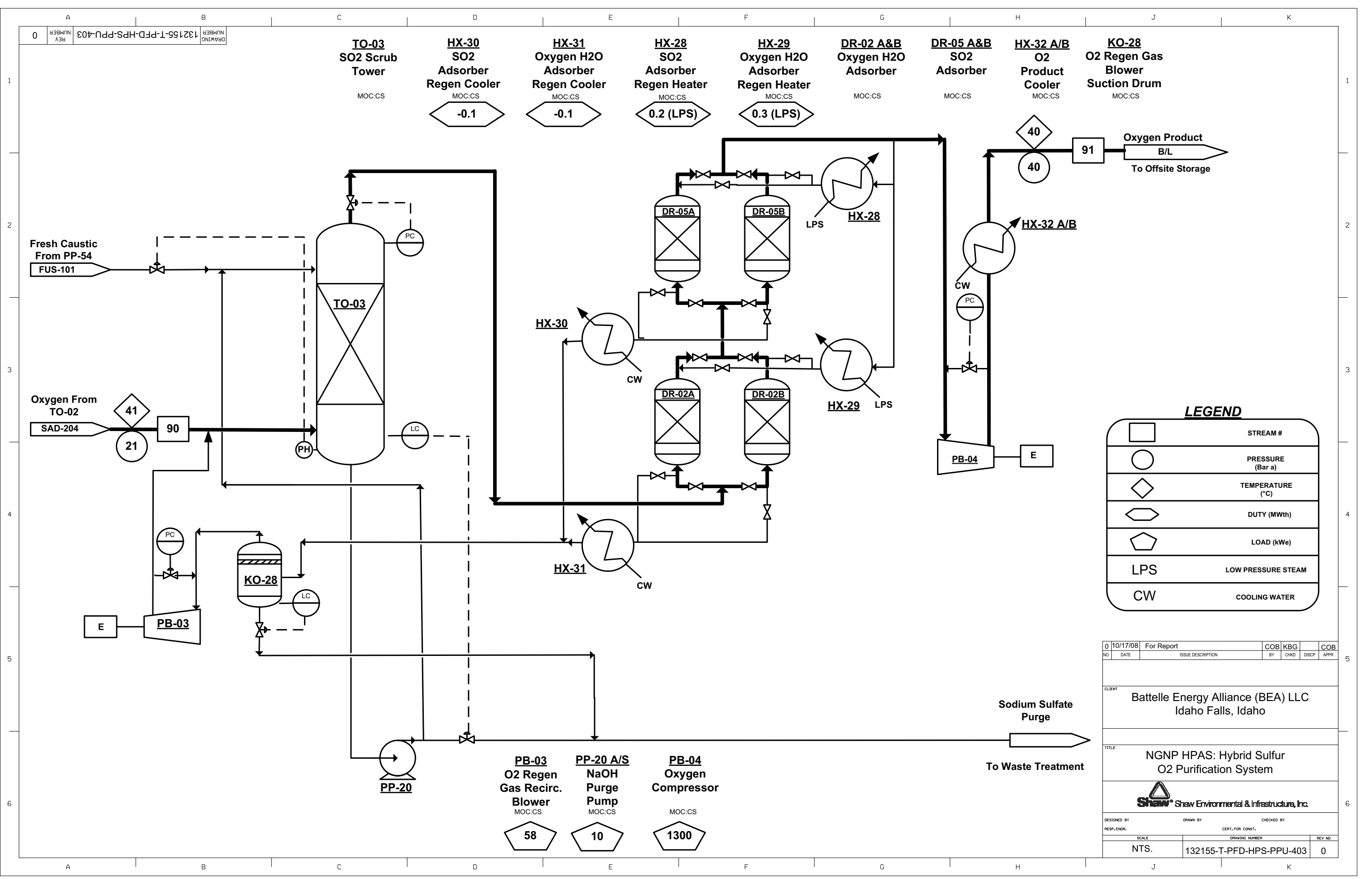


0	10/31/08	For Report	COB	KBG		COB
NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISC	APPR
CLIENT						
Battelle Energy Alliance (BEA) LLC Idaho Falls, Idaho						
TITLE						
NGNP HPAS: Hybrid Sulfur Electrolysis						
DESIGNED BY: RESP. ENGR. DRAWN BY: CHECKED BY: CERT. FOR CONST.						
SCALE		DRAWING NUMBER			REV NO	
NTS.		132155-T-PFD-HPS-ELE-301			0	

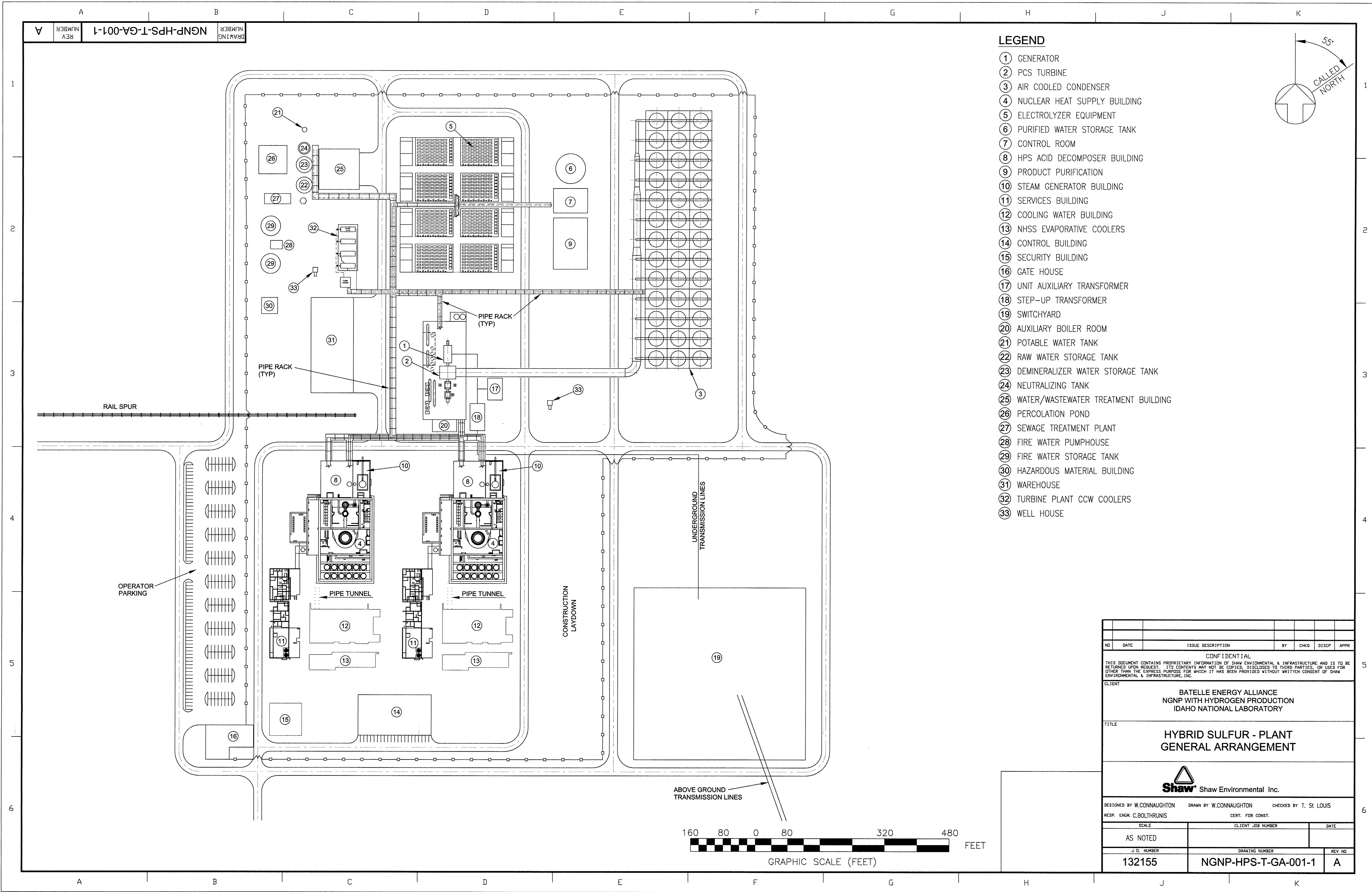


0	10/3/08	For Report	COB	KBG		COB
NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISCP	APPR
CLIENT						
Battelle Energy Alliance (BEA) LLC Idaho Falls, Idaho						
TITLE						
NGNP HPAS: Hybrid Sulfur H2 Compression and Drying						
DESIGNED BY						
RESP. ENGR.						
DRAWN BY						
CERT. FOR CONST.						
CHECKED BY						
SCALE						
DRAWING NUMBER						
REV NO						
NTS.			132155-T-PFD-HPS-PPU-401			0





8.1.4 Summary Plot Plan Layout



8.1.5 Sized Equipment List

Battelle Energy Alliance, LLC (BEA)
Next Generation Nuclear Plant
Idaho Falls, Idaho
Hybrid Sulfur Hydrogen
Feed and Utility Supply
Equipment List

Shaw E&I Project No. 132155

ISSUE	DATE	DESCRIPTION	ORIGR	CHK'R	SDE	PEM	INTERDISCIPLINE REVIEW		
							DISCIPLINE	REV'R	DATE
							Process		
							Mechanical		
							Civil/Structural		
							Control Systems		
							Power Systems		
							Piping		
							Material & Corr.		
0	11/18/2008	For Report	COB	COB	COB				
FILE NAME NGNP HPAS HyS Feed & Utility Equipment List 08.doc			SHEET 1 of 7			DOC.NO. 132155-T-EQL-HPS-HYS-FUS-0			

EQUIPMENT LIST - TOWERS										
Client: Battelle Energy Alliance (BEA), LLC					Signature:					
Unit: NGNP HPS Hybrid Sulfur					Location: Idaho Falls, Idaho					
Item No.	Name	Diameter (mm)	Height (mm)	Packing/ Trays	Mechanical Design		Material		PFD	Remarks
					Press (bar g)	Temp (°C)	Shell C.A. (mm)	Packing Trays		
HPS-FUS TO-04	Sulfuric Acid Vent Scrubber	4300	12900	30 m ³ CS Chevron disengaging packing	3.5	130	CS	CS	FUS- 101	Spray tower

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/18/2008	SHEET 2 of 7	DOC NO 132155-T-EQL-HPS-HYS-FUS-0

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA), LLC					Signature:				
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho				
Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure bar (g)	Temp (°C)			
HPS-FUS KO-51	Sulfuric Acid Degassing Drum	3000	8000	Vertical	3.5	130	CS-TFE Lined	FUS-101	

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 11/18/2008	SHEET 3 of 7	DOC NO 132155-T-EQL-HPS-HYS-FUS-0

EQUIPMENT LIST – LOW PRESSURE TANKS

Client: Battelle Energy Alliance (BEA) LLC					Signature:			
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho			
Item No.	Name	Diameter (mm)	Height (mm)	Mechanical Design		Material C.A. (mm)	PFD	Remarks
				Pressure mm WG	Temperature (°C)			
HPS-FUS MT-51	H ₂ SO ₄ Storage Tank	6700	7300	150	130	CS-TFE Lined	FUS-101	
HPS-FUS MT-52	Caustic Storage Tank	12400	11000	150	75	CS	FUS-101	
HPS-FUS MT-53	Treated Water Storage Tank	22500	12800	150	75	316 SS	FUS-102	Included in the cost of GZ-102

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 11/18/2008	SHEET 4 of 7	DOC NO 132155-T-EQL-HPS-HYS-FUS-0

EQUIPMENT LIST – PUMPS									
Client: Battelle Energy Alliance (BEA) LLC					Signature:				
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho				
Item No.	Name	Type	Rated Flow (m ³ /h)	Differential Pressure (bar)	Motor kW	Material		PFD	Remarks
						Casing	Impeller		
HPS-FUS PP-51 A/B/S	H ₂ SO ₄ Make-Up Pump	ANSI Centrif.	18	0.3	0.55	20CB3	20CB3	FUS-101	Static Head allowed 15m
HPS-FUS PD-52A/S	H ₂ SO ₄ Feed Pump	Rotary Gear	1.7	20	2.2	20CB3	20CB3	FUS-101	Static Head allowed 15m
HPS-FUS PP-53 A/B/S	NaOH Make-up Pump	ANSI Centrif.	18	0.3	0.55	CS	CS	FUS-101	Static Head allowed 15m
HPS-FUS PD-54 A/S	NaOH Solution Supply Pump	Rotary Gear	9	21.3	11	CS	CS	FUS-101	Static Head allowed 15m
HPS-FUS PP-55A/B	Water Transfer Pumps	Multi-stg. Centrif.	77	20.8	90	316 SS	316 SS	FUS-102	Static Head allowed 15m

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE	DATE	SHEET	DOC NO
	0	11/18/2008	5 of 7	132155-T-EQL-HPS-HYS-FUS-0

EQUIPMENT LIST – MISCELLANEOUS

Client: Battelle Energy Alliance (BEA) LLC			Signature:	
Unit: NGNP Hybrid Sulfur			Location: Idaho Falls, Idaho	
Item No.	Name	Material	PFD	Duty - Description - Remarks
HYS-FUS GZ-101	Water Pretreatment Filter/Softener System	Various	FUS 102	Water treatment multimedia and zeolite softener system. System consists of two trains, each train having a capacity of 80 m ³ /hr (360 gpm product). Vessels are plasite lined carbon steel. System consists of skid mounted feed pumps (2 x 100%), skid mounted backwash pumps (2 x 100%), skid mounted regeneration pumps (2 x 100%), two multi-media filter vessels (10 ft diameter each), two zeolite vessels (8 ft diameter each), and one salt dissolving tank. Total equipment cost: \$1 Million for equipment described above plus PLC controls. Estimated from quote from Aquatech via email dated 10/3/08. Building/foundation costs included in GZ-02.
HYS-FUS GZ-102	Water Treatment RO/EDI System	Various	FUS 102	Reverse Osmosis, Electric Deionization System, 4 x 120 gpm RO/EDI trains. System capacity 360 gpm (product), with 120 gpm installed spare capacity. RO/EDI equipment pricing based on Jan 2008 estimate for Duke Buck combined cycle plant. 3,300 m ³ purified water tank, 48 hrs storage, \$528/m ³ installed cost. Water Purification Building, 550 m ² , \$3122/m ² installed. Total Installed System Cost: \$14 Million (including tank, building and foundations and electrical)
HYS-WTD GZ-103	Waste Water Treatment System	Various		Corrugated inclined plate oil/water separator, 200 gpm capacity. Equipment includes tank, separation media, pumps and control panel. Neutralization, physical treatment system with Mixing tank, piping valves, metering pumps for pH neutralization system. Allowance also for potential physical/chemical treatment, if required. Total Installed System Cost: \$2.5 Million (allowance)

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/18/2008	SHEET 6 of 7	DOC NO 132155-T-EQL-HPS-HYS-FUS-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC					Signature:		
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho		
Item No.	Name	Area (m ²)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-FUS HX-51	H ₂ SO ₄ Storage Tank Heater/Cooler	1050	CS 3 150	20CB3 30 90	BEU	FUS-101	
HPS-FUS HX-52	NaOH Tank Heater/Cooler	2	CS 3 150	CS 23 90	Double Pipe	FUS-101	

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/18/2008	SHEET 7 of 7	DOC NO 132155-T-EQL-HPS-HYS-FUS-0

Battelle Energy Alliance, LLC (BEA)
Next Generation Nuclear Plant
Idaho Falls, Idaho
Hybrid Sulfur Hydrogen
Sulfuric Acid Decomposition
Equipment List

Shaw E&I Project No. 132155

ISSUE	DATE	DESCRIPTION	ORIGR	CHK'R	SDE	PEM	INTERDISCIPLINE REVIEW		
							DISCIPLINE	REV'R	DATE
							Process		
							Mechanical		
							Civil/Structural		
							Control Systems		
							Power Systems		
							Piping		
							Material & Corr.		
0	11/18/2008	For Estimate	COB	TS	COB	COB			
FILE NAME BEA LLC SAD Equipment List 08.doc			SHEET 1 of 11			DOC.NO. 132155-T-EQL-HPS-HYS-SAD-0			

EQUIPMENT LIST - TOWERS										
Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottarini</i>					
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho					
Item No.	Name	Diameter (mm)	Height (mm)	Packing/ Trays	Mechanical Design		Material		PFD	Remarks
					Press (bar g)	Temp (°C)	Shell C.A. (mm)	Packing Trays		
HPS-SAD TO-01 A/B/C/D	Vacuum Column	Top: 6300 Bottom: 4400	14000	Packing	3.5 /FV	155	Alloy B3 Clad CS	Ceramic	SAD- 202	Koch Flexiramic 88 or equal packing
HPS-SAD TO-02	Absorber Column	1450	12800	Packing	22	100	316L SS	Ceramic	SAD- 204	Koch Flexiramic 88 or equal packing

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw ® Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/18/2008	SHEET 2 of 11	DOC NO 132155-T-EQL-HPS-HYS-SAD-0

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottarini</i>				
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho				
Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temp (°C)			
HPS-SAD RX-01 A/B	Sulfuric Acid Decomposer	4800	10300	Vertical	95	300	He (Shell) side: Internally insulated CS, Process side (Tube side) TFE lined CS, Silicon Carbide tubes	SAD-203	Similar to a large, vertical, tubular heat exchanger. Alloy B3 piping on sulfuric acid side; Incoloy 800H piping on the Helium side. Hemispherical heads, cold wall design 2 Units at \$27 million for both units, not installed
HPS-SAD KO-02 A/B/C/D	50% Acid Flash Drum #1	1900	4800	Vertical	3.5 /FV	105	20Cb3 Clad CS	SAD-201	
HPS-SAD KO-03 A/B/C/D	50% Acid Flash Drum #2	2300	6900	Horizontal	3.5 /FV	105	20Cb3 Clad CS	SAD-201	
HPS-SAD KO-04A/B	Reactor Effluent Flash Drum	4000	11750	Horizontal	92	285	Alloy B3 Clad CS	SAD-203	
HPS-SAD KO-05	Recycle Acid Flash Drum	2600	7600	Horizontal	23	265	Alloy B3 Clad CS	SAD-203	
HPS-SAD KO-06 A/B/C/D	1 st Water Removal Flash Drum	2100	5450	Vertical	3.5 /FV	200	Alloy B3 Clad CS	SAD-201	

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/18/2008	SHEET 3 of 11	DOC NO 132155-T-EQL-HPS-HYS-SAD-0

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottarini</i>				
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho				
Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temp (°C)			
HPS-SAD KO-07 A/B/C/D	2 nd Water Removal Flash Drum	2100	5000	Vertical	3.5 /FV	140	Alloy B3 Clad CS	SAD-201	
HPS-SAD KO-10	Weak SO2 Flash Drum	1900	5600	Horizontal	90	80	316L SS	SAD-203	
HPS-SAD KO-12	SO ₂ recycle compressor suction drum	3000	5000	Vertical	3.5/ FV	80	316L SS	SAD-205	
HPS-SAD KO-13	SO2 Compressor 3rd Stage KO Drum	1000	3000	Vertical	22	80	316L SS	SAD-206	
HPS-SAD KO-14	Second Stage Ejector Suction Drum	2000	5000	Vertical	3.5/ FV	75	316L SS	SAD-205	
HPS-SAD KO-21	HP Recycle Acid Vapor KO Drum	1300	3900	Horizontal	22	80	316L SS	SAD-203	

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 11/18/2008	SHEET 4 of 11	DOC NO 132155-T-EQL-HPS-HYS-SAD-0

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottarini</i>				
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho				
Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temp (°C)			
HPS-SAD KO-17	Ejector Condensate Surge Pot	1200	3200	Vertical	3.5/ FV	130	316L SS	SAD-205	
HPS-SAD KO-20	SO2 Compressor 1 st Stage KO Drum	2300	5000	Vertical	3.5	80	316L SS	SAD-206	
HPS-SAD KO-22	SO2 Compressor 2 nd Stage KO Drum	1300	3000	Vertical	7.0	80	316L SS	SAD-206	
HPS-SAD KO-25 A/B/C/D	Vacuum Column Reflux Drum	1400	4200	Horizontal	3.5/FV	75	316L SS	SAD-202	One drum per TO-01 column train; 4 trains
HPS-SAD TK-01	Anolyte Prep Tank	4600	18400	Horizontal	22	125	TFE-lined CS	SAD-204	

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 11/18/2008	SHEET 5 of 11	DOC NO 132155-T-EQL-HPS-HYS-SAD-0

EQUIPMENT LIST – PUMPS

Client: Battelle Energy Alliance (BEA) LLC						Signature: <i>Charles R. Bottarini</i>			
Unit: NGNP Hybrid Sulfur						Location: Idaho Falls, IdahoCO			
Item No.	Name	Type	Rated Flow (m ³ /h)	Differential Pressure (bar)	Motor KW	Material		PFD	Remarks
						Casing	Impeller		
HPS-SAD PP-03 A/B/C/D/S	Reactor Feed Pump	Multi-stage Centrif.	191	87	775	Alloy B3	Alloy B3	SAD-202	Static Head allowed 20 m
HPS-SAD PP-04A/S	1 st Stage Discharge Pump	Rotary Gear	3	19	3.7	316L SS	316L SS	SAD-206	Static Head allowed 15 m
HPS-SAD PP-05A/S	2 nd Stage Discharge Pump	Multi-stage Centrif.	20	14	22	316L SS	316L SS	SAD-206	Static Head allowed 15 m
HPS-SAD PP-06 A/S	Second Stage Condensate Pump	Multi-stage Centrif.	53	20	75	316L SS	316L SS	SAD-205	Static Head allowed 15 m
HPS-SAD PP-07 A/S	First Stage Condensate Pump	Multi-stage Centrif.	42	21	55	316L SS	316L SS	SAD-205	Static Head allowed 15 m
HPS-SAD PP-08 A/B/C/D/S	Vacuum Column Reflux/Overhead Product Pump	Multi-stage Centrif.	94	21	110	316L SS	316L SS	SAD-202	Static Head allowed 30 m
HPS-SAD PP-09A/S	Ejector Condensate Pump	Dia- phragm	0.5	1	2.2	316L SS	316L SS	SAD-205	Static Head allowed 15 m
HPS-SAD PP-10 A/B/C/D/S	Anolyte Circulating Pump	Lg. End Suction Centrif	830	3	150	20Cb3	20Cb3	SAD-204	Static Head allowed 15 m

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EQUIPMENT LIST – PUMPS

Client: Battelle Energy Alliance (BEA) LLC

Signature: *Charles R. Bottarini*

Unit: NGNP Hybrid Sulfur

Location: Idaho Falls, IdahoCO

Item No.	Name	Type	Rated Flow (m ³ /h)	Differential Pressure (bar)	Motor KW	Material		PFD	Remarks
						Casing	Impeller		
HPS-SAD PP-02 A/B/C/D/S	50% Acid Booster Pump	Centrif.	150	0.4	7.5	20Cb3	20Cb3	SAD-201	
HPS-SAD PP-12 A/B/C/D/S	65% Acid Booster Pump	Centrif.	110	0.3	5.5	Alloy B3	Alloy B3	SAD-201	

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 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/18/2008	SHEET 7 of 11	DOC NO 132155-T-EQL-HPS-HYS-SAD-0

EQUIPMENT LIST – COMPRESSORS / BLOWERS / VACUUM PUMPS

Client: Battelle Energy Alliance (BEA) LLC						Signature: <i>Charles R. Bottarini</i>				
Unit: NGNP Hybrid Sulfur						Location: Idaho Falls, Idaho				
Item No.	Name	Type	Capacity (Am ³ /h)	Suction Pressure (bar a)	Differential Pressure (bar)	Driver		Material C.A.(mm)	PFD	Remarks
						Type	Rated Power (kW)			
HPS-SAD EJ-02	Second Stage Vacuum Column Ejector	Steam Ejector	77000	0.12	0.9	-	-	316L SS	SAD-205	
HPS-SAD EJ-01	First Stage Vacuum Column Ejector	Steam Ejector	4100	0.11	0.11	-	-	316L SS	SAD-205	
HPS-SAD CO-01	SO ₂ Recycle Compressor	Three Stage Centrif.	45000	0.9	20.1	Electric	5300	316L SS	SAD-206	

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EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC				Signature: <i>Charles R. Bottorini</i>			
Unit: NGNP Hybrid Sulfur				Location: Idaho Falls, Idaho			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-SAD CO-01 HX1	SO ₂ Recycle 1 st Stage Aftercooler	5	316L SS 5 200	CS/ 316L SS 7 80	BEU	SAD-206	
HPS-SAD CO-01 HX2	SO ₂ Recycle 2 nd Stage Aftercooler	35	316L SS 7 200	CS/ 316L SS 7 80	BEU	SAD-206	
HPS-SAD CO-01HX3	SO ₂ Recycle 3 rd Stage Aftercooler	65	316L SS 22 200	CS/ 316L SS 16 80	BEU	SAD-206	
HPS-SAD EX-01	Reactor Product Condenser	400	20Cb3b Clad CS 63 126	316L ss/ 20CB3 91 132	DEU	SAD-203	
HPS-SAD HX-03	Recycle Acid Trim Cooler	85	B3/CS 22 260	B3/CS 16 80	BEU	SAD-203	
HPS-SAD HX-04	Reactor Product Trim Cooler	300	316 L SS 92 260	316 L SS 63 80	BEU	SAD-203	

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 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/18/2008	SHEET 9 of 11	DOC NO 132155-T-EQL-HPS-HYS-SAD-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC				Signature: <i>Charles R. Bottorini</i>			
Unit: NGNP Hybrid Sulfur				Location: Idaho Falls, Idaho			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-SAD HX-07	KO-02 O/Head Vapor Cooler	35	316 L SS 7/FV 105	316L SS 10 100	BEU	SAD-201	
HPS-SAD EX-05	HP Recycle Acid Flash Condenser	180	316 L SS 24 265	316L SS 16 120	BEU	SAD-203	
HPS-SAD EX-03 A/B/C/D	LP Recycle Acid Flash Condenser	105	316 L SS 3.5/FV 205	316L SS 3.5/FV 120	BEU	SAD-201	Area shown is per shell
HPS-SAD HX-09 A/B/C/D	KO-03 Condenser	165	316L SS 7/FV 100	CS/ 316L SS 10 100	BEU	SAD-201	Area shown is per shell
HPS-SAD HX-11	EJ-02 Discharge Condenser	155	316L SS 7/FV 130	316L SS 10 100	BEU	SAD-205	
HPS-SAD HX-12	EJ-01 Discharge Condenser	25	316L SS 7/ FV 130	316L SS 10 100	BEU	SAD-205	

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 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 11/18/2008	SHEET 10 of 11	DOC NO 132155-T-EQL-HPS-HYS-SAD-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC				Signature: <i>Charles R. Bottarini</i>			
Unit: NGNP Hybrid Sulfur				Location: Idaho Falls, Idaho			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-SAD TO-01 HX1 A/B/C/D	Vacuum Column Condenser	4495	316L SS 3.5/FV 126	CS/ 316L SS 3.5/FV 100	BXM	SAD-202	One condenser shell per TO-01 column train; area shown is for one shell
HPS-SAD TO-01 HX2 A/B/C/D	Vacuum Column Reboiler	365	CS 7 170	Alloy B3 5/FV 155	BEM	SAD-202	One reboiler per TO-01 column; area shown is for one shell

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Battelle Energy Alliance, LLC (BEA)
Next Generation Nuclear Plant
Idaho Falls, Idaho
Hybrid Sulfur Hydrogen
Electrolysis System
Equipment List

Shaw E&I Project No. 132155

ISSUE	DATE	DESCRIPTION	ORIGR	CHK'R	SDE	PEM	INTERDISCIPLINE REVIEW		
							DISCIPLINE	REV'R	DATE
							Process		
							Mechanical		
							Civil/Structural		
							Control Systems		
							Power Systems		
							Piping		
							Material & Corr.		
0	11/24/2008	For Estimate	MM	COB	COB	COB			
FILE NAME			SHEET			DOC.NO.			
BEA LLC EL Equipment List 08 .doc			1 of 5			132155-T-EQL-HPS-HYS-ELE-0			

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA) LLC

Signature: *Charles R. Bottarini*

Unit: NGNP Hybrid Sulfur

Location: Idaho Falls, Idaho

Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temperature (°C)			
HPS-ELE KO-1 A/B/C/D	Wet Hydrogen Knockout Drum	2200	8800	Horizontal	23	140	TFE lined CS	ELE-301	
HPS-ELE KO-15 A/B/C/D	Catholyte Surge Drum	5200	15600	Horizontal	23	130	TFE lined CS	ELE-301	

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 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/24/2008	SHEET 2 of 5	DOC NO 132155-T-EQL-HPS-HYS-ELE-0

EQUIPMENT LIST – PUMPS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottarini</i>				
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho				
Item No.	Name	Type	Rated Flow (m ³ /h)	Differential Pressure bar	Motor kW (HP)	Material		PFD	Remarks
						Casing	Impeller		
HPS-ELE PP-01 A/B/C/D/S	Electrolyzer Catholyte Recirculation Pumps	Centrifugal	935	2	90	Alloy B3	Alloy B3	ELE-301	Static Head allowed 3 m

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 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 11/24/2008	SHEET 3 of 5	DOC NO 132155-T-EQL-HPS-HYS-ELE-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC				Signature: <i>Charles R. Bottarini</i>			
Unit: NGNP Hybrid Sulfur				Location: Idaho Falls, Idaho			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-ELE EX-04	Hydrogen Vapor Cooler	1115	20Cb3 23 140	20Cb3 16/FV 120	BEU	ELE-301	
HPS-ELE EX-02	Anolyte Cooler	1155	Alloy B3 23 140	Alloy B3/ 20Cb3 16/FV 120	BEU	ELE-301	
HPS-ELE HX-01	Anolyte Trim Cooler	90	Alloy B3 23 140	Alloy B3/CS 16 120	BEU	ELE-301	

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 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 11/24/2008	SHEET 4 of 5	DOC NO 132155-T-EQL-HPS-HYS-ELE-0

EQUIPMENT LIST – MISCELLANEOUS

Client: Battelle Energy Alliance (BEA) LLC

Signature: *Charles R. Bottarini*

Unit: NGNP Hybrid Sulfur

Location: Idaho Falls, Idaho

Item No.	Name	Material	PFD	Duty - Description - Remarks
HPS-ELE EL-01 A: A-BB/ B: A -BB/ C: A-BB/ D: A-BB	Electrolyzer	Graphite	ELE-301	4 banks of 54 modules each; 216 modules Design pressure: 300 psig. Cylindrical module made up of 200 circular bipolar plate cells with an OD of 1.22 meters (48 inches). The total thickness of each cell is 0.5 inches; the overall length of the 200 cell stack is 2.54 meters (100 inches). The overall length of a module, including the end plates and other structural components, is 3.15 meters (124 inches). Weight per module is about 8 tons Cost of module F.O.B. at manufacturer's plant: \$300,000; Electricals: \$19.5 Million (Materials only; installation not included) Improved Estimate PENDING A building is needed to house the electrolyzers, electricals and control room: Total floor area: about 45,000 sq. ft.
HPS-ELE FF-01 A-H	Electrolyzer Catholyte Filters	TFE lined CS	ELE-301	PALL Fluoryte™ High Flow Filter (Cartridge filter) PTFE cartridge elements; Des. P: 23 bar g; Des. T: 100°C Diameter= 1.33 m; Length = 1.2 m.; 28 cartridges per case , 8 cases
HPS-ELE FF-02 A-AJ	Electrolyzer Anolyte Filters	TFE lined CS	ELE-301	PALL Fluoryte™ High Flow Filter (Cartridge filter) PTFE cartridge elements; Des. P: 23 bar g; Des. T: 100°C Diameter= 1.33m; Length = 1.2 m.; 24 cartridges per case PTFE elements, 36 cases

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 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/24/2008	SHEET 5 of 5	DOC NO 132155-T-EQL-HPS-HYS-ELE-0

Battelle Energy Alliance, LLC (BEA)
Next Generation Nuclear Plant
Idaho Falls, Idaho
Hybrid Sulfur Hydrogen
Product Purification
Equipment List

Shaw E&I Project No. 132155

ISSUE	DATE	DESCRIPTION	ORIGR	CHK'R	SDE	PEM	INTERDISCIPLINE REVIEW		
							DISCIPLINE	REV'R	DATE
							Process		
							Mechanical		
							Civil/Structural		
							Control Systems		
							Power Systems		
							Piping		
							Material & Corr.		
0	11/24/2008	For Estimate	COB	KG	COB	COB			
FILE NAME NGNP HPAS HyS Product purification Equipment List 08.doc			SHEET 1 of 7			DOC.NO. 132155-T-EQL-HPS-HYS-PPU-0			

EQUIPMENT LIST - TOWERS										
Client: Battelle Energy Alliance (BEA), LLC					Signature: <i>Charles D. Bottarini</i>					
Unit: NGNP HPS Hybrid Sulfur					Location: Idaho Falls, Idaho					
Item No.	Name	Diameter (mm)	Height (mm)	Packing/Trays	Mechanical Design		Material		PFD	Remarks
					Press (bar g)	Temp (°C)	Shell C.A. (mm)	Packing Trays		
HPS-PPU TO-03	SO ₂ Scrub Tower	2600	7000	33.4 m ³ of 1 inch IMTP #25 Packing	27	100	CS	CS	PPU- 403	

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 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/25/2008	SHEET 2 of 7	DOC NO 132155-T-EQL-HPS-HYS-PPU-0

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottorini</i>				
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho				
Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temp (°C)			
HPS-PPU RX-02	Hydrogenator	2600	3200	Vertical	53	400	1 ¼ Cr, ½ Mo.	PPU-402	13.6 m³ CoMo hydrogenation catalyst; \$312,000 per load
HPS-PPU DR-01 A/B	Hydrogen H₂O Adsorber	3000	5800	Vertical	53	110	CS	PPU-401	2 beds @ 32.8 m³ of 3A mol sieve \$138,000 per bed
HPS-PPU DR-02 A/B	Oxygen H₂O Adsorber	2800	6000	Vertical	26	100	CS	PPU-403	2 beds @ 29.6 m³ of 3A mol sieve \$125,000 per bed
HPS-PPU DR-03 A/B/C/D	Desulfurizer Beds	3800	6000	Vertical	53	400	1 ¼ Cr, ½ Mo.	PPU-402	4 beds @ 54.4 m³ of Zinc Oxide \$865,000 per bed
HPS-PPU DR-04 A/B	Trace H₂O Adsorber	1200	3600	Vertical	53	107	CS	PPU-402	2 beds @ 3.3 m³ of 3A mol sieve \$14,000 per bed
HPS-PPU DR-05 A/B	SO₂ Adsorber	2800	6000	Vertical	26	100	CS	PPU-403	2 beds @ 29.6 m³ of 4A mol sieve \$114,000 per bed
HPS-PPU KO-26	Hydrogen Compressor Discharge Drum	1000	2600	Vertical	53	110	CS	PPU-401	
HPS-PPU KO-27	Regen Heater Knockout Drum	1000	2400	Vertical	53	110	CS	PPU-402	
HPS-PPU KO-28	O₂ Regen Gas Blower Suction Drum	800	2900	Vertical	26	100	CS	PPU-403	

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 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/25/2008	SHEET 3 of 7	DOC NO 132155-T-EQL-HPS-HYS-PPU-0

EQUIPMENT LIST – PUMPS									
Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottarini</i>				
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho				
Item No.	Name	Type	Rated Flow (m ³ /h)	Differential Pressure bar	Motor kW	Material		PFD	Remarks
						Casing	Impeller		
HPS-PPU PP-20A/S	NaOH Purge Pump	Centrif.	9	2	1.1	CS	CS	PPU-403	

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 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/25/2008	SHEET 4 of 7	DOC NO 132155-T-EQL-HPS-HYS-PPU-0

EQUIPMENT LIST – COMPRESSORS / BLOWERS / VACUUM PUMPS

Client: Battelle Energy Alliance (BEA) LLC						Signature: <i>Charles R. Bottorini</i>				
Unit: NGNP Hybrid Sulfur						Location: Idaho Falls, Idaho				
Item No.	Name	Type	Capacity (Am ³ /h)	Suction Pressure (bar a)	Differential Pressure (bar)	Driver		Material C.A.(mm)	PFD	Remarks
						Type	Rated Power (kW)			
HPS-PPU PB-01	Hydrogen Recirculation Blower	Rotary Blower	500	39.6	1	Electric	160	CS	PPU-401	
HPS-PPU PB-02	Hydrogen Compressor	Recipr.	5660	20	30	Steam	3500	CS	PPU-401	
HPS-PPU PB-03	O2 Regen Gas Recirc. Blower	Rotary Blower	315	20	25	Electric	75	CS	PPU-403	
HPS-PPU PB-04	Oxygen Compressor	2 Stage Centrif.	2126	39.5	5	Steam Turbine	1400	CS	PPU-403	2 Stage Compressor w/ intercooler and after cooler supplied as packaged unit.

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 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 11/25/2008	SHEET 5 of 7	DOC NO 132155-T-EQL-HPS-HYS-PPU-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC				Signature: <i>Charles R. Bottarini</i>			
Unit: NGNP Hybrid Sulfur				Location: Idaho Falls, Idaho			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-PPU HX-20	Hydrogen Compressor Aftercooler	280	CS 53 110	CS 41 100	BEU	PPU-401	
HPS-PPU HX-21	H2O Absorber Regeneration cooler	65	CS 54 110	CS 41 100	BEU	PPU-401	
HPS-PPU HX-22	HDS System Heat Economizer	1350	1 ¼ Cr, ½ Mo. 52 405	1 ¼ Cr, ½ Mo. 52 405	BEU	PPU-402	
HPS-PPU HX-23	HDS Feed Heater		1 ¼ Cr, ½ Mo. 52 400		Electric Heater	PPU-402	60 kW
HPS-PPU HX-24	HDS Trim Cooler	650	CS 52 110	CS 40 100	BEU	PPU-402	
HPS-PPU HX-25	Trace H2O Absorber Regen Heater		CS 52 200		Electric Heater	PPU-402	80 kW
HPS-PPU HX-26	Trace H2O Adsorber Regen Cooler	5	CS 52 110	CS 40 100	BEU	PPU-402	5

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 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 11/25/2008	SHEET 6 of 7	DOC NO 132155-T-EQL-HPS-HYS-PPU-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC

Signature: *Charles R. Bottarini*

Unit: NGNP Hybrid Sulfur

Location: Idaho Falls, Idaho

Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-PPU HX-27	Hydrogen H2O Adsorber Regen Heater	35	CS 40 200	CS 52 110	BEU	PPU-402	35
HPS-PPU HX-28	SO2 Adsorber Regen Heater	5	CS 19 200	CS 25 100	BEU	PPU-403	5
HPS-PPU HX-29	H2O Adsorber Regen Heater	10	CS 19 200	CS 25 100	BEU	PPU-403	10
HPS-PPU HX-30	SO2 Adsorber Regen Cooler	5	CS 25 100	CS 19 100	BEU	PPU-403	5
HPS-PPU HX-31	H2O Adsorber Regen Cooler	15	CS 25 100	CS 19 100	BEU	PPU-403	15
HPS-PPU HX-32 A/B	O2 Product Cooler	150	CS	CS	BEU	PPU-403	

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8.1.6 Preliminary Hazards Analysis

Section 8.1.6: NGNP HyS Preliminary Hazards Assessment

Item	Risk	Comments
Concentrated H ₂ SO ₄ at high pressure and temperature	Loss of containment of a highly corrosive acid. High pressure can result in a jet or spray leak.	Concentration of sulfuric acid is practiced industrially. The high pressure employed in this process present a hazard over the low pressure industrial process in that leaks have a potential to spray personnel at a significant distance from the leak point. Since the corrosion resistances of metals to sulfuric acid are strong functions of temperature, fluid velocity and concentration, care must be taken to ensure that operating conditions are well understood before equipment is specified and that actual operating conditions do not significantly vary from design. Joints should be minimized to minimize the potential for leaks. Splash guards should be employed around pumps and any joints located near where personnel may work or pass.
Concentrated SO ₂ at high pressure	Loss of containment of a toxic gas	Large quantities of concentrated SO₂ at high pressure represent a serious toxicity hazard. Industrial experience with the safe operation of Claus plants may be a useful reference. The possibility of the release of large quantities of SO₂ from the anolyte solution given a change in temperature or pressure should be considered in the hazards review.
H ₂ purification and compression	Loss of containment of a flammable gas at high pressure and temperature resulting in a fire or explosion	The conditions of these operations are within industrial gases industry experience. Standard safety measures should be incorporated into the design. Due to the flammability of H₂, joints, and fittings should be avoided in this piping system. The possibilities of a jet fire or a confined vapor cloud explosion in the region of potential leak points should be considered in the development of the plant layout.

Item	Risk	Comments
O ₂ purification and compression	The enhanced flammability of materials in O ₂ resulting in an equipment fire	All piping, fittings and equipment exposed to > 25% oxygen must be oxygen-clean before start up. Fittings that are O₂-cleaned at the factory must be shipped sealed. The use of soft materials and lubricants should be minimized with oxygen-enriched streams. Fluorinated compounds such as Teflon™ and Viton™ are normally used for seals and per-fluorinated materials as lubricants. The use of O₂ as the regeneration gas for the TSA's will require that the maximum regeneration temperature and pressure be considered in the specification of the materials of construction for the adsorber vessels (and piping that will be exposed to the hot gas). It is standard industry practice to place O₂ compressors inside of barriers for containment and personnel protection in case of a fire. The frequency of fires in such equipment should be considered in plant layout
He exchange at decomposer	Loss of containment of high pressure He or cross contamination between primary and secondary He streams due to acid corrosion of He heat exchange equipment	Keeping the pressure of the He stream above that of the decomposer should minimize acid leakage into the He in the event of a leak.
Water treatment		This system should be standard equipment routinely used in industry with standard safety measures.

8.1.7 Capital Cost Estimate

Section 8.1.7 – HyS Capital Cost Estimate

ELE System

<u>Equipment</u>		<u>Qty</u>	<u>Cost</u>
Electrolyzers	each module		881,104
	total	192	169,172,000
Electrolyzer Catholyte Filter Housing		16	823,000
Electrolyzer Catholyte Filters			1,120,000
Electrolyzer Anolyte Filter Housing		72	1,233,000
Electrolyzer Anolyte Filters			4,320,000
Wet Hydrogen KO Drum		8	1,870,000
Catholyte Surge Drum		8	12,917,000
Electrolyzer Catholyte Recirculation Pumps		10	1,872,000
Hydrogen Vapor Cooler		2	1,701,000
Anolyte Cooler		2	2,545,000
Anolyte Trim Cooler		2	396,000
	Subtotal Equipment		197,969,000
<u>Installation</u>			
Construction			
	Labor		46,226,000
	Expenses & Supplies		2,550,000
	Construction Equipment		4,560,000
	Vendor Services		300,000
	Sub-subtotal Construction		53,636,000
	Bulk Material		92,426,000
	EPC Engineering		12,480,000
	Spares		4,356,000
	Freight		14,501,000
	Other Costs - Catalyst, Desiccant		0
	Subtotal Installation		177,399,000
	ELE System Total		375,368,000

SAD System

<u>Equipment</u>	<u>Qty</u>	<u>Cost</u>	
Vacuum Column Top & Bottom	8	9,566,000	
Vacuum Column Internals	8	9,324,000	
Absorber Column Top	2	571,000	
Absorber Column Internals	2	212,000	
First Stage Vacuum Column Ejector	2	132,000	
Second Stage Vacuum Column Ejector	2	1,027,000	
Sulfuric Acid Decomposer	4	21,600,000	
Sulfuric Acid Decomposer Internals	4	32,800,000	incl. cat.
50% Acid Flash Drum #1	8	140,000	
50% Acid Flash Drum #2	8	222,000	
Reactor Effluent Flash Drum	4	3,612,000	
Recycle Acid Flash Drum	2	149,000	
1st Water Removal Flash Drum	8	183,000	
2nd Water Removal Flash Drum	8	178,000	
Weak SO2 Flash Drum	2	226,000	
SO2 Recycle Compressor Suction Drum	2	74,000	
SO2 Compressor 3rd Stage KO Drum	2	24,000	
Second Stage Ejector Suction Drum	2	42,000	
Ejector Condensate Surge Pot	2	19,000	
SO2 Compressor 1st Stage KO Drum	2	50,000	
HP Recycle Acid Vapor KO Drum	2	39,000	
SO2 Compressor 2nd Stage KO Drum	2	22,000	
Vacuum Column Reflux Drum	8	96,000	
Anolyte Prep Tank	2	3,986,000	
Reactor Feed Pump	10	16,043,000	
1st Stage Discharge Pump	4	178,000	
2nd Stage Discharge Pump	4	246,000	
Second Stage Condensate Pump	4	454,000	
First Stage Condensate Pump	4	365,000	
Vacuum Column Reflux/Ovhd Product Pump	10	1,670,000	
Ejector Condensate Pump	4	68,000	
Anolyte Circulating Pump	10	2,104,000	
50% Acid Booster Pump	10	361,000	
65% Acid Booster Pump	10	379,000	
SO2 Recycle Compressor	2	14,357,000	
SO2 Recycle 1st Stage Aftercooler	2	47,000	
SO2 Recycle 2nd Stage Aftercooler	2	129,000	
SO2 Recycle 3rd Stage Aftercooler	2	195,000	
Reactor Product Condenser	2	1,192,000	
Recycle Acid Trim Cooler	2	512,000	
Reactor Product Trim Cooler	2	482,000	
KO-02 O/Head Vapor Cooler	2	129,000	

SAD System

	<u>Qty</u>	<u>Cost</u>
HP Recycle Acid Flash Condenser	2	330,000
LP Recycle Acid Flash Condenser	2	447,000
KO-03 Condenser	2	709,000
EJ-02 Discharge Condenser	2	277,000
EJ-01 Discharge Condenser	2	108,000
Vacuum Column Condenser	8	21,396,000
Vacuum Column Reboiler	8	3,001,000
Helium Control Valves	12	2,400,000

Subtotal Equipment	151,873,000

Installation

Construction	
Labor	76,025,000
Equipment & Supplies	3,974,000
Construction Equipment	7,108,000
Vendor Services	150,000

Sub-subtotal Construction	87,257,000

Bulk Material	92,416,000
EPC Engineering	30,264,000
Spares	3,485,000
Freight	11,587,000
Other Costs - Catalyst, Desiccant	1,000,000

Subtotal Installation	226,009,000

SAD System Total	377,882,000

FUS System

	<u>Qty</u>	<u>Cost</u>
<u>Equipment</u>		
Sulfuric Acid Vent Scrubber	1	201,000
Sulfuric Acid Vent Scrubber Internals	1	159,000
Water Pretreatment Filter/Softener System	1	1,000,000
Water Treatment RO/EDI System	1	14,000,000
Waste Water Treatment System	1	1,000,000
Sulfuric Acid Degassing Drum	1	125,000
H2SO4 Make-up Pump	3	61,000
H2SO4 Feed Pump	2	95,000
NaOH Make-up Pump	3	37,000
NaOH Solution Supply Pump	2	82,000
Water Transfer Pump	2	235,000
H2SO4 Storage Tank	1	58,000
Caustic Storage Tank	1	118,000
H2SO4 Storage Tank Heater/Cooler	1	803,000
NaOH Tank Heater/Cooler	1	4,000
Subtotal Equipment		17,978,000
<u>Installation</u>		
Construction		
Labor		6,887,000
Equipment & Supplies		380,000
Construction Equipment		683,000
Vendor Services		0
Sub-subtotal Construction		7,950,000
Bulk Material		4,608,000
EPC Engineering		2,970,000
Spares		127,000
Freight		414,000
Other Costs - Catalyst, Desiccant		0
Subtotal Installation		16,069,000
FUS System Total		\$ 34,047,000

PPU System

	<u>Qty/Train</u>	<u>Cost</u>	
SO2 Scrub Tower	2	453,000	
SO2 Scrub Tower Internals	2	265,000	
Hydrogenator	2	551,000	ints. & cat.
H2O Absorber #1	4	1,139,000	ints. & cat.
H2O Absorber #2	4	564,000	ints. & cat.
Desulfurizer Beds	8	6,635,000	ints. & cat.
Trace H2O Adsorber	4	173,000	ints. & cat.
SO2 Adsorber	4	564,000	ints. & cat.
Hydrogen Compressor Discharge Drum	2	45,000	
Regen Heater Knockout Drum	2	43,000	
O2 Regen Gas Blower Suction Drum	2	27,000	
NaOH Purge Pump	4	80,000	
Hydrogen Recirculation Blower	2	2,067,000	
Hydrogen Compressor	2	6,075,000	
O2 Regen Gas Recirc. Blower	2	1,830,000	
Oxygen Compressor	2	5,242,000	
Hydrogen Compressor Aftercooler	2	125,000	
H2O Absorber Regeneration Cooler	2	59,000	
HDS System Heat Economizer	2	971,000	
HDS Feed Heater	2	150,000	
HDS Trim Cooler	2	233,000	
Trace H2O Absorber Regen Heater	2	120,000	
Trace H2O Absorber Regen Cooler	2	16,000	
H2O Absorber Regen Heater #1	2	43,000	
SO2 Absorber Regen Heater	2	15,000	
H2O Absorber Regen Heater #2	2	22,000	
SO2 Absorber Regen Cooler	2	15,000	
H2O Absorber Regen Cooler	2	26,000	
O2 Product Cooler	4	181,000	
Subtotal Equipment		27,729,000	

Installation

Construction	
Labor	40,969,000
Equipment & Supplies	2,245,000
Construction Equipment	4,017,000
Vendor Services	0
Sub-subtotal Construction	47,231,000

Bulk Material	30,634,000
EPC Engineering	11,544,000
Spares	876,000
Freight	2,898,000
Other Costs - Catalyst, Desiccant	9,756,000
Subtotal Installation	102,939,000
PPU system total	130,668,000

Total HyS Hydrogen Production System Cost

ELE System Total	375,368,000
SAD System Total	377,882,000
FUS System Total	34,047,000
PPU System Total	130,668,000

Grand Total (for 2 operating HPS train)	917,965,000

8.1.8 Operating Cost Estimate

Section 8.1.8 – Operating Cost Estimate, HyS

8.1.8.1: Overall Plant Operating Costs

Fixed Operation & Maintenance				\$/year	
Total plant staff (Direct labor)					
	HPS		52	FTEs	
	PCS		25	FTEs	
	BOP		36	FTEs	
	Total		113	FTEs	
Composite rate			50	\$/hr	
Overhead rate			60	%	
Burdened rate			80		
Annual labor					\$ 18,803,200
G&A					
rate			20	%	
G&A					\$ 3,760,640
Material costs for maintenance and repairs					
	HPS				\$ 823,575
	PCS				\$ 100,000
	BOP				\$ 100,000
			Subtotal Material Costs		\$ 1,023,575
Licenses					
Property Tax & Insurance					\$ 26,517,908
Other					
				Subtotal	\$ 50,105,323
Heat					
	Use	1055.78	MWt		
	Rate	30	\$/MWt-h		
	Cost				\$ 277,458,984
Total Fixed O&M					\$ 327,564,307

Variable Operation & Maintenance

					<u>\$/year</u>	
Electric power consumption					\$ 122,072,076	
rate	75	\$/MWe-h				
annual cost						
Cooling water consumption					\$ 6,828,423	
q	50,622	m ³ /hr	=	934.27	gal/kg H ₂	
trains	4			3.515	m ³ /sec	
C _{S,u}	0.016	\$/m ³				
Process steam					\$ 26,375,066	
q	413,592	kg/hr	=	114.89	kg/sec	
trains	4			28.72	m ³ /sec	
p	7.9	bar				
C _{S,u}	0.008	\$/kg				
Process water						
supply - natural water						
q	182	m ³ /hr	=	3.36	gal/kg H ₂	
				0.05	m ³ /sec	
C _{S,u}	0.069	\$/m ³		\$ 102,711		
softening						
q	164	m ³ /hr				
	0.079	\$/m ³		\$ 106,312		
RO/EDI						
q	130	m ³ /hr				
	0.403	\$/m ³		\$ 429,892		
Total Unit Cost						
			0.002	\$/gal		
Total Water Cost				└───────────┐		
				└───────────┘		
					\$	638,915

Other Material Costs				<u>\$/year</u>	
Decomposer Tubes				in Replacement Capital	
Electrolyzer refurbishment				in Replacement Capital	
Filter replacement	133	\$/hr		\$	1,091,347
Make-up catalyst	520	\$/hr		\$	4,266,921
ZnO	360	\$/hr		\$	2,954,022
Mol sieves	163	\$/hr		\$	1,337,515
Hydrogenation Catalyst	39	\$/hr		\$	320,019
Make-up acid	223	\$/hr		\$	1,829,852
Make-up caustic	608	\$/hr		\$	4,989,015
Total Other Material Costs				\$	16,788,691
Waste treatment costs				\$	31,045,355
q	16.97	kg/s			
C _{S,u}	0.186	\$/kg	÷ 3 =	0.06193	\$/kg
Solid waste disposal costs				\$	3,049
q	2	kg/hr			
C _{S,u}	0.186	\$/kg			
Total Unplanned Replacement Capital Cost Factor					
(% of total direct depreciable costs/year)				0.50	%
Total Variable O&M				\$	135,392,113

8.1.8.2: Detail, Hydrogen Production System Operating Costs**NGNP HPAS HyS Operating Usages**

[All usages are on a per train basis. HTSE Plant has One (1) train]

Number of trains:

2

Staffing:

Operations:

6 per shift

Maintenance

4 per shift

8 additional, day shift only (these should cover the electrolyzer replacement labor)

Supervision & Engineering

Plant Mgr, Assistant, Engineer and Administrative assistant.

Electricity

		Hourly Total	Per train
Electrolysis total	MW _e /h	236.3	118.1
Other users (hydrogen plant only)	MW _e /h	26.0	13.0

Steam

kg/h	413,592	206,796

Cooling Water

Plant total	m ³ /h	50,622	25,311

Catalyst and Chemicals

Water softening chemicals

(included in process water cost)

		Hourly Total	per plant as 100%, kg/h	per train as 50%, kg/h	Cost, \$ per tonne	
Sulfuric Acid make-up		\$ 223	1935	1935	\$ 115	
Caustic		\$ 608	1578	1578	\$ 385	
		Hourly Total	Cost of a load or unit	Loads or units per train	Life, hours	Cost per train-hour
Decomposition catalyst		\$ 520	\$ 2,600,000	2	20,000	\$ 260
Zinc oxide	Katalco 32-5	\$ 360	\$ 865,000	1	4,800	\$ 180
Hydrogenation catalyst	Katalco 61-1	\$ 39	\$ 312,000	1	16,000	\$ 20
	UOP Molsiv					
Mol sieves	3A & 4A	\$ 163	\$ 391,000	1	4,800	\$ 81
Subtotal Catalyst & Chemicals		\$ 1,913				

Replacements

		Hourly Total	Cost of a load or unit	Loads or units per train	Life, hours	Cost per train-hour
Electrolyzers		\$ 717	\$ 300,000	196	164,000	\$ 359
Cell replacement		\$ 1,165	\$ 984	39,200	41,000	\$ 582
RO membranes			(included in process water cost)			
Electrolyzer filters		\$ 133	\$ 2,500	1088	41,000	66
Decomposer tubes		\$ 435	\$ 23,800	750	82,000	218
Subtotal Replacements		\$ 2,450				

Process Water

Usage	50.16	kg/s
Density	999.6	kg/m ³
Blowdown	1%	

Supply	182	m ³ /h
Softened	164	m ³ /h
RO/EDI	130	m ³ /h

Costs	Supply	0.069	\$/m ³
	Softening	0.079	\$/m ³
	RO/EDI	0.403	\$/m ³

Ulrich & Vasudevan, "How to estimate Utility Costs," Chem. Eng., Apr 2006, pp. 66-69: Natural Water Pumped and screened.

Wastes

Liquid Effluent	From Softening	5.02	kg/s
	From RO/EDI	9.56	kg/s
	Sodium sulfite waste	2.39	kg/s
	Total	16.97	kg/s
		61,095	kg/h
		0.186	\$/kg

1/3 of Ulrich, "Conventional Liquid Waste"

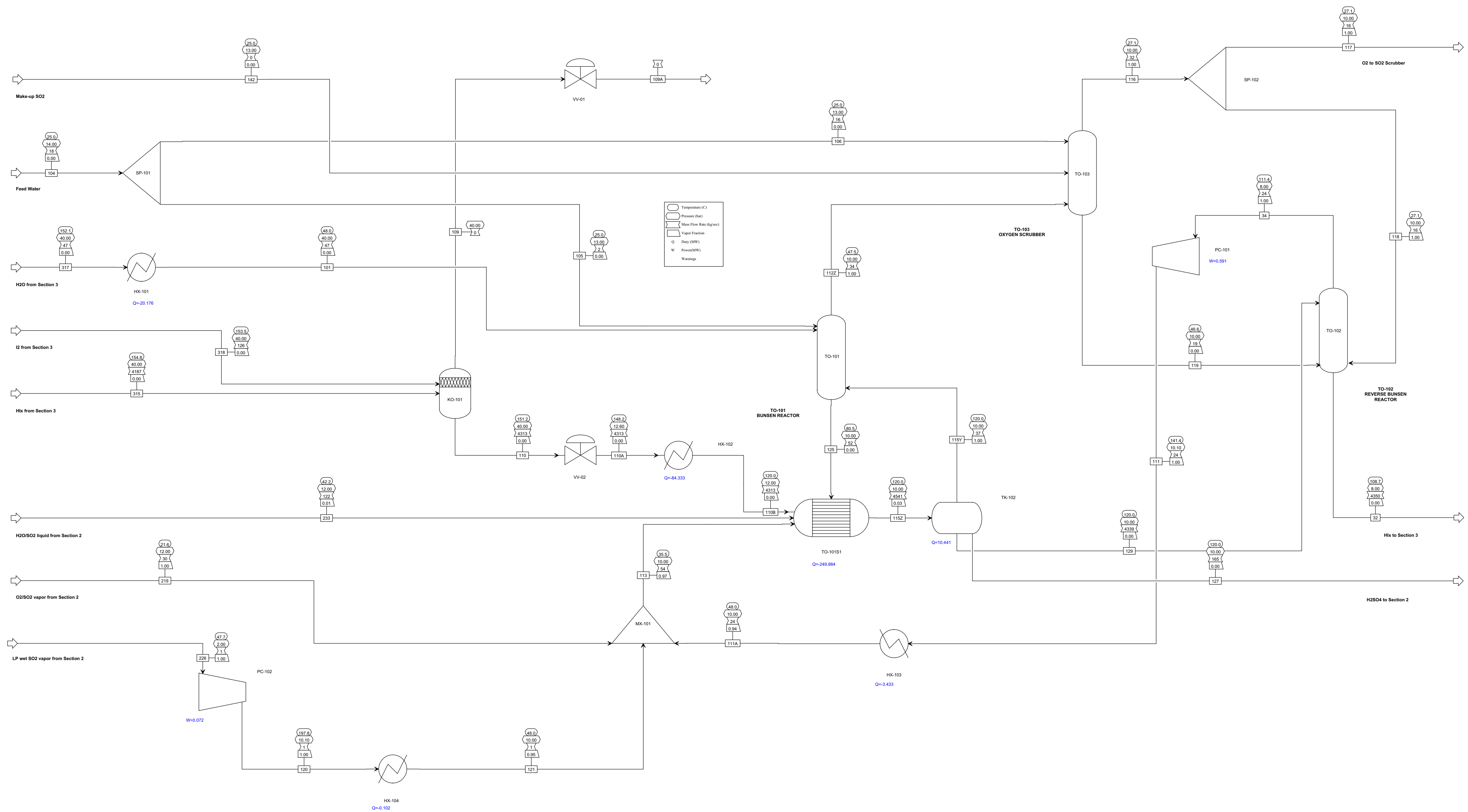
Solid Wastes	Damaged stacks	Assumed damaged stacks are returned to the manufacturer for recycle	
	SiC tubes and spent filters	2	kg/h
			Ulrich, "Conventional Solid Waste"

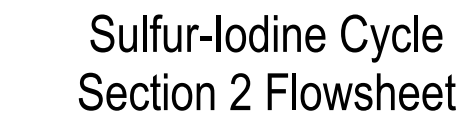
8.2 SULFUR IODINE PROCESS

- 8.2.1 Simulation Diagrams
- 8.2.2 Mass and Energy Balances
- 8.2.3 Process Flow Diagrams
- 8.2.4 Summary Plot Plan Layout
- 8.2.5 Sized Equipment List
- 8.2.6 Preliminary Hazards Analysis
- 8.2.7 Capital Cost Estimate
- 8.2.8 Operating Cost Estimate

8.2.1 Simulation Diagrams

BUNSEN REACTION SIMULATION MODEL

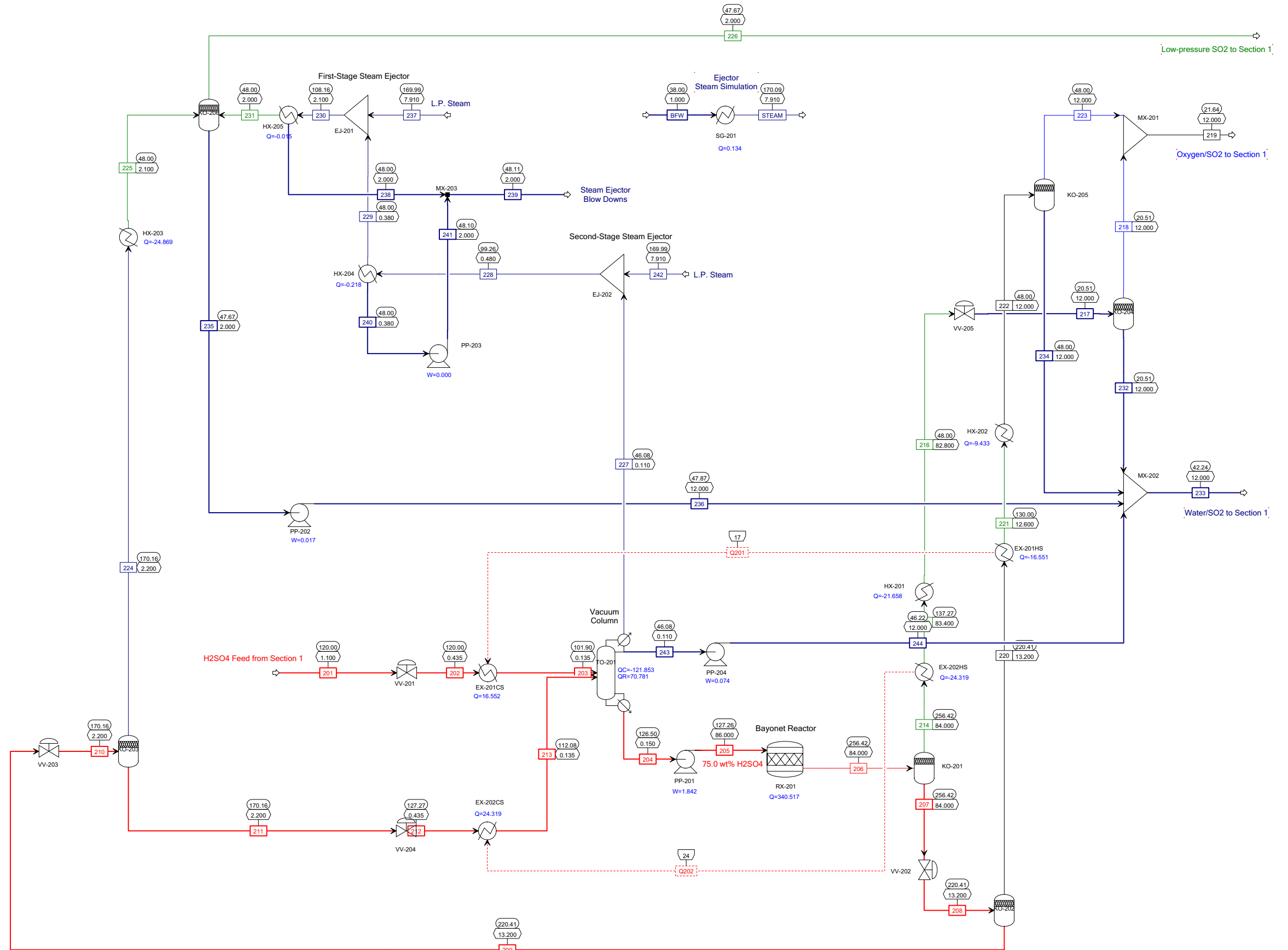




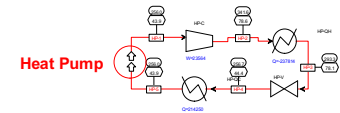
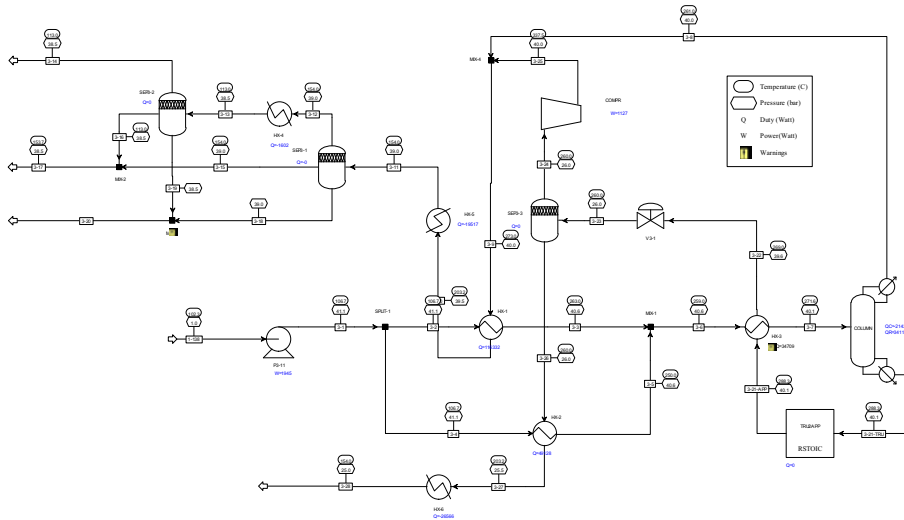
Bunsen reaction feed at 120°C, 1.1 bar

Vacuum Column at 0.11 bar using
2-stage steam ejector, 48°C
condenser

	Temperature (C)
	Pressure (bar)
	Duty (MW)
Q	Duty (MW)
W	Power (MW)



SI Cycle Flowsheet - Section 3



8.2.2 Mass and Energy Balances

	32	34	101	104	105	106	110	110A	110B	111	111A	112Z	113	115Y	115Z
	PC-101	TO-101	SP-101	TO-101	TO-103	VV-02	HX-102	TO-101S1	HX-103	MX-101	TO-103	TO-101S1	TO-101	TK-102	
	TO-102	TO-102	HX-101	SP-101	SP-101	KO-101	VV-02	HX-102	PC-101	HX-103	TO-101	MX-101	TK-102	TO-101S1	
	LIQUID	VAPOR	MIXED	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	VAPOR	MIXED	VAPOR	MIXED	VAPOR	MIXED	
Substream: MIXED															
Mole Flow kmol/sec															
H2O	12.22	0.03	1.82	0.73	0.07	0.65	10.75	10.75	10.75	0.03	0.03	0.01	0.03	0.04	14.06
H2SO4	0.00	0.00	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.78
SO2	0.02	0.06	-	-	-	-	-	-	-	0.06	0.06	0.00	0.22	0.01	0.01
HI	2.61	0.00	0.00	-	-	-	1.21	1.21	1.21	0.00	0.00	0.00	0.00	0.00	2.78
I2	10.26	0.01	0.01	-	-	-	10.97	10.97	10.97	0.01	0.01	0.01	0.01	0.01	10.20
H2	0.00	0.00	0.00	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O2	0.00	0.36	-	-	-	-	-	-	-	0.36	0.36	0.72	0.73	0.72	0.73
Mole Frac															
H2O	0.4866	0.0567	0.9951	1.0000	1.0000	1.0000	0.4689	0.4689	0.4689	0.0567	0.0567	0.0116	0.0278	0.0535	0.4923
H2SO4	0.0000	0.0000	-	-	-	-	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0273
SO2	0.0008	0.1235	-	-	-	-	-	-	-	0.1235	0.1235	0.0000	0.2244	0.0065	0.0003
HI	0.1041	0.0000	0.0013	-	-	-	0.0530	0.0530	0.0530	0.0000	0.0000	0.0000	0.0000	0.0000	0.0972
I2	0.4084	0.0129	0.0030	-	-	-	0.4781	0.4781	0.4781	0.0129	0.0129	0.0083	0.0059	0.0138	0.3574
H2	0.0000	0.0027	0.0005	-	-	-	0.0000	0.0000	0.0000	0.0027	0.0027	0.0033	0.0012	0.0019	0.0001
O2	0.0001	0.8042	-	-	-	-	-	-	-	0.8042	0.8042	0.9768	0.7405	0.9244	0.0254
Total Flow kmol/sec	25.12	0.45	1.83	0.73	0.07	0.65	22.94	22.94	22.94	0.45	0.45	0.74	0.98	0.78	28.55
Total Flow kg/sec	3159.30	17.09	34.50	13.08	1.31	11.78	3132.31	3132.31	3132.31	17.09	17.09	24.85	39.27	26.95	3297.93
Total Flow cum/sec	0.961	1.786	0.034	0.013	0.001	0.012	0.966	0.964	0.944	1.526	1.118	1.959	2.389	2.546	3.587
Temperature C	108.6822	111.3968	48	25	25.02217	25.02217	151.1576	148.1576	120	141.353	48	47.45574	35.52863	120	120
Pressure bar	8	8	40	14	13	13	40	12.6	12	10.1	10	10	10	10	10
Vapor Frac	0	1	1.79E-05	0	0	0	0	0	0	1	0.9414532	1	0.9705488	1	0.027403
Liquid Frac	1	0	0.9999821	1	1	1	1	1	1	0	0.0585468	0	0.0294511	0	0.9725969
Solid Frac	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy J/kmol	-1.42E+08	-4.69E+07	-2.83E+08	-2.86E+08	-2.86E+08	-2.86E+08	-1.25E+08	-1.25E+08	-1.28E+08	-4.60E+07	-5.15E+07	-1.70E+06	-7.42E+07	-1.12E+07	-1.66E+08
Enthalpy J/kg	-1.13E+06	-1.24E+06	-1.50E+07	-1.59E+07	-1.59E+07	-1.59E+07	-9.16E+05	-9.18E+05	-9.38E+05	-1.21E+06	-1.36E+06	-50660.03	-1.85E+06	-3.25E+05	-1.44E+06
Enthalpy MW	-3571.315	-21.128	-517.031	-207.583	-20.758	-186.825	-2868.231	-2875.374	-2936.626	-20.699	-23.193	-1.259	-72.640	-8.770	-4742.819
Entropy J/kmol-K	-1.70E+05	-2956.207	-1.58E+05	-1.63E+05	-1.63E+05	-1.63E+05	-94515.34	-95160.5	-1.01E+05	-2492.406	-17934.74	-15277.03	-14128.71	-8379.624	-1.76E+05
Entropy J/kg-K	-1351.837	-77.8856	-8378.491	-9056.322	-9055.979	-9055.979	-692.062	-696.786	-741.9523	-65.66606	-472.5168	-454.9014	-352.443	-243.2104	-1521.265
Density kmol/cum	26.14686	0.2520407	54.49634	55.38351	55.38071	55.38071	23.75184	23.79856	24.29646	0.2950673	0.4026494	0.3776818	0.4100236	0.3072272	7.95839
Density kg/cum	3288.982	9.566397	1028.158	997.7495	997.6991	997.6991	3243.803	3250.185	3318.183	11.19951	15.28287	12.68375	16.437	10.58527	919.3457
Average MW	125.7888	37.95575	18.86655	18.01528	18.01528	18.01528	136.5706	136.5706	136.5706	37.95577	37.95577	33.58317	40.08793	34.45422	115.5191
Liq Vol 60F cum/sec	1.017	0.023	0.033	0.013	0.001	0.012	0.959	0.959	0.959	0.023	0.023	0.039	0.052	0.041	1.135

	116	117	118	119	120	121	125	127	129	142	219	226	233	315	317
	SP-102		TO-102	TO-102	HX-104	MX-101	TO-101S1		TO-102	TO-103	MX-101	PC-102	TO-101S1	KO-101	HX-101
	TO-103	SP-102	SP-102	TO-103	PC-102	HX-104	TO-101	TK-102	TK-102						
	VAPOR	VAPOR	VAPOR	LIQUID	VAPOR	MIXED	LIQUID	LIQUID	LIQUID	LIQUID	MIXED	MIXED	MIXED	LIQUID	LIQUID
Substream: MIXED															
Mole Flow kmol/sec															
H2O	0.00	0.00	0.00	0.66	0.00	0.00	1.92	2.57	11.44	-	0.00	0.00	2.91	10.74	1.82
H2SO4	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.71	0.07	-	-	0.00	0.00	-	-
SO2	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.16	0.01	0.56	-	-
HI	0.00	0.00	0.00	0.00	-	-	0.01	0.02	2.76	-	-	-	-	1.21	0.00
I2	0.00	0.00	0.00	0.01	-	-	0.01	0.01	10.19	-	-	-	-	10.61	0.01
H2	0.00	0.00	0.00	0.00	-	-	0.00	0.00	0.00	-	-	-	-	0.00	0.00
O2	0.72	0.36	0.36	0.00	0.00	0.00	0.00	0.00	0.00	-	0.36	0.00	0.00	-	-
Mole Frac															
H2O	0.0039	0.0039	0.0039	0.9883	0.0556	0.0556	0.9881	0.7779	0.4678	-	0.0025	0.0556	0.8376	0.4760	0.9951
H2SO4	0.0000	0.0000	0.0000	0.0011	0.0000	0.0000	0.0026	0.2143	0.0029	-	-	0.0000	0.0000	-	-
SO2	0.0026	0.0026	0.0026	0.0000	0.9414	0.9414	0.0000	0.0001	0.0001	1.0000	0.3000	0.9414	0.1623	-	-
HI	0.0000	0.0000	0.0000	0.0021	-	-	0.0065	0.0059	0.1127	-	-	-	-	0.0538	0.0013
I2	0.0000	0.0000	0.0000	0.0082	-	-	0.0026	0.0018	0.4164	-	-	-	-	0.4701	0.0030
H2	0.0034	0.0034	0.0034	0.0000	-	-	0.0000	0.0000	0.0000	-	-	-	-	0.0000	0.0005
O2	0.9901	0.9901	0.9901	0.0003	0.0030	0.0030	0.0002	0.0000	0.0001	-	0.6975	0.0030	0.0001	-	-
Total Flow kmol/sec	0.73	0.36	0.36	0.67	0.01	0.01	1.94	3.30	24.46	0.00	0.52	0.01	3.47	22.56	1.83
Total Flow kg/sec	23.30	11.65	11.65	13.49	0.52	0.52	37.91	119.74	3151.24	0.17	21.67	0.52	88.45	3041.10	34.50
Total Flow cum/sec	1.809	0.904	0.904	0.012	0.032	0.019	0.036	0.085	0.955	0.000	1.025	0.110	0.152	0.944	0.036
Temperature C	27.14029	27.14029	27.14029	46.5932	197.8134		80.47304	120	120	25	21.64315	47.66607	42.24105	154.7684	152.1402
Pressure bar	10	10	10	10	10.1		10	10	10	13	12	2	12	40	40
Vapor Frac	1	1	1	0	1	0.9492604	0	0	0	0	0.9997489	0.999234	0.0112926	0	0
Liquid Frac	0	0	0	1	0	0.0507395	1	1	1	1	2.51E-04	7.66E-04	0.9887074	1	1
Solid Frac	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Enthalpy J/kmol	-1.75E+06	-1.75E+06	-1.75E+06	-2.82E+08	-2.86E+08	-2.95E+08	-2.81E+08	-4.00E+08	-1.39E+08	-3.20E+08	-9.01E+07	-2.92E+08	-2.90E+08	-1.27E+08	-2.75E+08
Enthalpy J/kg	-54670.4	-54670.4	-54670.4	-1.39E+07	-4.66E+06	-4.80E+06	-1.44E+07	-1.10E+07	-1.08E+06	-4.99E+06	-2.17E+06	-4.76E+06	-1.14E+07	-9.45E+05	-1.46E+07
Enthalpy MW	-1.274	-0.637	-0.637	-187.656	-2.413	-2.487	-545.300	-1322.316	-3404.151	-0.846	-46.960	-2.465	-1006.758	-2872.983	-502.377
Entropy J/kmol-K	-18618.6	-18618.6	-18618.6	-1.56E+05	10250.1	-12966.42	-1.56E+05	-2.01E+05	-1.77E+05	-76504.34	-12928.62	7541.72	-1.45E+05	-97278.41	-1.37E+05
Entropy J/kg-K	-583.1286	-583.1286	-583.1286	-7718.356	166.9199	-211.1542	-7980.993	-5558.495	-1370.156	-1194.171	-310.8968	122.8147	-5675.485	-721.7114	-7237.592
Density kmol/cum	0.4035164	0.4035164	0.4035164	53.70252	0.2671153	0.441739	53.27269	39.0765	25.61334	21.2811	0.5085102	0.0765693	22.81287	23.8882	50.4666
Density kg/cum	12.8838	12.8838	12.8838	1088.461	16.40284	27.12601	1041.814	1416.496	3299.376	1363.37	21.14635	4.701919	581.5463	3219.854	952.1308
Average MW	31.92881	31.92881	31.92881	20.26835	61.40732	61.40732	19.55625	36.2493	128.8147	64.0648	41.58492	61.40732	25.49202	134.7885	18.86655
Liq Vol 60F cum/sec	0.039	0.019	0.019	0.012	0.000	0.000	0.036	0.086	1.009	0.000	0.028	0.000	0.083	0.936	0.033

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KO-101

LIQUID

Substream: MIXED		
Mole Flow kmol/sec		
H2O		0.01
H2SO4		-
SO2		-
HI		0.00
I2		0.36
H2		0.00
O2		-
Mole Frac		
H2O		0.0399
H2SO4		-
SO2		-
HI		0.0002
I2		0.9594
H2		0.0005
O2		-
Total Flow kmol/sec		0.37
Total Flow kg/sec		91.21
Total Flow cum/sec		0.024
Temperature C		153.4902
Pressure bar		40
Vapor Frac		0
Liquid Frac		1
Solid Frac		0
Enthalpy J/kmol		1.27E+07
Enthalpy J/kg		52102.61
Enthalpy MW		4.752
Entropy J/kmol-K		56952.48
Entropy J/kg-K		233.1804
Density kmol/cum		15.676
Density kg/cum		3828.739
Average MW		244.2421
Liq Vol 60F cum/sec		0.023

	201	202	203	204	205	206	207	208	209	210	211	212	213
VV-201	EX-201CS	TO-201	PP-201	RX-201	KO-201	VV-202	KO-202	VV-203	KO-203	VV-204	EX-202CS	TO-201	
LIQUID	LIQUID	EX-201CS	TO-201	PP-201	RX-201	KO-201	VV-202	KO-202	VV-203	KO-203	VV-204	EX-202CS	TO-201
		MIXED	LIQUID	LIQUID	LIQUID	MIXED	LIQUID	MIXED	LIQUID	MIXED	LIQUID	MIXED	MIXED
Substream: MIXED													
Mole Flow kmol/sec													
H2O	2.910	2.910	2.910	4.234	4.234	4.234	3.874	3.874	3.565	3.565	3.187	3.187	3.187
H2SO4	-	-	0.000	0.000	-	0.000	-	0.000	-	0.000	-	0.000	0.000
H2	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	-	-	-	0.000	-	0.364	0.006	0.006	0.000	0.000	0.000	0.000	0.000
SO2	0.000	0.000	0.000	0.000	-	0.727	0.164	0.164	0.017	0.017	0.000	0.000	0.000
SO3	0.727	0.727	0.727	1.504	1.504	0.777	0.777	0.777	0.777	0.777	0.777	0.777	0.777
Mole Frac													
H2O	0.800	0.800	0.800	0.738	0.738	0.694	0.804	0.804	0.818	0.818	0.804	0.804	0.804
H2SO4	-	-	0.000	0.000	-	0.000	-	0.000	-	0.000	-	0.000	0.000
H2	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	-	-	-	0.000	-	0.060	0.001	0.001	0.000	0.000	0.000	0.000	0.000
SO2	0.000	0.000	0.000	0.000	-	0.119	0.034	0.034	0.004	0.004	0.000	0.000	0.000
SO3	0.200	0.200	0.200	0.262	0.262	0.127	0.161	0.161	0.178	0.178	0.196	0.196	0.196
Mass Frac													
H2O	0.474	0.474	0.474	0.388	0.388	0.388	0.489	0.489	0.504	0.504	0.480	0.480	0.480
H2SO4	-	-	0.000	0.000	-	0.000	-	0.000	-	0.000	-	0.000	0.000
H2	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	-	-	-	0.000	-	0.059	0.001	0.001	0.000	0.000	0.000	0.000	0.000
SO2	0.000	0.000	0.000	0.000	-	0.237	0.074	0.074	0.008	0.008	0.000	0.000	0.000
SO3	0.526	0.526	0.526	0.612	0.612	0.316	0.436	0.436	0.488	0.488	0.520	0.520	0.520
Total Flow kmol/sec	3.637	3.637	3.637	5.739	5.739	6.102	4.821	4.821	4.359	4.359	3.965	3.965	3.965
Total Flow kg/sec	110.66	110.66	110.66	196.73	196.73	196.73	142.69	142.69	127.52	127.52	119.66	119.66	119.66
Total Flow cum/sec	0.0763	0.0763	82.5710	0.1302	0.1302	0.7146	0.1209	1.4685	0.1043	6.6002	0.0891	22.3743	177.4686
Temperature C	120.0	120.0	101.9	126.5	127.3	256.4	256.4	220.4	220.4	170.2	170.2	127.3	112.1
Pressure bar	1.10	0.44	0.14	0.15	86.00	84.00	84.00	13.20	13.20	2.20	2.20	0.44	0.14
Vapor Frac	0.00	0.00	0.10	0.00	0.00	0.21	0.00	0.10	0.00	0.09	0.00	0.07	0.19
Liquid Frac	1.00	1.00	0.90	1.00	1.00	0.79	1.00	0.90	1.00	0.91	1.00	0.93	0.81
Solid Frac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Enthalpy J/kmol	-3.38E+08	-3.38E+08	-3.34E+08	-3.53E+08	-3.52E+08	-2.91E+08	-3.17E+08	-3.17E+08	-3.24E+08	-3.24E+08	-3.32E+08	-3.32E+08	-3.28E+08
Enthalpy J/kg	-1.11E+07	-1.11E+07	-1.10E+07	-1.03E+07	-1.03E+07	-9.02E+06	-1.07E+07	-1.07E+07	-1.11E+07	-1.11E+07	-1.10E+07	-1.10E+07	-1.09E+07
Enthalpy MW	-1227.5	-1227.5	-1215.5	-2023.1	-2021.8	-1774.4	-1528.0	-1528.0	-1412.5	-1412.5	-1318.1	-1318.1	-1300.5
Entropy J/kmol-K	6.64E+04	6.64E+04	7.68E+04	6.36E+04	6.36E+04	1.13E+05	8.95E+04	9.24E+04	8.06E+04	8.47E+04	7.34E+04	7.68E+04	9.10E+04
Entropy J/kg-K	2.18E+03	2.18E+03	2.52E+03	1.85E+03	1.85E+03	3.50E+03	3.03E+03	3.12E+03	2.75E+03	2.90E+03	2.43E+03	2.54E+03	3.01E+03
Density kmol/cum	47.66	47.66	0.04	44.08	44.09	8.54	39.89	3.28	41.78	0.66	44.48	0.18	0.02
Density kg/cum	1450.0	1450.0	1.3	1511.3	1511.3	275.3	1180.7	97.2	1222.2	19.3	1342.3	5.3	0.7
Average MW	30.43	30.43	30.43	34.28	34.28	32.24	29.60	29.60	29.25	29.25	30.18	30.18	30.18
Liq Vol 60F cum/sec	0.0915	0.0915	0.0915	0.1570	0.1570	0.1765	0.1206	0.1206	0.1069	0.1069	0.0992	0.0992	0.0992

	214	215	216	217	218	219	220	221	222	223	224	225	226
	EX-202HS	HX-201	VV-205	KO-204	MX-201	EX-201HS	HX-202	KO-205	MX-201	HX-203	KO-206		
	KO-201	EX-202HS	HX-201	VV-205	KO-204	MX-201	KO-202	EX-201HS	HX-202	KO-205	KO-203	HX-203	KO-206
	VAPOR	MIXED	MIXED	MIXED	VAPOR	MIXED	VAPOR	MIXED	MIXED	VAPOR	VAPOR	MIXED	VAPOR
Substream: MIXED													
Mole Flow kmol/sec													
H2O	0.360	0.360	0.360	0.360	0.001	0.001	0.309	0.309	0.309	0.000	0.378	0.378	0.000
H2SO4	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H2	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.358	0.358	0.358	0.358	0.358	0.363	0.006	0.006	0.006	0.006	0.000	0.000	0.000
SO2	0.564	0.564	0.564	0.564	0.147	0.156	0.147	0.147	0.147	0.010	0.016	0.016	0.008
SO3	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mole Frac													
H2O	0.281	0.281	0.281	0.281	0.002	0.002	0.669	0.669	0.669	0.010	0.958	0.958	0.056
H2SO4	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H2	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.279	0.279	0.279	0.279	0.707	0.697	0.013	0.013	0.013	0.375	0.000	0.000	0.003
SO2	0.440	0.440	0.440	0.440	0.290	0.300	0.318	0.318	0.318	0.615	0.042	0.042	0.941
SO3	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mass Frac													
H2O	0.120	0.120	0.120	0.120	0.001	0.001	0.367	0.367	0.367	0.004	0.866	0.866	0.016
H2SO4	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H2	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.212	0.212	0.212	0.212	0.548	0.537	0.012	0.012	0.012	0.232	0.000	0.000	0.002
SO2	0.668	0.668	0.668	0.668	0.451	0.462	0.620	0.620	0.620	0.764	0.134	0.134	0.982
SO3	0.000	0.000	0.000	0.000	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total Flow kmol/sec	1.281	1.281	1.281	1.281	0.506	0.521	0.462	0.462	0.462	0.016	0.394	0.394	0.008
Total Flow kg/sec	54.04	54.04	54.04	54.04	20.87	21.67	15.18	15.18	15.18	0.80	7.85	7.85	0.52
Total Flow cum/sec	0.5938	0.3057	0.1504	1.0131	0.9911	1.0243	1.3641	0.4706	0.0431	0.0321	6.5111	0.1051	0.1099
Temperature C	256.4	137.3	48.0	20.5	20.5	21.6	220.4	130.0	48.0	48.0	170.2	48.0	47.7
Pressure bar	84.00	83.40	82.80	12.00	12.00	12.00	13.20	12.60	12.00	12.00	2.20	2.10	2.00
Vapor Frac	1.00	0.75	0.33	0.39	1.00	1.00	1.00	0.41	0.03	1.00	1.00	0.02	1.00
Liquid Frac	0.00	0.25	0.67	0.61	0.00	0.00	0.00	0.59	0.97	0.00	0.00	0.98	0.00
Solid Frac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Enthalpy J/kmol	-1.92E+08	-2.06E+08	-2.18E+08	-2.18E+08	-8.72E+07	-9.02E+07	-2.50E+08	-2.76E+08	-2.91E+08	-1.85E+08	-2.39E+08	-2.85E+08	-2.92E+08
Enthalpy J/kg	-4.56E+06	-4.89E+06	-5.18E+06	-5.18E+06	-2.11E+06	-2.17E+06	-7.61E+06	-8.40E+06	-8.86E+06	-3.59E+06	-1.20E+07	-1.43E+07	-4.76E+06
Enthalpy MW	-246.4	-264.1	-279.8	-279.8	-44.1	-47.0	-115.5	-127.5	-134.4	-2.9	-94.4	-112.4	-2.5
Entropy J/kmol-K	2.01E+05	1.73E+05	-4.57E+09	8.43E+08	1.96E+05	1.96E+05	2.04E+05	1.47E+05	-2.78E+09	2.12E+05	1.98E+05	7.99E+04	2.42E+05
Entropy J/kg-K	4.76E+03	4.11E+03	-1.08E+08	2.00E+07	4.75E+03	4.72E+03	6.22E+03	4.49E+03	-8.45E+07	4.12E+03	9.95E+03	4.01E+03	3.94E+03
Density kmol/cum	2.16	4.19	8.52	1.26	0.51	0.51	0.34	0.98	10.72	0.48	0.06	3.75	0.08
Density kg/cum	91.0	176.8	359.4	53.3	21.1	21.2	11.1	32.2	351.9	24.9	1.2	74.7	4.7
Average MW	42.18	42.18	42.18	42.18	41.28	41.58	32.84	32.84	32.84	51.57	19.93	19.93	61.41
Liq Vol 60F cum/sec	0.0558	0.0558	0.0558	0.0558	0.0270	0.0279	0.0138	0.0138	0.0138	0.0008	0.0077	0.0077	0.0004

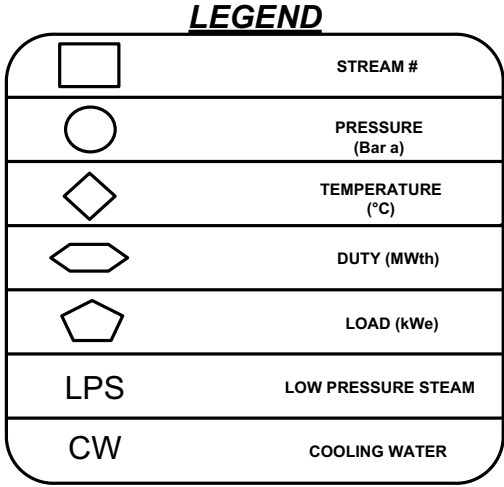
	227	228	229	230	231	232	233	234	235	236	237	238	239
	EJ-202	HX-204	EJ-201	HX-205	KO-206	MX-202	MX-202	PP-202	MX-202	EJ-201	MX-203		
	TO-201	EJ-202	HX-204	EJ-201	HX-205	KO-204	MX-202	KO-205	KO-206	PP-202	HX-205	MX-203	
	VAPOR	VAPOR	VAPOR	MIXED	VAPOR	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	MIXED	LIQUID	LIQUID
Substream: MIXED													
Mole Flow kmol/sec													
H2O	0.002	0.004	0.000	0.000	0.000	0.359	2.906	0.309	0.377	0.377	0.000	0.000	0.004
H2SO4	0.000	-	-	-	-	-	-	-	-	-	-	-	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000
SO2	0.000	0.000	0.000	0.000	0.000	0.417	0.563	0.137	0.009	0.009	-	0.000	0.000
SO3	0.000	-	-	-	-	0.000	0.000	0.000	0.000	0.000	-	-	-
Mole Frac													
H2O	0.922	0.961	0.294	0.647	0.057	0.462	0.838	0.692	0.978	0.978	1.000	0.978	0.995
H2SO4	0.000	-	-	-	-	-	-	-	-	-	-	-	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000
SO2	0.078	0.039	0.706	0.353	0.943	0.537	0.162	0.308	0.022	0.022	-	0.022	0.005
SO3	0.000	-	-	-	-	0.000	0.000	0.000	0.000	0.000	-	-	-
Mass Frac													
H2O	0.768	0.873	0.105	0.340	0.017	0.195	0.592	0.387	0.925	0.925	1.000	0.926	0.984
H2SO4	0.000	-	-	-	-	-	-	-	-	-	-	-	-
H2	-	-	-	-	-	-	-	-	-	-	-	-	-
O2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	0.000	0.000
SO2	0.232	0.127	0.895	0.660	0.983	0.805	0.408	0.612	0.075	0.075	-	0.074	0.016
SO3	0.000	-	-	-	-	0.000	0.000	0.000	0.000	0.000	-	-	-
Total Flow kmol/sec	0.002	0.004	0.000	0.000	0.000	0.776	3.470	0.447	0.386	0.386	0.000	0.000	0.004
Total Flow kg/sec	0.04	0.07	0.01	0.01	0.01	33.17	88.45	14.38	7.34	7.34	0.00	0.00	0.07
Total Flow cum/sec	0.4487	0.2391	0.0132	0.0056	0.0018	0.0220	0.0744	0.0110	0.0072	0.0072	0.0008	0.0000	0.0001
Temperature C	46.1	99.3	48.0	108.2	48.0	20.5	42.2	48.0	47.7	47.9	170.0	48.0	48.1
Pressure bar	0.11	0.48	0.38	2.10	2.00	12.00	12.00	12.00	2.00	12.00	7.91	2.00	2.00
Vapor Frac	1.00	1.00	1.00	0.99	1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
Liquid Frac	0.00	0.00	0.00	0.01	0.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00
Solid Frac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Enthalpy J/kmol	-2.46E+08	-2.42E+08	-2.80E+08	-2.59E+08	-2.93E+08	-3.04E+08	-2.90E+08	-2.94E+08	-2.85E+08	-2.85E+08	-2.38E+08	-2.85E+08	-2.84E+08
Enthalpy J/kg	-1.14E+07	-1.22E+07	-5.54E+06	-7.56E+06	-4.77E+06	-7.11E+06	-1.14E+07	-9.15E+06	-1.50E+07	-1.50E+07	-1.32E+07	-1.50E+07	-1.56E+07
Enthalpy MW	-0.5	-0.9	-0.1	-0.1	0.0	-235.7	-1006.7	-131.5	-110.0	-110.0	0.0	-0.1	-1.1
Entropy J/kmol-K	2.14E+05	2.05E+05	2.42E+05	2.12E+05	2.42E+05	1.39E+09	-7.07E+08	-2.87E+09	7.65E+04	7.65E+04	1.84E+05	7.66E+04	7.56E+04
Entropy J/kg-K	9.91E+03	1.03E+04	4.79E+03	6.18E+03	3.94E+03	3.26E+07	-2.78E+07	-8.92E+07	4.02E+03	4.02E+03	1.02E+04	4.02E+03	4.15E+03
Density kmol/cum	0.00	0.02	0.01	0.07	0.08	35.27	46.64	40.59	53.68	53.70	0.23	53.68	54.66
Density kg/cum	0.1	0.3	0.7	2.3	4.7	1508.3	1188.9	1306.5	1021.8	1022.2	4.1	1021.4	996.5
Average MW	21.62	19.82	50.51	34.26	61.46	42.77	25.49	32.18	19.04	19.04	18.02	19.03	18.23
Liq Vol 60F cum/sec	0.0000	0.0001	0.0000	0.0000	0.0000	0.0288	0.0826	0.0129	0.0073	0.0073	0.0000	0.0000	0.0001

	240	241	242	243	244 BFW	STEAM	
	PP-203	MX-203	EJ-202	PP-204	MX-202	SG-201	
	HX-204	PP-203		TO-201	PP-204		SG-201
	LIQUID	LIQUID	MIXED	LIQUID	LIQUID	LIQUID	VAPOR
Substream: MIXED							
Mole Flow kmol/sec							
H2O	0.004	0.004	0.002	1.861	1.861	0.002	0.002
H2SO4	-	-	-	0.000	-	-	-
H2	-	-	-	-	-	-	-
O2	0.000	0.000	-	0.000	0.000	-	-
SO2	0.000	0.000	-	0.000	0.000	-	-
SO3	-	-	-	0.000	-	-	-
Mole Frac							
H2O	0.997	0.997	1.000	1.000	1.000	1.000	1.000
H2SO4	-	-	-	0.000	-	-	-
H2	-	-	-	-	-	-	-
O2	0.000	0.000	-	0.000	0.000	-	-
SO2	0.003	0.003	-	0.000	0.000	-	-
SO3	-	-	-	0.000	-	-	-
Mass Frac							
H2O	0.988	0.988	1.000	0.999	0.999	1.000	1.000
H2SO4	-	-	-	0.000	-	-	-
H2	-	-	-	-	-	-	-
O2	0.000	0.000	-	0.000	0.000	-	-
SO2	0.012	0.012	-	0.001	0.001	-	-
SO3	-	-	-	0.000	-	-	-
Total Flow kmol/sec	0.004	0.004	0.002	1.862	1.862	0.002	0.002
Total Flow kg/sec	0.06	0.06	0.03	33.56	33.56	0.04	0.04
Total Flow cum/sec	0.0001	0.0001	0.0082	0.0339	0.0339	0.0000	0.0091
Temperature C	48.0	48.1	170.0	46.1	46.2	38.0	170.1
Pressure bar	0.38	2.00	7.91	0.11	12.00	1.00	7.91
Vapor Frac	0.00	0.00	1.00	0.00	0.00	0.00	1.00
Liquid Frac	1.00	1.00	0.00	1.00	1.00	1.00	0.00
Solid Frac	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Enthalpy J/kmol	-2.84E+08	-2.84E+08	-2.38E+08	-2.84E+08	-2.84E+08	-2.85E+08	-2.38E+08
Enthalpy J/kg	-1.56E+07	-1.56E+07	-1.32E+07	-1.58E+07	-1.58E+07	-1.58E+07	-1.32E+07
Enthalpy MW	-1.0	-1.0	-0.4	-529.5	-529.4	-0.6	-0.5
Entropy J/kmol-K	7.56E+04	7.56E+04	1.84E+05	7.50E+04	7.50E+04	7.31E+04	1.84E+05
Entropy J/kg-K	4.16E+03	4.16E+03	1.02E+04	4.16E+03	4.16E+03	4.06E+03	1.02E+04
Density kmol/cum	54.73	54.73	0.23	54.93	54.96	55.12	0.23
Density kg/cum	994.7	994.7	4.1	990.2	990.7	993.0	4.1
Average MW	18.18	18.18	18.02	18.03	18.03	18.02	18.02
Liq Vol 60F cum/sec	0.0001	0.0001	0.0000	0.0336	0.0336	0.0000	0.0000

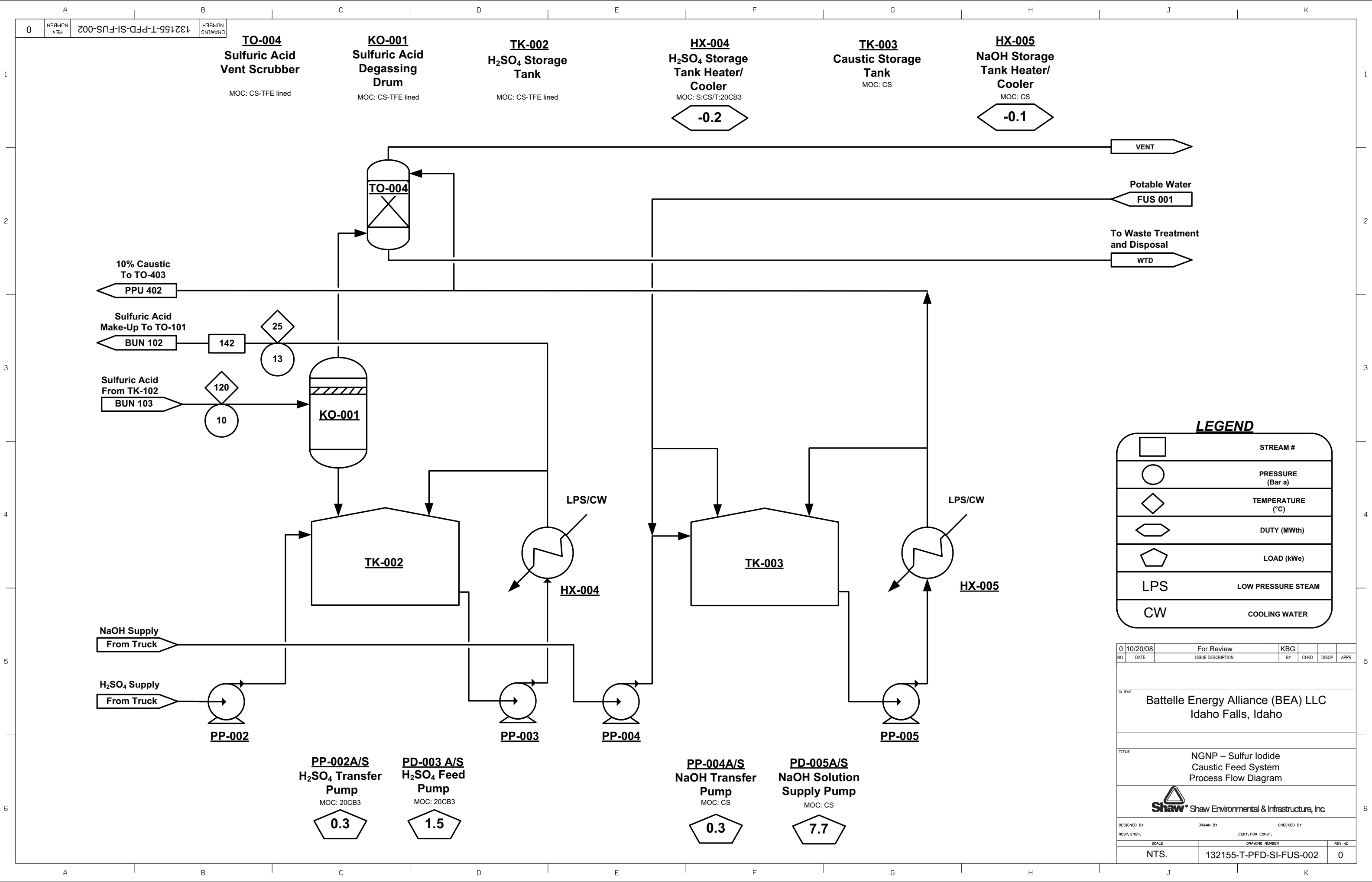
	1-138	3-1	3-2	3-3	3-4	3-5	3-6	3-7	3-8	3-9	3-10	3-11	3-12	3-13	3-14	3-15	3-16
	P3-11	SPLIT-1	HX-1	MIX-1	HX-2	MIX-1	HX-3	COLUMN	MIX-4	HX-1	HX-5	SEP3-1	HX-4	SEP3-2		MIX-2	MIX-2
	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	COLUMN	MIX-4	HX-1	HX-5	SEP3-1	HX-4	SEP3-2	LIQUID	LIQUID
Substream: MIXED																	
Mole Flow kmol/s																	
H2O	12.484	12.484	8.265	8.265	4.219	4.219	12.484	12.484	6.600	7.482	7.482	7.482	0.113	0.113	0.033	7.369	0.080
I2	10.141	10.141	6.714	6.714	3.427	3.427	10.141	10.141	0.001	0.248	0.248	0.248	0.001	0.001	0.001	0.247	0.000
HI	2.649	2.649	1.754	1.754	0.895	0.895	2.649	2.649	0.255	0.313	0.313	0.313	0.000	0.000	0.000	0.313	0.000
H2	-	-	-	-	-	-	-	-	0.726	0.726	0.726	0.726	0.723	0.723	0.723	0.004	0.000
Mole Frac																	
H2O	0.494	0.494	0.494	0.494	0.494	0.494	0.494	0.494	0.871	0.853	0.853	0.853	0.135	0.135	0.043	0.929	0.999
I2	0.401	0.401	0.401	0.401	0.401	0.401	0.401	0.401	0.000	0.028	0.028	0.028	0.001	0.001	0.001	0.031	0.000
HI	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.034	0.036	0.036	0.036	0.000	0.000	0.000	0.039	0.000
H2	-	-	-	-	-	-	-	-	0.096	0.083	0.083	0.083	0.864	0.864	0.955	0.000	0.001
Total Flow kmol/s	25.27	25.27	16.73	16.73	8.54	8.54	25.27	25.27	7.58	8.77	8.77	8.77	0.84	0.84	0.76	7.93	0.08
Total Flow kg/s	3,137.7	3,137.7	2,077.3	2,077.3	1,060.4	1,060.4	3,137.7	3,137.7	153.2	239.1	239.1	239.1	3.7	3.7	2.3	235.4	1.4
Total Flow cum/s	0.952	0.955	0.632	0.729	0.323	0.366	1.096	1.115	7.654	9.016	1.393	0.939	0.769	0.643	0.642	0.169	0.002
Temperature C	102.3	106.7	106.7	263.0	106.7	250.0	259.0	271.6	261.0	273.0	203.2	154.0	154.0	113.0	113.0	154.0	113.0
Pressure bar	1.01	41.06	41.06	40.56	41.06	40.56	40.56	40.06	40	40	39.5	39	39	38.5	38.5	39	38.5
Vapor Frac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.14	0.10	1.00	0.90	1.00	0.00	0.00
Liquid Frac	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	0.86	0.90	0.00	0.10	0.00	1.00	1.00
Solid Frac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Enthalpy J/kmol	-1.39E+08	-1.39E+08	-1.39E+08	-1.20E+08	-1.39E+08	-1.24E+08	-1.21E+08	-1.18E+08	-2.03E+08	-1.97E+08	-2.31E+08	-2.37E+08	-2.87E+07	-3.37E+07	-7.88E+06	-2.59E+08	-2.79E+08
Enthalpy J/kg	-1.12E+06	-1.12E+06	-1.12E+06	-9.70E+05	-1.12E+06	-9.95E+05	-9.78E+05	-9.49E+05	-1.00E+07	-7.21E+06	-8.48E+06	-8.70E+06	-6.49E+06	-7.62E+06	-2.63E+06	-8.73E+06	-1.55E+07
Enthalpy MW	-3507.5	-3502.4	-2318.7	-2014.5	-1183.7	-1055.2	-3069.7	-2979.0	-1538.8	-1724.0	-2028.2	-2079.2	-24.0	-28.2	-6.0	-2055.2	-22.2
Entropy J/kmol-K	-5.78E+04	-5.71E+04	-5.71E+04	-1.98E+04	-5.71E+04	-2.51E+04	-2.16E+04	-1.57E+04	-4.43E+04	-3.78E+04	-1.03E+05	-1.16E+05	-2.24E+04	-3.45E+04	-2.31E+04	-1.26E+05	-1.44E+05
Entropy J/kg-K	-4.65E+02	-4.60E+02	-4.60E+02	-1.60E+02	-4.60E+02	-2.02E+02	-1.74E+02	-1.26E+02	-2.19E+03	-1.38E+03	-3.79E+03	-4.26E+03	-5.05E+03	-7.80E+03	-7.70E+03	-4.24E+03	-7.96E+03
Density kmol/cum	26.5437	26.48	26.48	22.94	26.48	23.33	23.06	22.67	0.99	0.97	6.30	9.34	1.09	1.30	1.18	46.92	52.61
Density kg/cum	3295.2	3286.7	3286.7	2847.9	3286.7	2896.1	2862.9	2814.4	20.0	26.5	171.7	254.8	4.8	5.8	3.5	1392.4	949.2
Average Mol Wt	124.14	124.14	124.14	124.14	124.14	124.14	124.14	124.14	20.20	27.27	27.27	27.27	4.43	4.43	2.99	29.68	18.04
Liq Vol 60F cum/hr	1.397	1.397	0.925	0.925	0.472	0.472	1.397	1.397	0.236	0.284	0.284	0.284	0.056	0.056	0.054	0.228	0.002

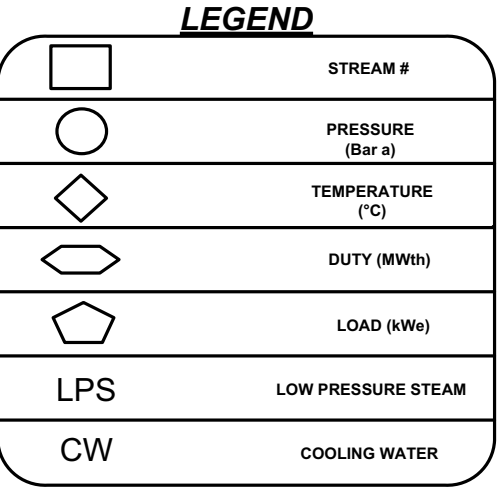
	3-17	3-21-APP	3-22	3-23	3-24	3-25	3-26	3-27	3-28	HP-1	HP-2	HP-3	HP-4	HP-5
	MIX-2	HX-3	V3-1	SEP3-3	COMPR	MIX-4	HX-2	HX-6		HP-C	HP-QH	HP-V	HP-QC	
	MIXED	LIQUID	LIQUID	MIXED	VAPOR	VAPOR	LIQUID	LIQUID	LIQUID	VAPOR	VAPOR	LIQUID	MIXED	HP-QC
Substream: MIXED														
Mole Flow kmol/s														
H2O	7.449	5.884	5.884	5.884	0.881	0.881	5.002	5.002	5.002	20.855	20.855	20.855	20.855	20.855
I2	0.247	10.867	10.867	10.867	0.247	0.247	10.620	10.620	10.620	-	-	-	-	-
HI	0.313	0.942	0.942	0.942	0.058	0.058	0.884	0.884	0.884	-	-	-	-	-
H2	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-
Mole Frac														
H2O	0.930	0.333	0.333	0.333	0.743	0.743	0.303	0.303	0.303	1.000	1.000	1.000	1.000	1.000
I2	0.031	0.614	0.614	0.614	0.208	0.208	0.643	0.643	0.643	-	-	-	-	-
HI	0.039	0.053	0.053	0.053	0.049	0.049	0.054	0.054	0.054	-	-	-	-	-
H2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-
Total Flow kmol/s	8.01	17.69	17.69	17.69	1.19	1.19	16.51	16.51	16.51	20.85	20.85	20.85	20.85	20.85
Total Flow kg/s	236.9	2,984.5	2,984.5	2,984.5	85.9	85.9	2,898.5	2,898.5	2,898.5	375.7	375.7	375.7	375.7	375.7
Total Flow cum/s	0.171	0.981	0.957	2.717	1.810	1.340	0.908	0.860	0.827	16.981	11.196	0.518	2.314	16.981
Temperature C	153.7	288.3	269.0	260.0	260.0	337.5	260.0	203.2	154.0	256.0	341.6	293.3	256.7	256.0
Pressure bar	38.5	40.09	39.59	26	26	40	26	25.5	25	43.91	78.57	78.07	44.41	43.91
Vapor Frac	0.00	0.00	0.00	0.07	1.00	1.00	0.00	0.00	0.00	1.00	1.00	0.00	0.11	1.00
Liquid Frac	1.00	1.00	1.00	0.93	0.00	0.00	1.00	1.00	1.00	0.00	0.00	1.00	0.89	0.00
Solid Frac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Enthalpy J/kmol	-2.59E+08	-6.27E+07	-6.78E+07	-6.78E+07	-1.59E+08	-1.56E+08	-6.13E+07	-6.90E+07	-7.32E+07	-2.37E+08	-2.35E+08	-2.64E+08	-2.64E+08	-2.37E+08
Enthalpy J/kg	-8.77E+06	-3.71E+05	-4.02E+05	-4.02E+05	-2.19E+06	-2.15E+06	-3.49E+05	-3.93E+05	-4.17E+05	-1.32E+07	-1.30E+07	-1.47E+07	-1.47E+07	-1.32E+07
Enthalpy MW	-2077.5	-1108.4	-1199.2	-1199.2	-188.2	-185.2	-1011.0	-1139.5	-1208.9	-4952.6	-4891.0	-5512.8	-5512.8	-4952.6
Entropy J/kmol-K	-1.26E+05	2.57E+04	1.73E+04	1.69E+04	-1.42E+03	-2.65E+02	1.82E+04	4.21E+03	-5.07E+03	-6.11E+04	-5.99E+04	-1.12E+05	-1.12E+05	-6.11E+04
Entropy J/kg-K	-4.27E+03	1.53E+02	1.02E+02	9.99E+01	-1.96E+01	-3.66E+00	1.03E+02	2.40E+01	-2.89E+01	-3.39E+03	-3.33E+03	-6.23E+03	-6.21E+03	-3.39E+03
Density kmol/cum	46.96	18.04	18.49	6.51	0.66	0.89	18.18	19.20	19.96	1.23	1.86	40.28	9.01	1.23
Density kg/cum	1388.2	3042.7	3119.7	1098.3	47.5	64.2	3192.9	3371.2	3505.3	22.1	33.6	725.7	162.4	22.1
Average Mol Wt	29.56	168.69	168.69	168.69	72.46	72.46	175.61	175.61	175.61	18.02	18.02	18.02	18.02	18.02
Liq Vol 60F cum/hr	0.230	1.171	1.171	1.171	0.048	0.048	1.123	1.123	1.123	0.518	0.518	0.518	0.518	0.518

8.2.3 Process Flow Diagrams

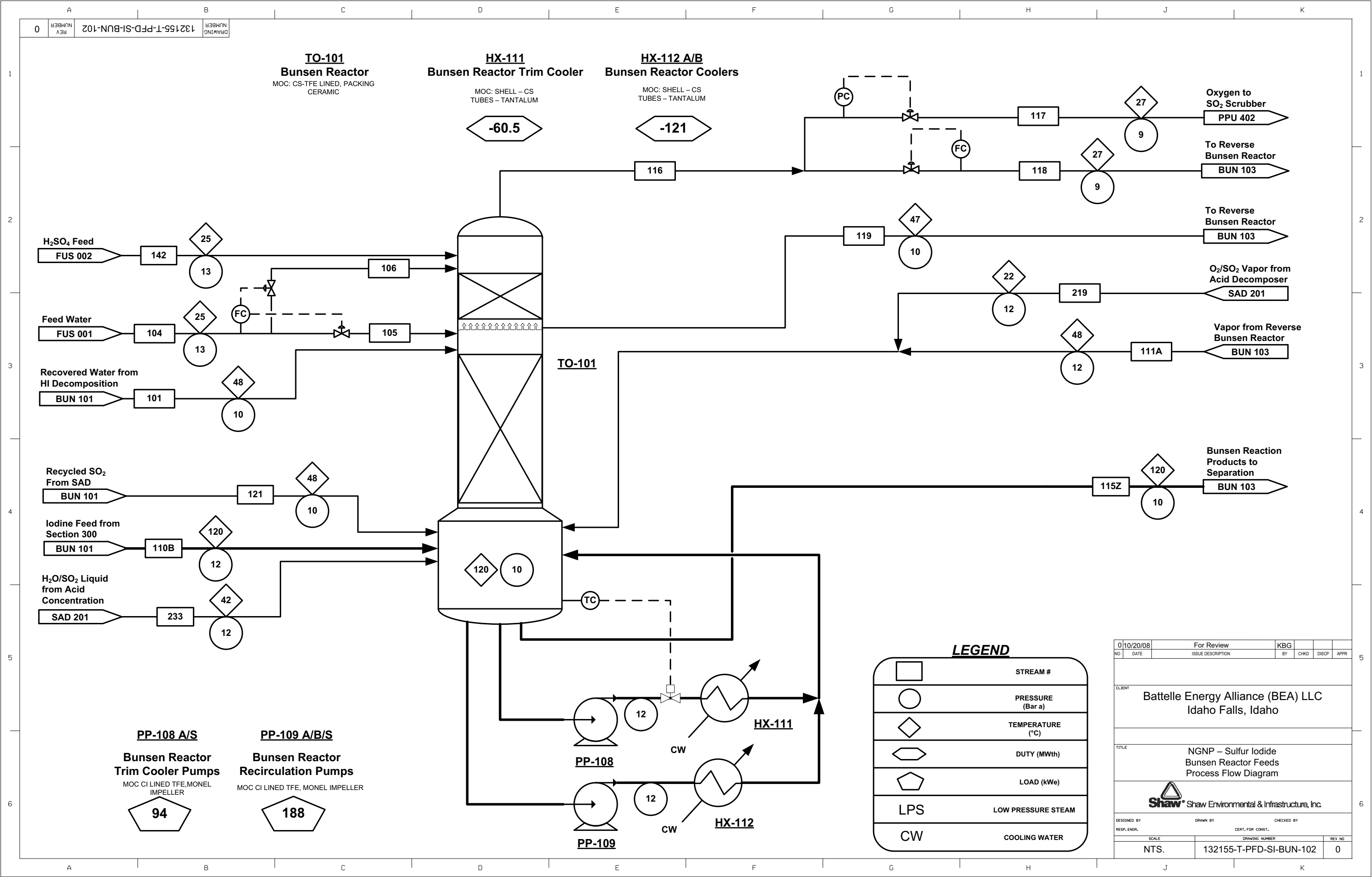


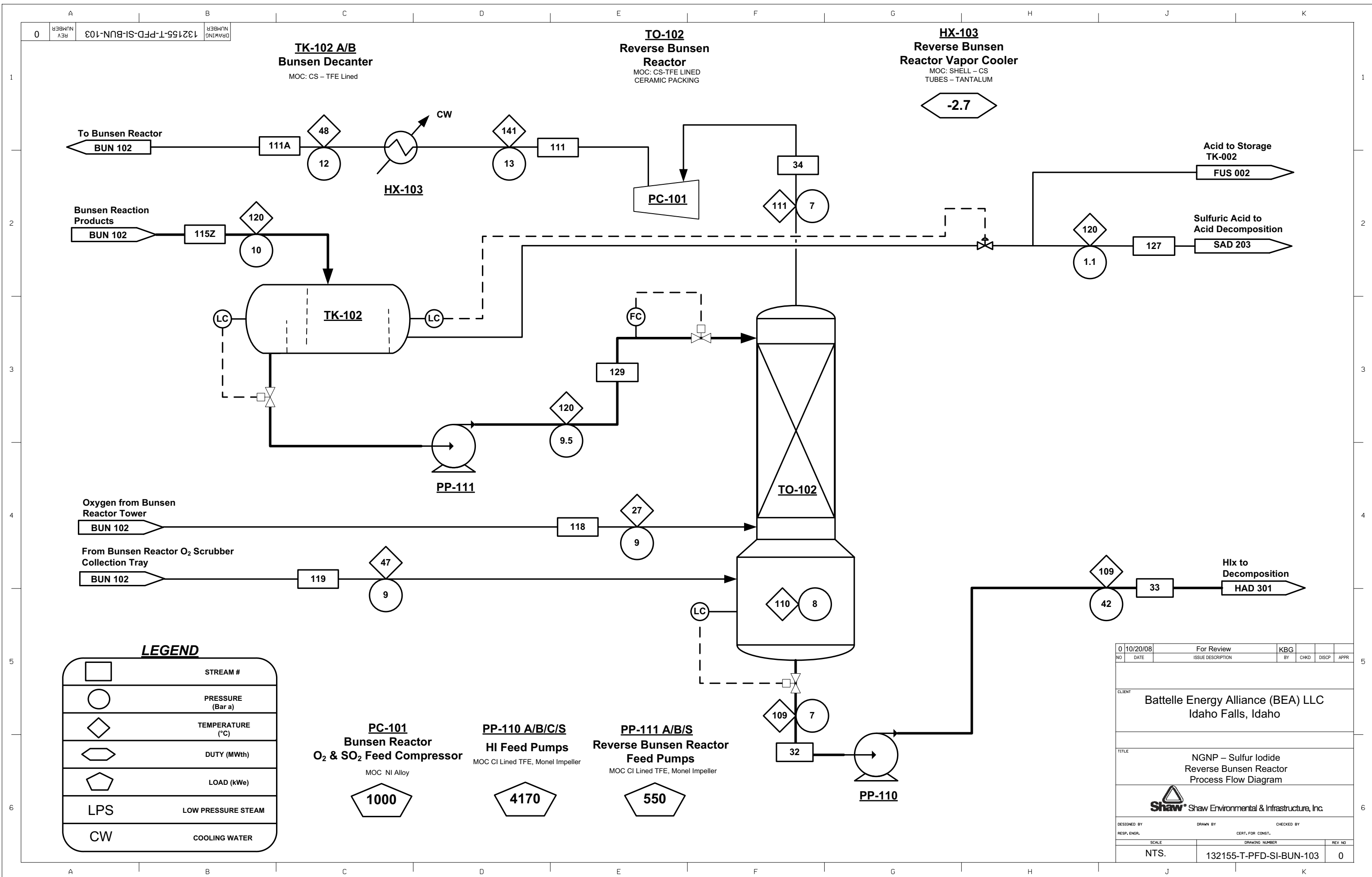
10/20/08	For Review		KBG		
NO.	DATE	ISSUE DESCRIPTION	BY	CHKD	DISCP
CLIENT Battelle Energy Alliance (BEA) LLC Idaho Falls, Idaho					
TITLE NGNP – Sulfur Iodine Water & Waste Water Treatment Process Flow Diagram					
 Shaw Environmental & Infrastructure, Inc.					
DESIGNED BY RESP. ENGR.		DRAWN BY	CHECKED BY		
			CERT. FOR CONST.		
SCALE		DRAWING NUMBER		REV NO	
NTS.		132155-T-PFD-SI-FUS-001		0	

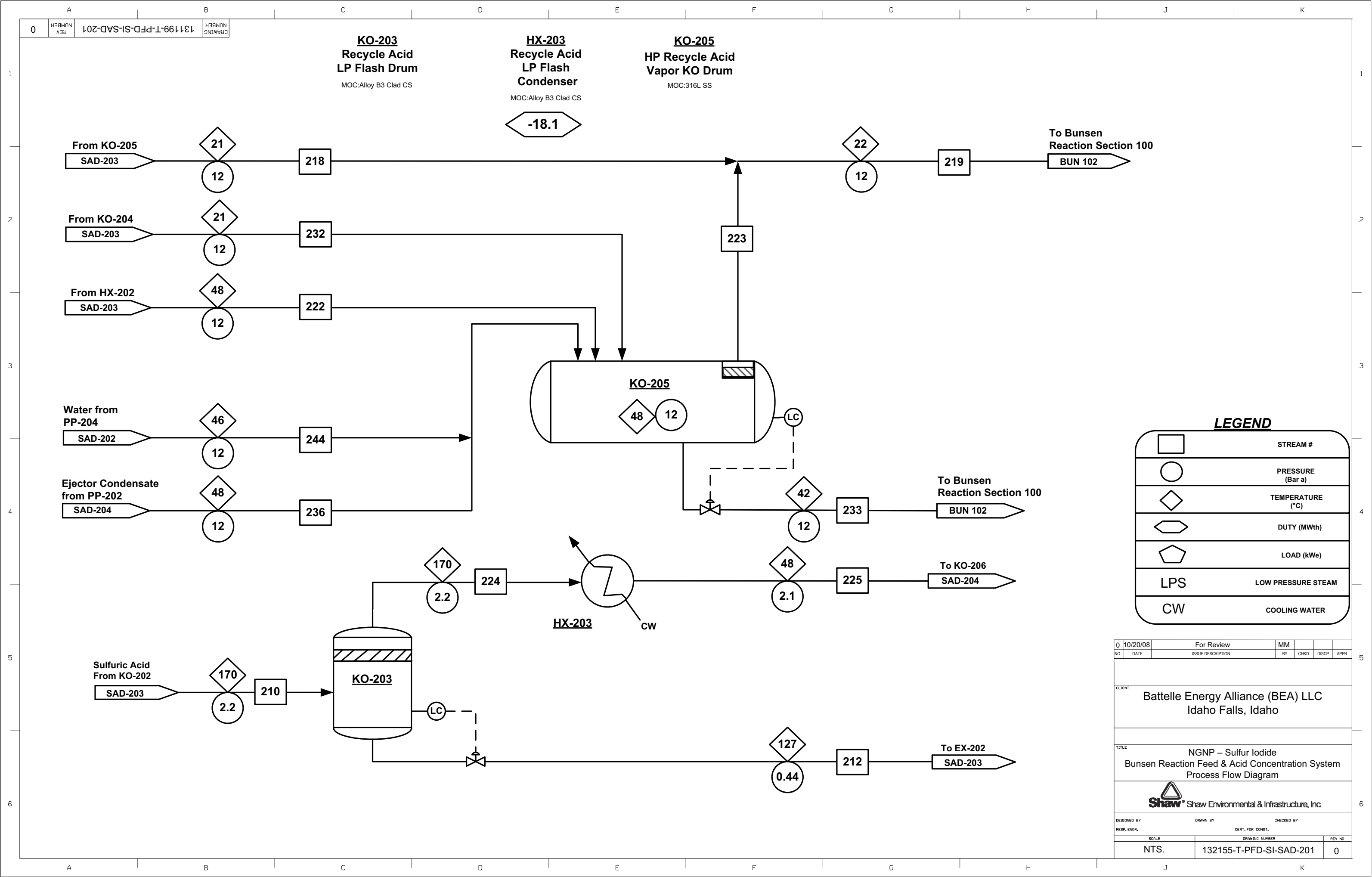


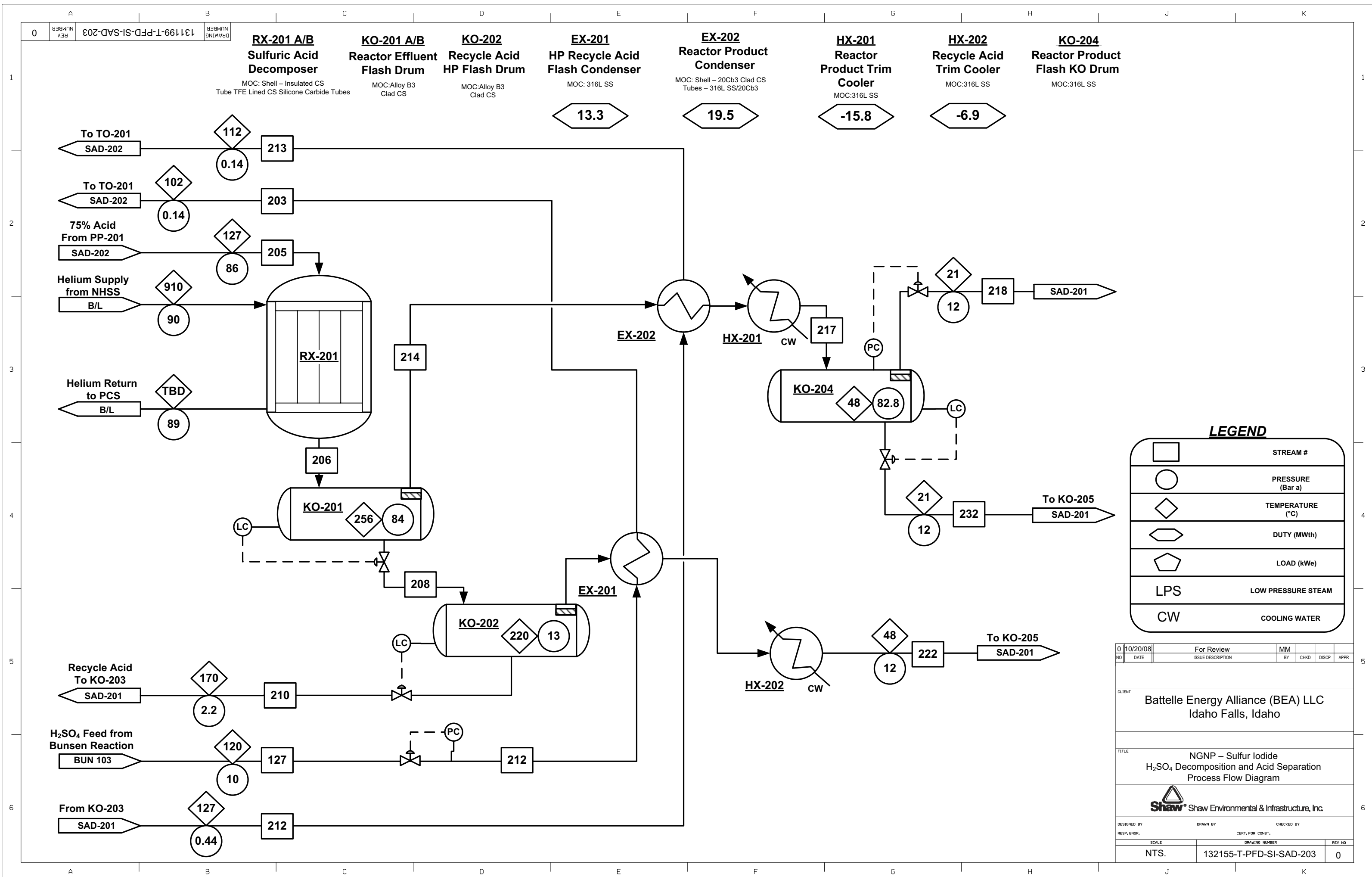


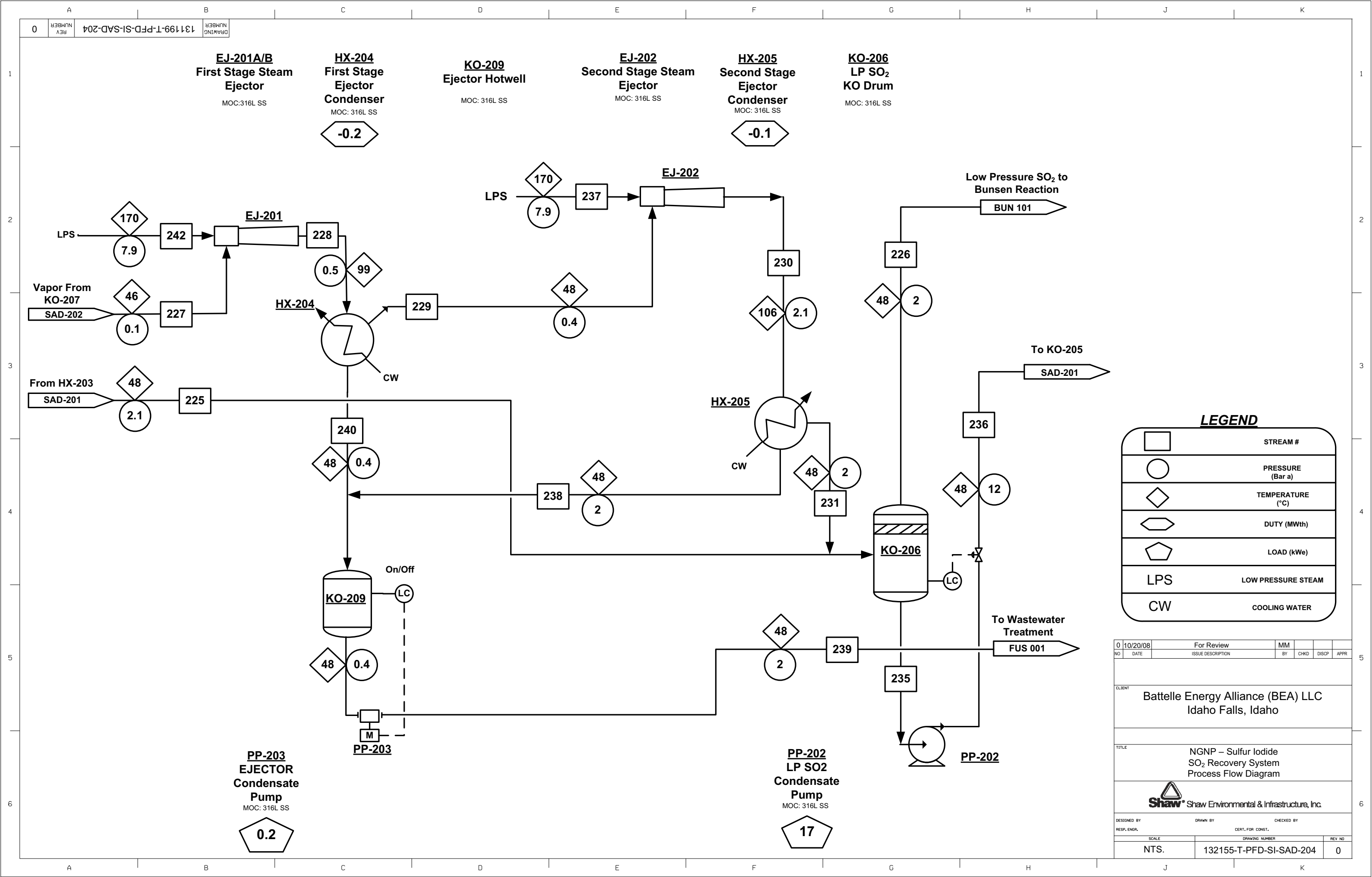
10/20/08		For Review		KBG	
NO	DATE	ISSUE DESCRIPTION		BY	CHKD
				DISCP	APPR
CLIENT Battelle Energy Alliance (BEA) LLC Idaho Falls, Idaho					
TITLE NGNP – Sulfur Iodide Bunsen Reactor Feeds Process Flow Diagram					
 Shaw Engineering & Infrastructure, Inc.					
DESIGNED BY		DRAWN BY		CHECKED BY	
RESP. ENGR.				CERT. FOR CONST.	
SCALE		DRAWING NUMBER			REV NO
NTS.		132155-T-PFD-SI-BUN 101			0



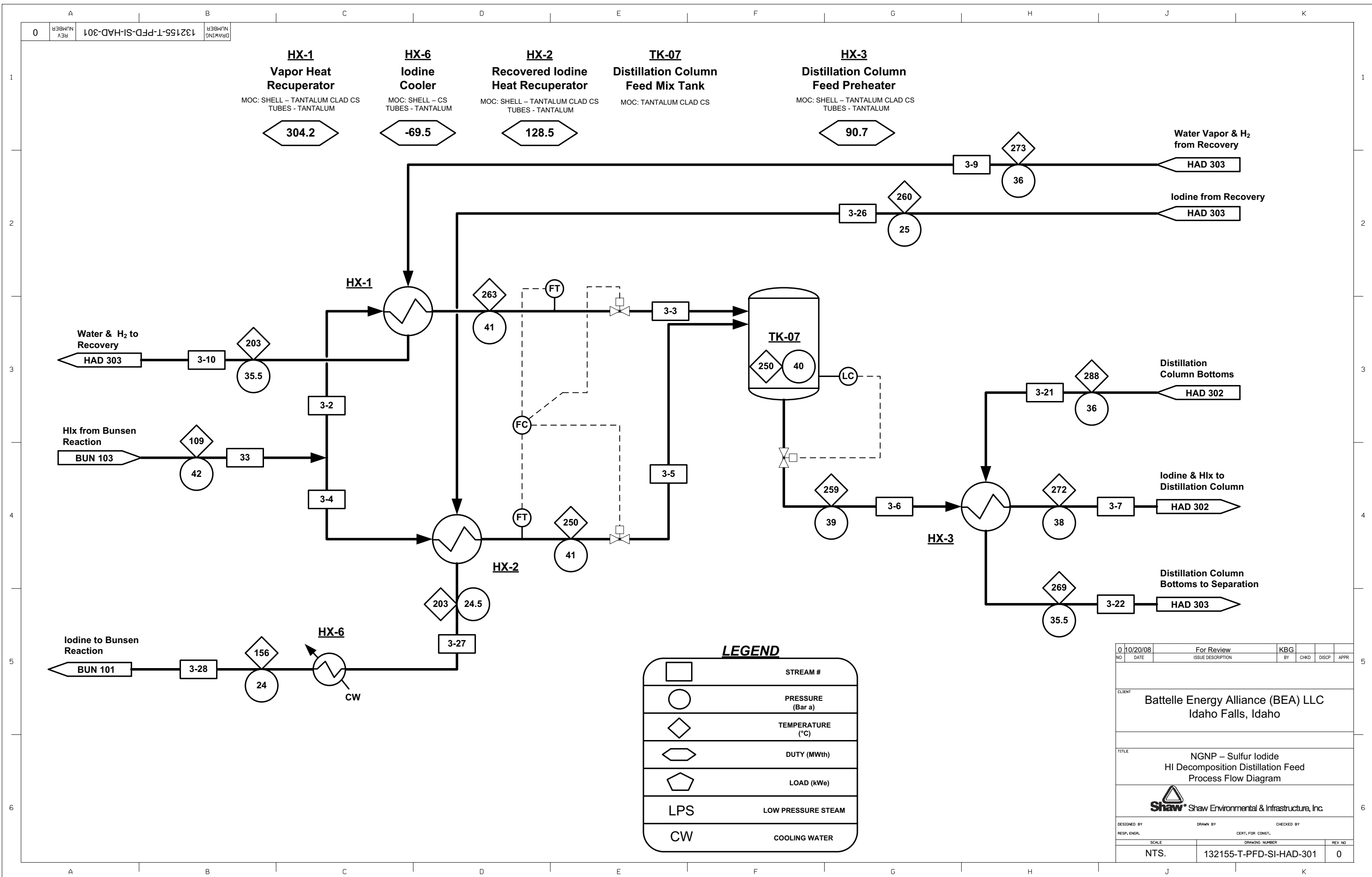


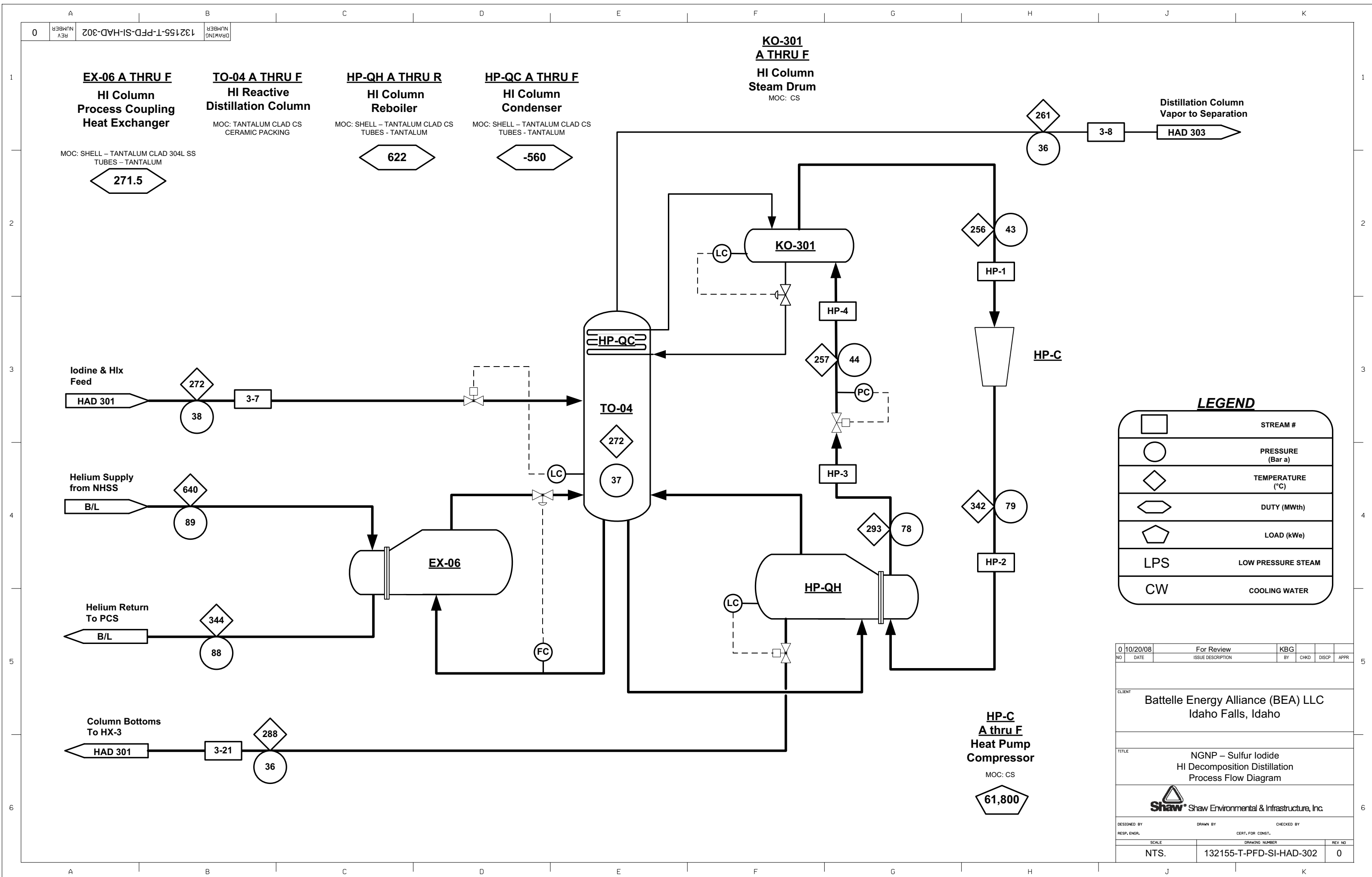


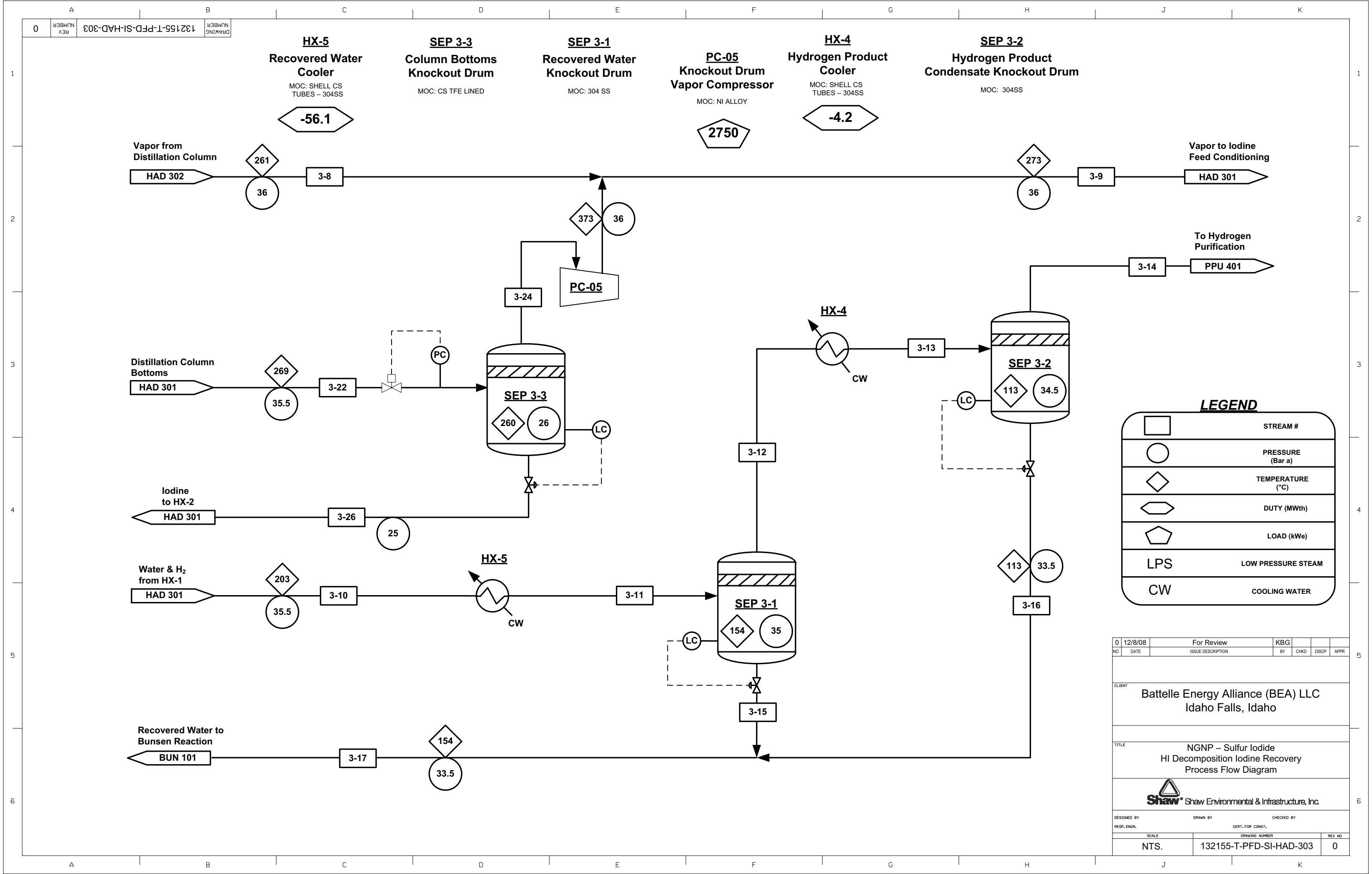


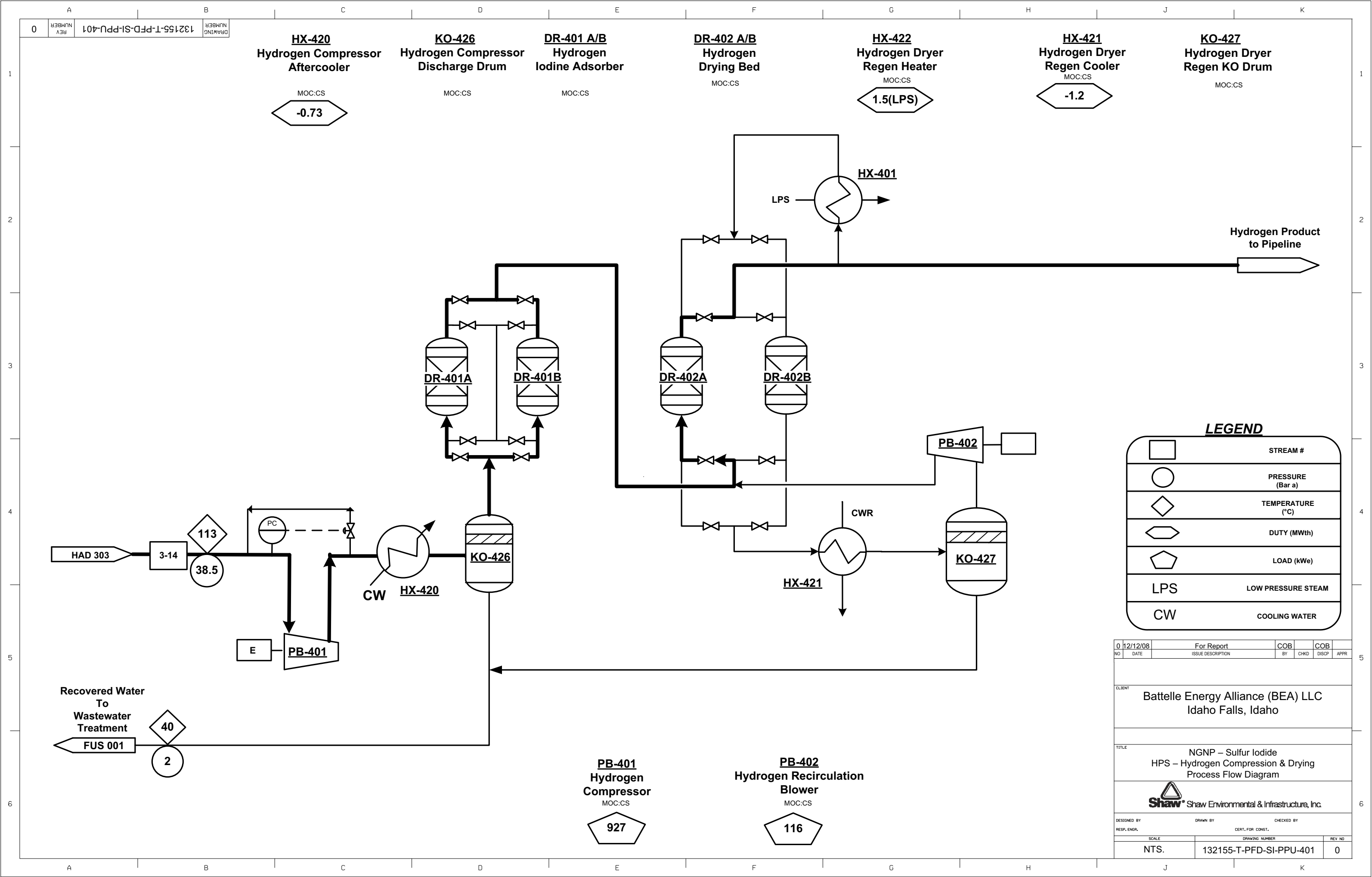


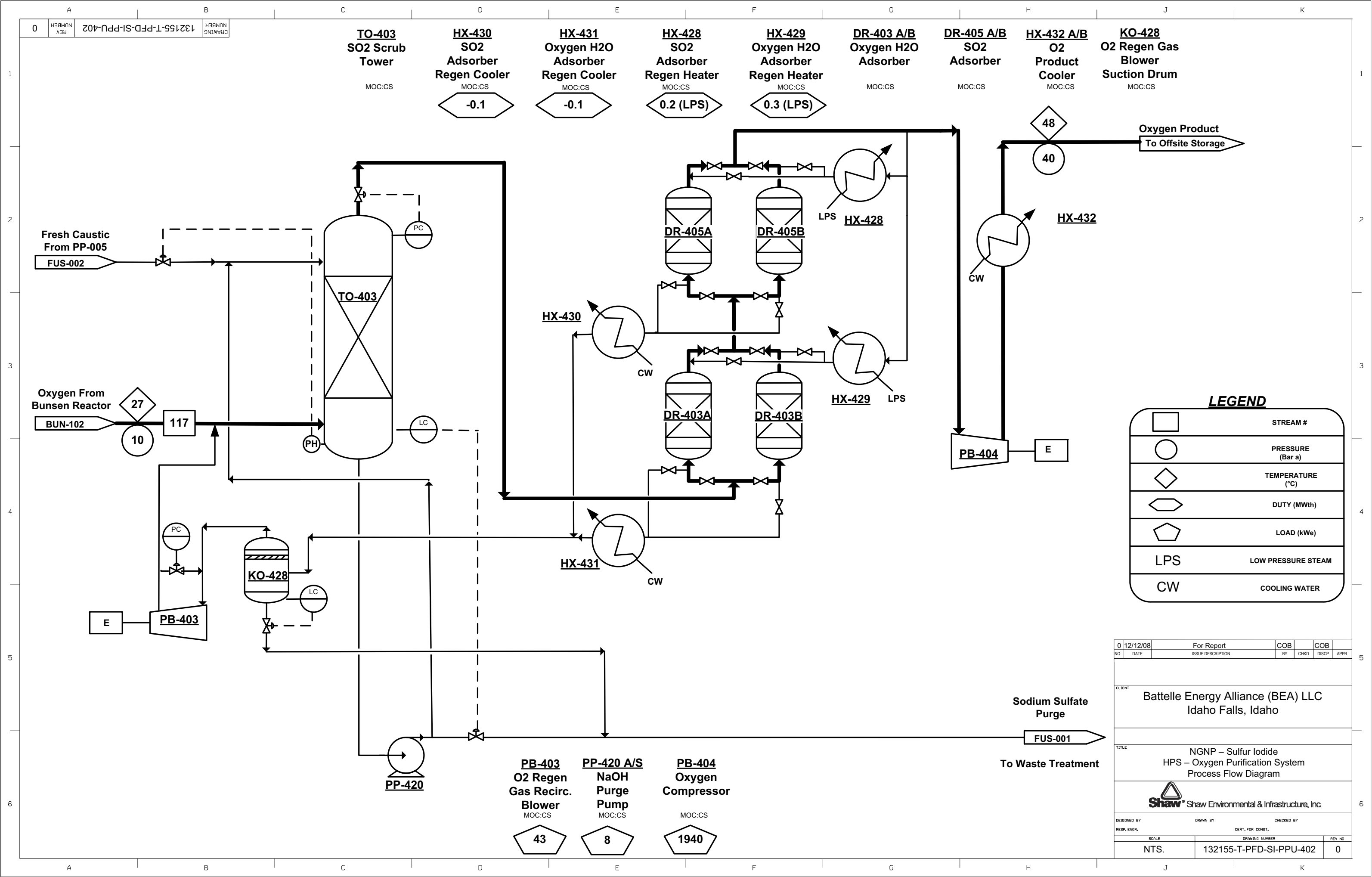
0	10/20/08	For Review	MM			
NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISCP	APPR
CLIENT						
Battelle Energy Alliance (BEA) LLC Idaho Falls, Idaho						
TITLE						
NGNP – Sulfur Iodide SO ₂ Recovery System Process Flow Diagram						
Shaw Environmental & Infrastructure, Inc.						
DESIGNED BY	DRAWN BY		CHECKED BY			
RESP. ENGR.			CERT. FOR CONST.			
SCALE		DRAWING NUMBER				REV NO
NTS.		132155-T-PFD-SI-SAD-204				0



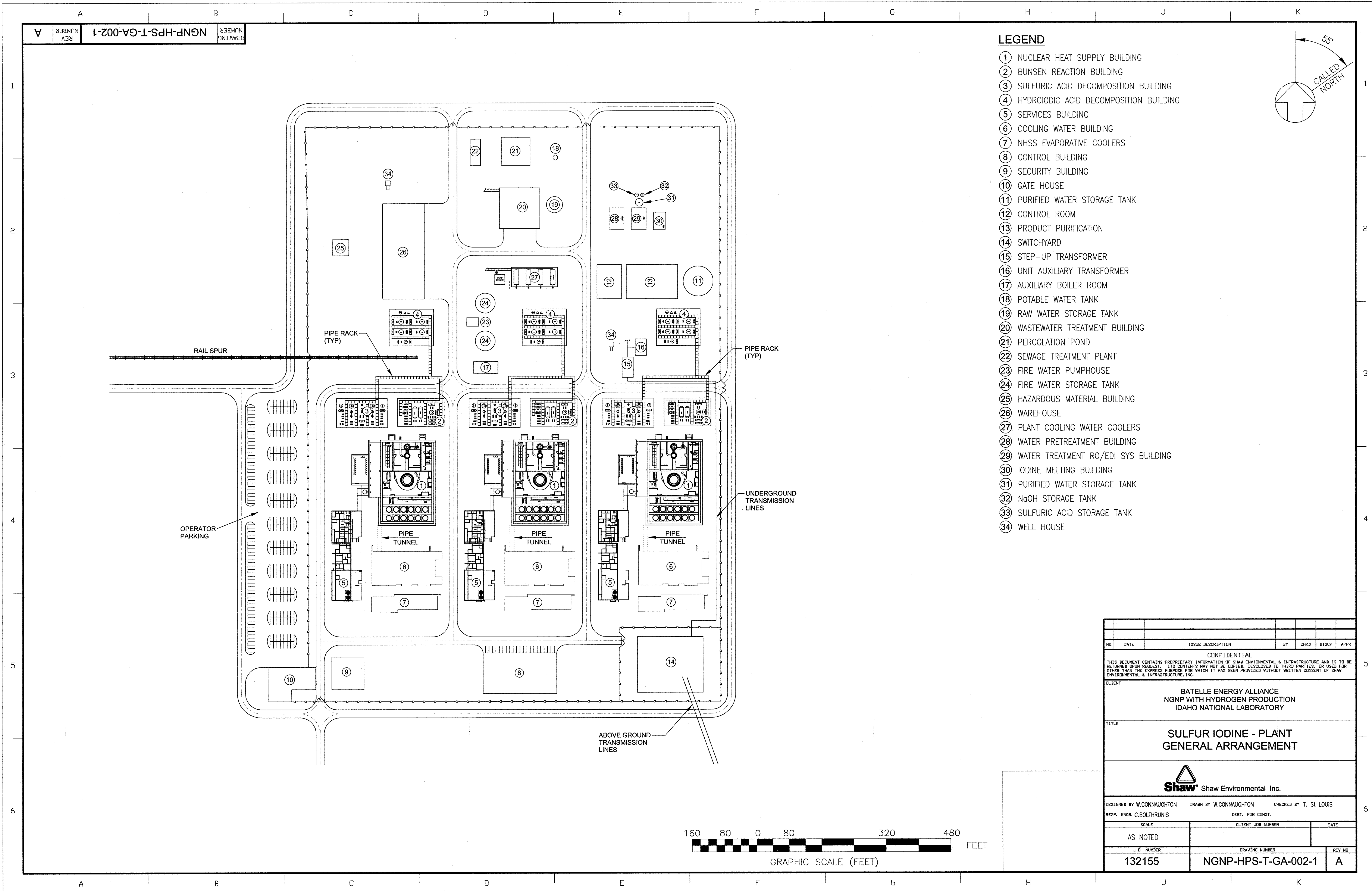








8.2.4 Summary Plot Plan Layout



- LEGEND**
- ① NUCLEAR HEAT SUPPLY BUILDING
 - ② BUNSEN REACTION BUILDING
 - ③ SULFURIC ACID DECOMPOSITION BUILDING
 - ④ HYDROIODIC ACID DECOMPOSITION BUILDING
 - ⑤ SERVICES BUILDING
 - ⑥ COOLING WATER BUILDING
 - ⑦ NHSS EVAPORATIVE COOLERS
 - ⑧ CONTROL BUILDING
 - ⑨ SECURITY BUILDING
 - ⑩ GATE HOUSE
 - ⑪ PURIFIED WATER STORAGE TANK
 - ⑫ CONTROL ROOM
 - ⑬ PRODUCT PURIFICATION
 - ⑭ SWITCHYARD
 - ⑮ STEP-UP TRANSFORMER
 - ⑯ UNIT AUXILIARY TRANSFORMER
 - ⑰ AUXILIARY BOILER ROOM
 - ⑱ POTABLE WATER TANK
 - ⑲ RAW WATER STORAGE TANK
 - ⑳ WASTEWATER TREATMENT BUILDING
 - ㉑ PERCOLATION POND
 - ㉒ SEWAGE TREATMENT PLANT
 - ㉓ FIRE WATER PUMPHOUSE
 - ㉔ FIRE WATER STORAGE TANK
 - ㉕ HAZARDOUS MATERIAL BUILDING
 - ㉖ WAREHOUSE
 - ㉗ PLANT COOLING WATER COOLERS
 - ㉘ WATER PRETREATMENT BUILDING
 - ㉙ WATER TREATMENT RO/EDI SYS BUILDING
 - ㉚ IODINE MELTING BUILDING
 - ㉛ PURIFIED WATER STORAGE TANK
 - ㉜ NaOH STORAGE TANK
 - ㉝ SULFURIC ACID STORAGE TANK
 - ㉞ WELL HOUSE

NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISC	APPR
CONFIDENTIAL						
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CLIENT						
BATELLE ENERGY ALLIANCE NGNP WITH HYDROGEN PRODUCTION IDAHO NATIONAL LABORATORY						
TITLE						
SULFUR IODINE - PLANT GENERAL ARRANGEMENT						
Shaw Environmental Inc.						
DESIGNED BY W.CONNAUGHTON DRAWN BY W.CONNAUGHTON CHECKED BY T. ST LOUIS						
RESP. ENGR. C.BOLTHRUIS CERT. FOR CONST.						
SCALE			CLIENT JOB NUMBER		DATE	
AS NOTED						
J.D. NUMBER			DRAWING NUMBER		REV NO	
132155			NGNP-HPS-T-GA-002-1		A	

8.2.5 Sized Equipment List

Battelle Energy Alliance, LLC (BEA)
Next Generation Nuclear Plant
Idaho Falls, Idaho
Sulfur Iodine Hydrogen
Feed and Utility Supply
Equipment List

Shaw E&I Project No. 132155

ISSUE	DATE	DESCRIPTION	ORIGR	CHK'R	SDE	PEM	INTERDISCIPLINE REVIEW		
							DISCIPLINE	REV'R	DATE
							Process		
							Mechanical		
							Civil/Structural		
							Control Systems		
							Power Systems		
							Piping		
							Material & Corr.		
0	11/18/2008	For Report	COB	COB	COB				
FILE NAME NGNP HPAS SI FUS Equip List 081203.doc			SHEET 1 of 7			DOC.NO. 132155-T-EQL-HPS-SI-FUS-0			

EQUIPMENT LIST - TOWERS										
Client: Battelle Energy Alliance (BEA), LLC					Signature: <i>Charles D. Bottorini</i>					
Unit: NGNP HPS Sulfur Iodine					Location: Idaho Falls, Idaho					
Item No.	Name	Diameter (mm)	Height (mm)	Packing/ Trays	Mechanical Design		Material		PFD	Remarks
					Press (bar g)	Temp (°C)	Shell C.A. (mm)	Packing Trays		
HPS-FUS TO-004	Sulfuric Acid Vent Scrubber	4300	12900	30 m ³ CS Chevron disengaging packing	3.5	130	CS	CS	FUS 002	Spray tower

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 12/3/2008	SHEET 2 of 7	DOC NO 132155-T-EQL-HPS-SI-FUS-0

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA), LLC					Signature: <i>Charles R. Bottarini</i>				
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho				
Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure bar (g)	Temp (°C)			
HPS-FUS KO-001	Sulfuric Acid Degassing Drum	3000	8000	Vertical	3.5	130	CS-TFE Lined	FUS 002	

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 12/3/2008	SHEET 3 of 7	DOC NO 132155-T-EQL-HPS-SI-FUS-0

EQUIPMENT LIST – LOW PRESSURE TANKS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottarini</i>			
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho			
Item No.	Name	Diameter (mm)	Height (mm)	Mechanical Design		Material C.A. (mm)	PFD	Remarks
				Pressure mm WG	Temperature (°C)			
HPS-FUS TK-002	H ₂ SO ₄ Storage Tank	6700	7300	150	130	CS-TFE Lined	FUS 002	
HPS-FUS TK-003	Caustic Storage Tank	12400	11000	150	75	CS	FUS 002	
HPS-FUS TK-001	Purified Water Storage Tank	22500	12800	150	75	316 SS	FUS 001	Included in the cost of GZ-002

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 12/3/2008	SHEET 4 of 7	DOC NO 132155-T-EQL-HPS-SI-FUS-0

EQUIPMENT LIST – PUMPS

Client: Battelle Energy Alliance (BEA) LLC

Signature: *Charles R. Bottarini*

Unit: NGNP Hybrid Sulfur

Location: Idaho Falls, Idaho

Item No.	Name	Type	Rated Flow (m ³ /h)	Differential Pressure (bar)	Motor kW	Material		PFD	Remarks
						Casing	Impeller		
HPS-FUS PP-002 A /S	H ₂ SO ₄ Transfer Pump	ANSI Centrif.	18	0.3	0.55	20CB3	20CB3	FUS-101	Static Head allowed 15m
HPS-FUS PD-003A/S	H ₂ SO ₄ Feed Pump	Rotary Gear	1.7	20	2.2	20CB3	20CB3	FUS-101	Static Head allowed 15m
HPS-FUS PP-004 A/B/S	NaOH Transfer Pump	ANSI Centrif.	18	0.3	0.55	CS	CS	FUS-101	Static Head allowed 15m
HPS-FUS PD-005 A/S	NaOH Solution Supply Pump	Rotary Gear	9	21.3	11	CS	CS	FUS-101	Static Head allowed 15m
HPS-FUS PP- 001A/B/C/S	Feed Water Pump	Multi-stg. Centrif.	26	20.8	37	316 SS	316 SS	FUS 001	Static Head allowed 15m

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 12/3/2008	SHEET 5 of 7	DOC NO 132155-T-EQL-HPS-SI-FUS-0

EQUIPMENT LIST – MISCELLANEOUS

Client: Battelle Energy Alliance (BEA) LLC			Signature: <i>Charles R. Bottarini</i>	
Unit: NGNP Hybrid Sulfur			Location: Idaho Falls, Idaho	
Item No.	Name	Material	PFD	Duty - Description - Remarks
HYS-FUS GZ-001	Water Pretreatment Filter/Softener System	Various	FUS 001	Water treatment multimedia and zeolite softener system. System consists of two trains, each train having a capacity of 80 m ³ /hr (360 gpm product). Vessels are plasite lined carbon steel. System consists of skid mounted feed pumps (2 x 100%), skid mounted backwash pumps (2 x 100%), skid mounted regeneration pumps (2 x 100%), two multi-media filter vessels (10 ft diameter each), two zeolite vessels (8 ft diameter each), and one salt dissolving tank. Total equipment cost: \$1 Million for equipment described above plus PLC controls. Estimated from quote from Aquatech via email dated 10/3/08. Building/foundation costs included in GZ-02.
HYS-FUS GZ-002	Water Treatment RO/EDI System	Various	FUS 001	Reverse Osmosis, Electric Deionization System, 4 x 120 gpm RO/EDI trains. System capacity 360 gpm (product), with 120 gpm installed spare capacity. RO/EDI equipment pricing based on Jan 2008 estimate for Duke Buck combined cycle plant. 3,300 m ³ purified water tank, 48 hrs storage, \$528/m ³ installed cost. Water Purification Building, 550 m ² , \$3122/m ² installed. Total Installed System Cost: \$14 Million (including tank, building and foundations and electrical)
HYS-WTD GZ-003	Waste Water Treatment System	Various	FUS 001	Corrugated inclined plate oil/water separator, 200 gpm capacity. Equipment includes tank, separation media, pumps and control panel. Neutralization, physical treatment system with Mixing tank, piping valves, metering pumps for pH neutralization system. Allowance also for potential physical/chemical treatment, if required. Total Installed System Cost: \$2.5 Million (allowance)
SI-WTD- GZ-006	Iodine Feedstock Preparation System	Various	Not shown	Iodine handling and iodine crystal melting system for processing of iodine feedstock. Total Installed System Cost: \$10 Million (allowance)

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 12/3/2008	SHEET 6 of 7	DOC NO 132155-T-EQL-HPS-SI-FUS-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC

Signature: *Charles R. Bottarini*

Unit: NGNP Hybrid Sulfur

Location: Idaho Falls, Idaho

Item No.	Name	Area (m ²)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-FUS HX-004	H ₂ SO ₄ Storage Tank Heater/Cooler	1050	CS 3 150	20CB3 30 90	BEU	FUS 002	
HPS-FUS HX-005	NaOH Tank Heater/Cooler	2	CS 3 150	CS 23 90	Double Pipe	FUS 002	

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 12/3/2008	SHEET 7 of 7	DOC NO 132155-T-EQL-HPS-SI-FUS-0

Battelle Energy Alliance, LLC (BEA)
Next Generation Nuclear Plant
Idaho Falls, Idaho
Sulfur Iodine
Bunsen Reaction
Equipment List

Shaw E&I Project No. 132155

ISSUE	DATE	DESCRIPTION	ORIGR	CHK'R	SDE	PEM	INTERDISCIPLINE REVIEW		
							DISCIPLINE	REV'R	DATE
							Process		
							Mechanical		
							Civil/Structural		
							Control Systems		
							Power Systems		
							Piping		
							Material & Corr.		
0	12/3/2008	For Estimate	KBG						
FILE NAME			SHEET			DOC.NO.			
NGNP HPAS SI BUN Equipment List 081210 Rev 0.doc			1 of 6			132155-T-EQL-HPS-SI-BUN-0			

EQUIPMENT LIST - TOWERS										
Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles D. Bottarini</i>					
Unit: SULFUR IODINE					Location: Idaho Falls, Idaho					
Item No.	Name	Diameter (mm)	Height (mm)	Packing/ Trays	Mechanical Design		Material		PFD	Remarks
					Press (bar g)	Temp (°C)	Shell C.A. (mm)	Packing Trays		
HPS-BUN TO-101	Bunsen Reactor	Top: 2,000 Bottom: 6,000	Top: 17,400 Bottom: 3,900	Packing	10	120	TFE-Lined CS	Koch Flexiramic 88 or equal packing	BUN 102	9 stages. 30 second detention time in bottom section.
HPS-BUN TO-102	Reverse Bunsen Reactor	Top: 1,700 Bottom: 3,400	Top: 6,900 Bottom: 3,200	Packing	8	110	TFE-Lined CS	Koch Flexiramic 88 or equal packing.	BUN 103	5 stages. 30 second detention time in bottom section.

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 12/3/2008	SHEET 2 of 6	DOC NO 132155-T-EQL-HPS-SI-BUN-0

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA) LLC

Signature: *Charles D. Bottarini*

Unit: SULFUR IODINE

Location: Idaho Falls, Idaho

Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temp (°C)			
HPS-BUN TK-102 A/B	Bunsen Decanter	5,500	15,200	Horizontal	10	150	TFE Lined CS	BUN 103	Assumes 5 minute detention time, 3 minute detention time in overflow sumps and additional 20% tank volume for vapor space.

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 12/3/2008	SHEET 3 of 6	DOC NO 132155-T-EQL-HPS-SI-BUN-0

EQUIPMENT LIST – PUMPS

Client: Battelle Energy Alliance (BEA) LLC						Signature: <i>Charles D. Bottarini</i>			
Unit: SULFUR IODINE						Location: Idaho Falls, Idaho CO			
Item No.	Name	Type	Rated Flow (m ³ /h)	Differential Pressure (bar)	Motor kW	Material		PFD	Remarks
						Casing	Impeller		
HPS-BUN PP-108 A/S	Bunsen Reactor Trim Cooler Pumps	Centrif.	1,800	1.8	150	TFE Lined Cast Iron	Monel	BUN 102	One operating and one spare pump.
HPS-BUN PP-109 A/B/S	Bunsen Reactor Recirculation Pumps	Centrif.	1,800	1.8	150	TFE Lined Cast Iron	Monel	BUN 102	One operating pump per Bunsen reactor cooler and one spare. 2 coolers total.
HPS-BUN PP-110 A/B/C/S	HI Feed Pumps	Multi-stage Centrif.	1,380	42.8	1870	TFE Lined Cast Iron	Monel	BUN 103	Three pumps operating, one spare.
HPS-BUN PP-111 A/B/ S1	Reverse Bunsen Reactor Feed Pumps	Multi-stage Centrif.	2,060	5.6	372	TFE Lined Cast Iron	Monel	BUN 103	One pump for each decant tank, one common spare pump. Total of 3 pumps.
HPS-BUN PP-112 A/B/C	SAD Feed Pumps	Multi-stage Centrif.	730	89	2240	20Cb3	20Cb3	BUN 103	Two pumps operating, one spare. Static Head allowed 20 m

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 12/3/2008	SHEET 4 of 6	DOC NO 132155-T-EQL-HPS-SI-BUN-0

EQUIPMENT LIST – COMPRESSORS / BLOWERS / VACUUM PUMPS

Client: Battelle Energy Alliance (BEA) LLC						Signature: <i>Charles D. Bottarini</i>				
Unit: SULFUR IODINE						Location: Idaho Falls, Idaho				
Item No.	Name	Type	Capacity (Am ³ /h)	Suction Pressure (bar a)	Differential Pressure (bar)	Driver		Material C.A.(mm)	PFD	Remarks
						Type	Rated Power (kW)			
HPS-BUN PC-102	Low Pressure SO ₂ Feed Compressor	Reciprocating	440	2	8	Electric	90	316L SS	BUN 101	
SI-BUN PC-101	Bunsen Reactor O ₂ and SO ₂ Feed Compressor	Centrifugal	7,060	7	6	Electric	1,120	NI Alloy	BUN 103	2 Stage Compressor

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 12/3/2008	SHEET 5 of 6	DOC NO 132155-T-EQL-HPS-SI-BUN-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC				Signature: <i>Charles D. Bottarini</i>			
Unit: SULFUR IODINE				Location: Idaho Falls, Idaho			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-BUN HX-101	Recovered Water Cooler	155	CS 29 70	316L SS 36 170	BEU	BUN 101	Cooling Duty approximately 16 MW
HPS-BUN HX-102	Iodine Feed Cooler	530	CS 10 70	Tantalum 13 180	BEU	BUN 101	Cooling Duty approximately 67.4 MW.
HPS-BUN HX-104	SAD Recycled SO ₂ Cooler	5	CS 10 70	316L SS 10 230	BEU	BUN 101	Cooling Duty approximately 0.082 MW.
HPS-BUN HX-111	Bunsen Reactor Trim Cooler	820	CS 10 70	Tantalum 12 130	BEU	BUN 102	One heat exchanger in parallel with HX-12 heat exchangers.
HPS-BUN HX-112 A/B	Bunsen Reactor Coolers	820	CS 10 70	Tantalum 12 130	BEU	BUN 102	Two heat exchangers in parallel.
HPS-BUN HX-103	Reverse Bunsen Reactor Vapor Cooler	95	CS 10 70	Tantalum 13 170	BEU	BUN 103	Cooling Duty approximately 2.7 MW.

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 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 12/3/2008	SHEET 6 of 6	DOC NO 132155-T-EQL-HPS-SI-BUN-0

Battelle Energy Alliance, LLC (BEA)

Next Generation Nuclear Plant

Idaho Falls, Idaho

Sulfur Iodine Hydrogen

Sulfuric Acid Decomposition

Equipment List

Shaw E&I Project No. 132155

ISSUE	DATE	DESCRIPTION	ORIGR	CHK'R	SDE	PEM	INTERDISCIPLINE REVIEW		
							DISCIPLINE	REV'R	DATE
							Process		
							Mechanical		
							Civil/Structural		
							Control Systems		
							Power Systems		
							Piping		
							Material & Corr.		
0	12/2/2008	For Estimate	COB	TS	COB	COB			
FILE NAME NGNP HPAS SI SAD Equipment List 081202.doc			SHEET 1 of 8			DOC.NO. 132155-T-EQL-HPS-SI-SAD-0			

EQUIPMENT LIST - TOWERS										
Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottarini</i>					
Unit: NGNP Sulfur Iodine					Location: Idaho Falls, Idaho					
Item No.	Name	Diameter (mm)	Height (mm)	Packing/ Trays	Mechanical Design		Material		PFD	Remarks
					Press (bar g)	Temp (°C)	Shell C.A. (mm)	Packing Trays		
HPS-SAD TO-201 A/B	Vacuum Column	Top: 5900 Bottom: 3700	14000	Packing	3.5 /FV	155	Alloy B3 Clad CS	Ceramic	SAD- 202	Koch Flexiramic 88 or equal packing

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 12/2/2008	SHEET 2 of 8	DOC NO 132155-T-EQL-HPS-SI-SAD-0

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottorini</i>				
Unit: NGNP Sulfur Iodine					Location: Idaho Falls, Idaho				
Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temp (°C)			
HPS-SAD RX-201 A/B	Sulfuric Acid Decomposer	3100	10300	Vertical	95	300	He (Shell) side: Internally insulated CS, Process side (Tube side) TFE lined CS, Silicon Carbide tubes	SAD-203	Similar to a large, vertical, tubular heat exchanger. Alloy B3 piping on sulfuric acid side; Incoloy 800H piping on the Helium side. Hemispherical heads, cold wall design. SiC bayonet tubes, including internal tube inserts 2 Units at \$11.9 million for two units, not installed
HPS-SAD KO-201A/B	Reactor Effluent Flash Drum	2400	7200	Vertical	92	285	Alloy B3 Clad CS	SAD-203	
HPS-SAD KO-202	Recycle Acid HP Flash Drum	2600	7800	Vertical	14	250	Alloy B3 Clad CS	SAD-203	
HPS-SAD KO-203	Recycle Acid LP Flash Drum	2300	6900	Vertical	3.5 /FV	200	Alloy B3 Clad CS	SAD-201	
HPS-SAD KO-204	Reactor Product Flash KO Drum	1600	4500	Vertical	92	80	316L SS	SAD-203	
HPS-SAD KO-205	HP Recycle Acid Vapor KO Drum	2000	6000	Horizontal	14	80	316L SS	SAD-201	
HPS-SAD KO-206	LP SO ₂ KO Drum	1100	3300	Vertical	3.5/FV	80	316L SS	SAD-204	

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 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 12/2/2008	SHEET 3 of 8	DOC NO 132155-T-EQL-HPS-SI-SAD-0

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottorini</i>				
Unit: NGNP Sulfur Iodine					Location: Idaho Falls, Idaho				
Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temp (°C)			
HPS-SAD KO-207 A/B	Vacuum Column Reflux Drum	1300	3900	Horizontal	3.5/FV	80	316L SS	SAD-202	One drum per TO-01 column train; 2 trains
HPS-SAD KO-209	Ejector Hotwell	1000	2000	Horizontal	3.5/ FV	100	316L SS	SAD-204	

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 12/2/2008	SHEET 4 of 8	DOC NO 132155-T-EQL-HPS-SI-SAD-0

EQUIPMENT LIST – PUMPS

Client: Battelle Energy Alliance (BEA) LLC						Signature: <i>Charles R. Bottorini</i>			
Unit: NGNP Sulfur Iodine						Location: Idaho Falls, Idaho			
Item No.	Name	Type	Rated Flow (m ³ /h)	Differential Pressure (bar)	Motor KW	Material		PFD	Remarks
						Casing	Impeller		
HPS-SAD PP-201 A/B/S	Reactor Feed Pump	Multi-stage Centrif.	281	87	1100	Alloy B3	Alloy B3	SAD-202	Static Head allowed 20 m
HPS-SAD PP-202A/S	LP SO ₂ Condensate Pump	Multi-stage Centrif	31	12	22	316L SS	316L SS	SAD-204	Static Head allowed 15 m
HPS-SAD PP-203A/S	Ejector Condensate Pump	Dia- phragm	0.5	2	2.2	316L SS	316L SS	SAD-204	Static Head allowed 15 m
HPS-SAD PP-204 A/B/S	Vacuum Column Reflux/Overhead Product Pump	Multi- stage Centrif.	81	13	55	316L SS	316L SS	SAD-202	Static Head allowed 30 m

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 12/2/2008	SHEET 5 of 8	DOC NO 132155-T-EQL-HPS-SI-SAD-0

EQUIPMENT LIST – COMPRESSORS / BLOWERS / VACUUM PUMPS

Client: Battelle Energy Alliance (BEA) LLC						Signature: <i>Charles R. Bottarini</i>				
Unit: NGNP Sulfur Iodine						Location: Idaho Falls, Idaho				
Item No.	Name	Type	Capacity (Am ³ /h)	Suction Pressure (bar a)	Differential Pressure (bar)	Driver		Material C.A.(mm)	PFD	Remarks
						Type	Rated Power (kW)			
HPS-SAD EJ-201A/B	First Stage Vacuum Column Ejector	Steam Ejector	1000	0.11	0.5	-	-	316L SS	SAD-204	
HPS-SAD EJ-202	Second Stage Vacuum Column Ejector	Steam Ejector	50	0.3	1.8	-	-	316L SS	SAD-204	

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 12/2/2008	SHEET 6 of 8	DOC NO 132155-T-EQL-HPS-SI-SAD-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC				Signature: <i>Charles R. Bottorini</i>			
Unit: NGNP Sulfur Iodine				Location: Idaho Falls, Idaho			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-SAD EX-201	HP Recycle Acid Flash Condenser	155	316 L SS 14 250	316L SS 10 50	BEU	SAD-203	
HPS-SAD EX-202	Reactor Product Condenser	215	20Cb3b Clad CS 63 155	316L ss/ 20CB3 91 285	DEU	SAD-203	
HPS-SAD HX-201	Reactor Product Trim Cooler	225	316 L SS 91 260	316 L SS 63 80	BEU	SAD-203	
HPS-SAD HX-202	Recycle Acid Trim Cooler	105	B3/CS 14 250	B3/CS 10 80	BEU	SAD-203	
HPS-SAD HX-204	EJ-201 Discharge Condenser	5	316L SS 7/ FV 130	316L SS 10 100	BEU	SAD-204	
HPS-SAD HX-205	EJ-202 Discharge Condenser	5	316L SS 7/FV 130	316L SS 10 100	BEU	SAD-204	

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EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC				Signature: <i>Charles R. Bottarini</i>			
Unit: NGNP Sulfur Iodine				Location: Idaho Falls, Idaho			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-SAD TO-201 HX1 A/B	Vacuum Column Condenser	2830	316L SS 3.5/FV 126	CS/ 316L SS 3.5/FV 100	BXM	SAD-202	One condenser shell per TO-201 column train; area shown is for one shell
HPS-SAD TO-201 HX2 A/B	Vacuum Column Reboiler	345	CS 7 170	Alloy B3 5/FV 155	BEM	SAD-202	One reboiler per TO-201 column; area shown is for one shell

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Battelle Energy Alliance, LLC (BEA)
Next Generation Nuclear Plant
Idaho Falls, Idaho
Sulfur Iodine
Hydroiodic Acid Decomposition
Equipment List

Shaw E&I Project No. 132155

ISSUE	DATE	DESCRIPTION	ORIGR	CHK'R	SDE	PEM	INTERDISCIPLINE REVIEW		
							DISCIPLINE	REV'R	DATE
							Process		
							Mechanical		
							Civil/Structural		
							Control Systems		
							Power Systems		
							Piping		
							Material & Corr.		
0	12/10/2008	For Estimate							
FILE NAME 2008Dec03_SI_HI_Decomposition_Equipment ListRevA.doc			SHEET 1 of 6			DOC.NO. 132155-T-EQL-HPS-SI-HAD-0			

EQUIPMENT LIST - TOWERS										
Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles D. Bottarini</i>					
Unit: SULFUR IODINE					Location: Idaho Falls, Idaho					
Item No.	Name	Diameter (mm)	Height (mm)	Packing/ Trays	Mechanical Design		Material		PFD	Remarks
					Press (bar g)	Temp (°C)	Shell C.A. (mm)	Packing Trays		
HPS-HAD TO-04 A thru F	Reactive Distillation Column	Top: 5,300 Bottom: 5,300	Top: 29,500 Bottom: 3,000	Koch Flexiramic 88 or equal packing,	40	320	Tantalum Clad - CS	Ceramic	HAD- 302	Internal condenser: see QP-QC

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles D. Bottarini</i>				
Unit: SULFUR IODINE					Location: Idaho Falls, Idaho				
Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temp (°C)			
HPS-HAD TK-07	Distillation Column Feed Mix Tank	4,000	11,400	Horizontal	43	280	Tantalum Clad CS	HAD 301	145 m ³ volume, for 2 minute mix time
HPS-HAD KO-301 A thru F	HI Column Steam Drum	2,800	8,400	Horizontal	48	285	CS	HAD 302	
HPS-HAD SEP 3-1	Recovered Water Knockout Drum	1,700	5,100	Vertical	38	205	304SS	HAD 303	
HPS-HAD SEP 3-2	Hydrogen Product Condensate Knockout Drum	2,000	6,300	Vertical	37	145	304SS	HAD 303	
HPS-HAD SEP 3-3	Column Bottoms Knockout Drum	3,800	11,400	Vertical	28	290	Tantalum clad CS	HAD 303	

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EQUIPMENT LIST – COMPRESSORS / BLOWERS / VACUUM PUMPS

Client: Battelle Energy Alliance (BEA) LLC						Signature: <i>Charles D. Bottarini</i>				
Unit: SULFUR IODINE						Location: Idaho Falls, Idaho				
Item No.	Name	Type	Capacity (Am ³ /h)	Suction Pressure (bar a)	Differential Pressure (bar)	Driver		Material C.A.(mm)	PFD	Remarks
						Type	Rated Power (kW)			
HPS-HAD HP-C A thru F	Heat Pump Compressor	Axial Multistage	10,200	44	35	Electric	11,300	CS	HAD 302	Divide into as many parallel units as necessary to meet the duty
SI-HAD PC-05	Knockout Drum Vapor Compressor	Rotary Screw	6500	28	42	Electric	3000	316SS	HAD-302	

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EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles D. Bottarini</i>		
Unit: SULFUR IODINE					Location: Idaho Falls, Idaho		
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-HAD HX-6	Iodine Cooler	370	CS 21 100	Tantalum 25 230	BEU	HAD 301	
HPS-HAD HX-1	Vapor Heat Recuperator	4,050	Tantalum Clad-CS 39 300	Tantalum 45 290	BEU	HAD 301	
HPS-HAD HX-2	Recovered Iodine Heat Recuperator	2,570	Tantalum Clad-CS 38 290	Tantalum 46 275	BEU	HAD 301	
HPS-HAD HX-3	HI Distillation Column Feed Preheater	5,330	Tantalum Clad-CS 39 315	Tantalum 42 300	BEU	HAD 301	
HPS-HAD EX-06 A thru F	HI Column Process Coupling Heat Exchanger	375	Tantalum Clad 304LSS 88 300	Tantalum 97 670	NKU	HAD 302	One PCHX shell per column. Area shown is for one shell
HPS-HAD QP-QH A thru R	HI Column Reboiler	4,425	Tantalum Clad CS 71 300	Tantalum 86 370	NKU	HAD-302	Three reboiler shells per column. Area shown is for one shell. Three shells per column

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 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 12/10/2008	SHEET 5 of 6	DOC NO 132155-T-EQL-HPS-SI-HAD-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles D. Bottarini</i>		
Unit: SULFUR IODINE					Location: Idaho Falls, Idaho		
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-HAD QP-QC A thru F	HI Column Condenser	9700	Internal to TO-04	Tantalum Clad CS 48 257	Internal U tube bundle	HAD 302	
HPS-HAD HX-5	Recovered Water Cooler	200	CS 31 100	304 SS 38 225	BEU	HAD 303	
HPS-HAD HX-4	Hydrogen Product Cooler	20	CS 31 100	304SS 38 180	BEU	HAD 303	

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 Shaw Environmental & Infrastructure, Inc.		ISSUE 0	DATE 12/10/2008	SHEET 6 of 6	DOC NO 132155-T-EQL-HPS-SI-HAD-0

Battelle Energy Alliance, LLC (BEA)

Next Generation Nuclear Plant

Idaho Falls, Idaho

Sulfur Iodine Hydrogen

Product Purification

Equipment List

Shaw E&I Project No. 132155

ISSUE	DATE	DESCRIPTION	ORIGR	CHK'R	SDE	PEM	INTERDISCIPLINE REVIEW		
							DISCIPLINE	REV'R	DATE
							Process		
							Mechanical		
							Civil/Structural		
							Control Systems		
							Power Systems		
							Piping		
							Material & Corr.		
0	12/11/2008	For Estimate	COB	KG	COB	COB			
FILE NAME NGNP HPAS HyS Product purification Equipment List 08.doc			SHEET 1 of 7			DOC.NO. 132155-T-EQL-HPS-SI-PPU-0			

EQUIPMENT LIST - TOWERS										
Client: Battelle Energy Alliance (BEA), LLC					Signature: <i>Charles R. Bottorini</i>					
Unit: NGNP HPS Sulfur Iodine					Location: Idaho Falls, Idaho					
Item No.	Name	Diameter (mm)	Height (mm)	Packing/Trays	Mechanical Design		Material		PFD	Remarks
					Press (bar g)	Temp (°C)	Shell C.A. (mm)	Packing Trays		
HPS-PPU TO-403	SO ₂ Scrub Tower	2200	7000	24.3 m ³ of 1 inch IMTP #25 Packing	10	70	CS	CS	PPU 402	

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EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance (BEA) LLC

Signature: *Charles R. Bottorini*

Unit: NGNP HPS Sulfur Iodine

Location: Idaho Falls, Idaho

Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temp (°C)			
HPS-PPU DR-401 A/B	Hydrogen Iodine Adsorber	2600	5800	Vertical	53	150	CS	PPU 401	2 beds @ 23.8 m ³ of mol sieve or activated carbon allow \$150,000 per bed
HPS-PPU DR-402 A/B	Hydrogen Drying Bed	2600	5800	Vertical	53	150	CS	PPU 401	2 beds @ 23.8 m ³ of 3A mol sieve \$100,000 per bed
HPS-PPU DR-403 A/B	Oxygen H2O Adsorber	2400	6000	Vertical	10	100	CS	PPU 402	2 beds @ 21.5 m ³ of 3A mol sieve \$91,000 per bed
HPS-PPU DR-405 A/B	SO2 Adsorber	2400	6000	Vertical	10	100	CS	PPU 402	2 beds @ 21.5 m ³ of 4A mol sieve \$83,000 per bed
HPS-PPU KO-426	Hydrogen Compressor Discharge Drum	850	2600	Vertical	53	150	CS	PPU 401	
HPS-PPU KO-427	Hydrogen Dryer Regen KO Drum	850	2400	Vertical	53	110	CS	PPU 401	
HPS-PPU KO-428	O2 Regen Gas Blower Suction Drum	800	2400	Vertical	10	100	CS	PPU 402	

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EQUIPMENT LIST – PUMPS									
Client: Battelle Energy Alliance (BEA) LLC					Signature: <i>Charles R. Bottorini</i>				
Unit: NGNP Hybrid Sulfur					Location: Idaho Falls, Idaho				
Item No.	Name	Type	Rated Flow (m ³ /h)	Differential Pressure bar	Motor kW	Material		PFD	Remarks
						Casing	Impeller		
HPS-PPU PP-420A/S	NaOH Purge Pump	Centrif.	7	2	0.75	CS	CS	PPU 402	

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 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 12/11/2008	SHEET 4 of 7	DOC NO 132155-T-EQL-HPS-SI-PPU-0

EQUIPMENT LIST – COMPRESSORS / BLOWERS / VACUUM PUMPS

Client: Battelle Energy Alliance (BEA) LLC						Signature: <i>Charles R. Botthorn</i>				
Unit: NGNP Hybrid Sulfur						Location: Idaho Falls, Idaho				
Item No.	Name	Type	Capacity (Am ³ /h)	Suction Pressure (bar a)	Differential Pressure (bar)	Driver		Material C.A.(mm)	PFD	Remarks
						Type	Rated Power (kW)			
HPS-PPU PB-402	Hydrogen Recirculation Blower	Rotary Blower	400	52	1	Electric	170	CS	PPU 401	
HPS-PPU PB-401	Hydrogen Compressor	Recipr.	1760	39.5	14.5	Electric	1120	CS	PPU 401	
HPS-PPU PB-403	O2 Regen Gas Recirc. Blower	Rotary Blower	460	10	4	Electric	45	CS	PPU 402	
HPS-PPU PB-404	Oxygen Compressor	3 Stage Centrif.	3670	8	33	Electric	1865	CS	PPU 402	3 Stage Compressor w/ intercooler and after cooler supplied as packaged unit.

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 Shaw Environmental & Infrastructure, Inc.	ISSUE 0	DATE 12/11/2008	SHEET 5 of 7	DOC NO 132155-T-EQL-HPS-SI-PPU-0

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC

Signature: *Charles R. Botthorn*

Unit: NGNP Hybrid Sulfur

Location: Idaho Falls, Idaho

Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-PPU HX-420	Hydrogen Compressor Aftercooler	15	CS 54 175	CS 44 100	BEU	PPU 401	
HPS-PPU HX-421	Hydrogen Dryer Regen Cooler	65	CS 54 110	CS 41 100	BEU	PPU 401	
HPS-PPU HX-422	Hydrogen Dryer Regen Heater	35	CS 40 200	CS 52 110	BEU	PPU 401	
HPS-PPU HX-428	SO2 Adsorber Regen Heater	5	CS 10 200	CS 20 100	BEU	PPU 402	
HPS-PPU HX-429	Oxygen H2O Adsorber Regen Heater	7	CS 10 200	CS 10 100	BEU	PPU 402	
HPS-PPU HX-430	SO2 Adsorber Regen Cooler	5	CS 10 100	CS 10 100	BEU	PPU 402	
HPS-PPU HX-431	Oxygen H2O Adsorber Regen Cooler	10	CS 10 100	CS 10 100	BEU	PPU 402	

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EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance (BEA) LLC				Signature: <i>Charles R. Bottorini</i>			
Unit: NGNP Hybrid Sulfur				Location: Idaho Falls, Idaho			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HPS-PPU HX-432 A/B	O2 Product Cooler	110	CS 45 150	CS 37 100	BEU	PPU 402	

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8.2.6 Preliminary Hazards Analysis

Section 8.2.6 – NNGP SI Preliminary Hazards Assessment

Item	Risk	Comments
Concentrated H_2SO_4 at high pressure and temperature	Loss of containment of a highly corrosive acid. High pressure can result in a jet or spray leak.	Concentration of sulfuric acid is practiced industrially. The high pressure employed in this process presents a hazard over the low pressure industrial process in that leaks have a potential to spray personnel at a significant distance from the leak point. Joints should be minimized to minimize the potential for leaks. Splash guards should be employed around pumps and any joints located near where personnel may work or pass. Since the corrosion resistances of metals to sulfuric acid are strong functions of temperature, fluid velocity and concentration, care must be taken to ensure that operating conditions are well understood before equipment is specified and that actual operating conditions do not significantly vary from design.
Concentrated SO_2 at high pressure	Loss of containment of a toxic gas	Large quantities of concentrated SO_2 at high pressure represent a serious toxicity hazard. Industrial experience with the safe operation of Claus plants may be a useful reference.
Hydroiodic acid at high pressure	Loss of containment of corrosive liquid	The high pressures employed in some parts of this process present a hazard in that leaks have a potential to spray personnel at a significant distance from the leak point. Joints should be minimized to minimize the potential for leaks. Splash guards should be employed around pumps and any joints located near where personnel may work or pass. The risk is mitigated by the relatively low concentrations used.
I_2 in vapor and liquid streams	Loss of containment of a toxic gas	A leak of a high temperature, high pressure stream containing dissolved I_2 would likely result in the release of some gaseous I_2 upon pressure letdown.
I_2 containing streams in heat exchangers	Excessive corrosion	The possibility of localized corrosion resulting from “boil to dryness” at points in exchangers and reboilers should be investigated and appropriately considered in equipment design.

Item	Risk	Comments
H ₂ purification and compression	Loss of containment of a flammable gas at high pressure and temperature resulting in a fire or explosion	The drying of H₂ at elevated pressures is within industrial gases industry experience. Standard safety measures should be incorporated into the design. The compression of H₂ to > 100 bar is within industrial gases industry experience. Standard safety measures should be incorporated into the design. Due to the flammability of H₂, joints, and fittings should be avoided in this piping system. The possibilities of a jet fire or a confined vapor cloud explosion in the region of potential leak points should be considered in the development of the plant layout.
O ₂ purification and compression	The enhanced flammability of materials in O ₂ resulting in an equipment fire	All piping, fittings and equipment exposed to > 25% oxygen must be oxygen-clean before start up. Fittings that are O₂-cleaned at the factory must be shipped sealed. The use of soft materials and lubricants should be minimized with oxygen-enriched streams. Fluorinated compounds such as Teflon™ and Viton™ are normally used for seals and per-fluorinated materials as lubricants. The use of O₂ as the regeneration gas for the TSA's will require that the maximum regeneration temperature and pressure be considered in the specification of the materials of construction for the adsorber vessels (and piping that will be exposed to the hot gas). It is standard industry practice to place O₂ compressors inside of barriers for containment and personnel protection in case of a fire. The frequency of fires in such equipment should be considered in plant layout
He exchange at decomposer	Loss of containment of high pressure He or cross contamination between primary and secondary He streams due to acid corrosion of He heat exchange equipment	Keeping the pressure of the He stream above that of the decomposer should minimize acid leakage into the He in the event of a leak.
Water treatment		This system should be standard equipment routinely used in industry with standard safety measures.

8.2.7 Capital Cost Estimate

Section 8.2.7 – SI Capital Cost Estimate

8.2.7.1: Reference SI HPS With Tantalum Lining

BUN System

<u>Equipment</u>	<u>Qty</u>	<u>Cost</u>
Bunsen Reactor Top	3	1,305,000
Bunsen Reactor Btm	3	3,726,000
Bunsen Reactor Internals	3	700,000
Reverse Bunsen Reactor Top	3	594,000
Reverse Bunsen Reactor Btm	3	1,026,000
Reverse Bunsen Reactor Internals	3	207,000
Bunsen Decanter	6	7,913,000
Bunsen Reactor Trim Cooler Pump	6	1,289,000
Bunsen Reactor Recirculation Pumps	9	1,933,000
Hi Feed Pumps	12	31,692,000
Reverse Bunsen Reactor Feed Pumps	9	5,329,000
SAD Feed Pumps	9	31,376,000
Low Pressure SO2 Feed Compressor	3	939,000
Bunsen Reactor O2 and SO2 Feed Compressor	3	15,824,000
Recovered Water Cooler	3	465,000
Iodine Feed Cooler	3	3,265,000
SAD Recycled SO2 Cooler	3	71,000
Bunsen Reactor Trim Cooler	3	5,055,000
Bunsen Reactor Coolers	6	10,109,000
Reverse Bunsen Reactor Vapor Cooler	3	1,233,000
Subtotal Equipment		124,051,000
<u>Installation</u>		
Construction		
Labor		59,030,000
Expenses & Supplies		2,968,000
Construction Equipment		5,308,000
Vendor Services		300,000
Sub-subtotal Construction		67,606,000
Bulk Material		52,739,000
EPC Engineering		18,144,000
Spares		2,652,000
Freight		8,808,000
Other Costs - Catalyst, Desiccant		0
Subtotal Installation		149,949,000
BUN System Total		274,000,000

HAD System

<u>Equipment</u>	<u>Qty</u>	<u>Cost</u>
Reactive Distillation Column Top	18	129,966,000
Reactive Distillation Column Btm	18	39,842,000
Reactive Distillation Column Internals	18	49,680,000
Distillation Column Feed Mix Tank	3	10,911,000
HI Column Steam Drum	18	3,759,000
Recovered Water KO Drum	3	393,000
Hydrogen Product KO Drum	3	612,000
Column Bottoms KO Drum	3	10,277,000
Heat Pump Compressor	18	87,025,000
KO Drum Vapor Compressor	3	16,092,000
Iodine Cooler	3	1,438,000
Vapor Heat Recuperator	3	19,437,000
Recovered Iodine Heat Recuperator	3	12,336,000
HI Distillation Column Feed Preheater	3	24,729,000
HI Column Process Coupling Heat Exchanger	18	16,386,000
HI Column Reboiler	54	536,226,000
HI Column Condenser	18	248,298,000
Recovered Water Cooler	3	265,000
Hydrogen Product Cooler	3	81,000
Helium Control Valves	36	7,200,000
Subtotal Equipment		1,214,953,000
<u>Installation</u>		
Construction		
Labor		230,085,000
Equipment & Supplies		11,731,000
Construction Equipment		20,978,000
Vendor Services		300,000
Sub-subtotal Construction		263,094,000
Bulk Material		325,743,000
EPC Engineering		38,232,000
Spares		23,003,000
Freight		76,503,000
Other Costs - Catalyst, Desiccant		0
Subtotal Installation		726,575,000
HAD System Total		1,941,528,000

SAD System

	<u>Qty</u>	<u>Cost</u>	
<u>Equipment</u>			
Vacuum Column Top & Bottom	6	9,390,000	
Vacuum Column Internals	6	5,405,000	
First Stage Vacuum Column Ejector	6	297,000	
Second Stage Vacuum Column Ejector	3	99,000	
Sulfuric Acid Decomposer	6	14,202,000	
Sulfuric Acid Decomposer Internals	6	21,498,000	incl. cat.
Reactor Effluent Flash Drum	6	10,155,000	
Recycle Acid HP Flash Drum	3	1,017,000	
Recycle Acid LP Flash Drum	3	653,000	
Reactor ProductFlash KO Drum	3	1,136,000	
HP Recycle Acid Vapor KO Drum	3	431,000	
LP SO2 KO Drum	3	104,000	
Vacuum Column Reflux Drum	6	257,000	
Ejector Hotwell	3	63,000	
Reactor Feed Pump	9	21,118,000	
LP SO2 Condensate Pump	6	413,000	
Ejector Condensate Pump	6	101,000	
Vacuum Column Reflux/Ovhd Product Pump	9	821,000	
HP Recycle Acid Flash Condenser	3	428,000	
Reactor Product Condenser	3	1,299,000	
Reactor Product Trim Cooler	3	623,000	
Recycle Acid Trim Cooler	3	797,000	
EJ-201 Discharge Condenser	3	71,000	
EJ-202 Discharge Condenser	3	71,000	
Vacuum Column Condenser	6	10,101,000	
Vacuum Column Reboiler	6	2,187,000	
Helium Control Valves	18	3,600,000	
	Subtotal Equipment	106,337,000	
<u>Installation</u>			
Construction			
Labor		61,023,000	
Equipment & Supplies		3,052,000	
Construction Equipment		5,461,000	
Vendor Services		150,000	
	Sub-subtotal Construction	69,686,000	

Bulk Material	82,181,000
EPC Engineering	17,982,000
Spares	2,633,000
Freight	8,750,000
Other Costs - Catalyst, Desiccant	1,000,000
Subtotal Installation	182,232,000
SAD System Total	\$288,569,000

FUS System

<u>Equipment</u>	<u>Qty</u>	<u>Cost</u>
Sulfuric Acid Vent Scrubber	1	201,000
Sulfuric Acid Vent Scrubber Internals	1	159,000
Water Pretreatment Filter/Softener System	1	1,000,000
Water Treatment RO/EDI System	1	14,000,000
Waste Water Treatment System	1	1,000,000
Iodine Feedstock Preparation System	1	10,000,000
Sulfuric Acid Degassing Drum	1	125,000
H2SO4 Make-up Pump	2	41,000
H2SO4 Feed Pump	2	95,000
NaOH Make-up Pump	3	37,000
NaOH Solution Supply Pump	2	82,000
Feed Water Pump	4	276,000
H2SO4 Storage Tank	1	58,000
Caustic Storage Tank	1	118,000
H2SO4 Storage Tank Heater/Cooler	1	803,000
NaOH Tank Heater/Cooler	1	4,000
Subtotal Equipment		27,999,000
<u>Installation</u>		
Construction		
Labor		7,495,000
Equipment & Supplies		414,000
Construction Equipment		740,000
Vendor Services		0
Sub-subtotal Construction		8,649,000

Bulk Material	4,955,000
EPC Engineering	3,240,000
Spares	132,000
Freight	432,000
Other Costs - Catalyst, Desiccant	0
Subtotal Installation	17,408,000
FUS System Total	\$ 45,407,000

PPU System

	<u>Qty/Train</u>	<u>Cost</u>	
SO2 Scrub Tower	3	283,000	
SO2 Scrub Tower Internals	3	279,000	
Hydrogen Iodine Adsorber	6	1,304,000	ints. & cat.
Hydrogen Drying Bed	6	1,304,000	ints. & cat.
Oxygen H2O Adsorber	6	386,000	ints. & cat.
SO2 Adsorber	6	386,000	ints. & cat.
Hydrogen Compressor Discharge Drum	3	58,000	
Hydrogen Dryer Regen Heater Knockout Drum	3	56,000	
O2 Regen Gas Blower Suction Drum	3	26,000	
NaOH Purge Pump	6	102,000	
Hydrogen Recirculation Blower	3	3,131,000	
Hydrogen Compressor	3	5,244,000	
O2 Regen Gas Recirc. Blower	3	2,528,000	
Oxygen Compressor	3	11,571,000	
Hydrogen Compressor Aftercooler	3	42,000	
Hydrogen Dryer Regen Cooler	3	88,000	
Hydrogen Dryer Regen Heater	3	64,000	
SO2 Adsorber Regen Heater	3	21,000	
Oxygen H2O Absorber Regen Heater	3	24,000	
SO2 Adsorber Regen Cooler	3	21,000	
Oxygen H2O Adsorber Regen Cooler	3	29,000	
O2 Product Cooler	6	231,000	
Subtotal Equipment		27,178,000	

Installation

Construction		
Labor		46,796,000
Equipment & Supplies		2,567,000
Construction Equipment		4,592,000
Vendor Services		0
Sub-subtotal Construction		53,955,000
Bulk Material		32,668,000
EPC Engineering		13,122,000
Spares		898,000
Freight		2,967,000
Other Costs - Catalyst, Desiccant		2,725,000
Subtotal Installation		106,335,000
PPU system total		133,513,000

Total SI Hydrogen Production System Cost (Tantalum Lining)

BUN System Total	274,000,000
HAD System Total	1,941,528,000
SAD System Total	288,569,000
FUS System Total	45,407,000
PPU System Total	133,513,000

Grand Total	2,683,017,000

8.2.7.2: SI HPS With Only Carbon Steel**BUN System**

<u>Equipment</u>	<u>Qty</u>	<u>Cost</u>
Bunsen Reactor Top	3	435,000
Bunsen Reactor Btm	3	1,242,000
Bunsen Reactor Internals	3	583,000
Reverse Bunsen Reactor Top	3	198,000
Reverse Bunsen Reactor Btm	3	342,000
Reverse Bunsen Reactor Internals	3	173,000
Bunsen Decanter	6	2,282,000
Bunsen Reactor Trim Cooler Pump	6	834,000
Bunsen Reactor Recirculation Pumps	9	1,251,000
Hi Feed Pumps	12	19,763,000
Reverse Bunsen Reactor Feed Pumps	9	3,390,000
SAD Feed Pumps	9	17,125,000
Low Pressure SO2 Feed Compressor	3	641,000
Bunsen Reactor O2 and SO2 Feed Compressor	3	7,585,000
Recovered Water Cooler	3	133,000
Iodine Feed Cooler	3	252,000
SAD Recycled SO2 Cooler	3	21,000
Bunsen Reactor Trim Cooler	3	389,000
Bunsen Reactor Coolers	6	778,000
Reverse Bunsen Reactor Vapor Cooler	3	95,000
Subtotal Equipment		57,512,000
<u>Installation</u>		
Construction		
Labor		54,271,000
Expenses & Supplies		2,712,000
Construction Equipment		4,850,000
Vendor Services		300,000
Sub-subtotal Construction		62,133,000
Bulk Material		31,632,000
EPC Engineering		18,144,000
Spares		1,338,000
Freight		4,426,000
Other Costs - Catalyst, Desiccant		0
Subtotal Installation		117,673,000
BUN system total		175,185,000

HAD System

<u>Equipment</u>	<u>Qty</u>	<u>Cost</u>
Reactive Distillation Column Top	18	43,865,000
Reactive Distillation Column Btm	18	13,448,000
Reactive Distillation Column Internals	18	41,400,000
Distillation Column Feed Mix Tank	3	1,380,000
HI Column Steam Drum	18	3,759,000
Recovered Water KO Drum	3	145,000
Hydrogen Product KO Drum	3	226,000
Column Bottoms KO Drum	3	872,000
Heat Pump Compressor	18	87,025,000
KO Drum Vapor Compressor	3	11,928,000
Iodine Cooler	3	206,000
Vapor Heat Recuperator	3	2,160,000
Recovered Iodine Heat Recuperator	3	1,371,000
HI Distillation Column Feed Preheater	3	2,748,000
HI Column Process Coupling Heat Exchanger	18	1,820,000
HI Column Reboiler	54	59,579,000
HI Column Condenser	18	27,589,000
Recovered Water Cooler	3	152,000
Hydrogen Product Cooler	3	46,000
Helium Control Valves	36	7,200,000
Subtotal Equipment		306,919,000
<u>Installation</u>		
Construction		
Labor		191,724,000
Equipment & Supplies		9,668,000
Construction Equipment		17,288,000
Vendor Services		300,000
Sub-subtotal Construction		218,980,000
Bulk Material		118,939,000
EPC Engineering		38,232,000
Spares		6,280,000
Freight		20,761,000
Other Costs - Catalyst, Desiccant		0
Subtotal Installation		403,192,000
HAD system total		710,111,000

SAD System

<u>Equipment</u>	<u>Qty</u>	<u>Cost</u>	
Vacuum Column Top & Bottom	6	2,008,000	
Vacuum Column Internals	6	2,703,000	
First Stage Vacuum Column Ejector	6	90,000	
Second Stage Vacuum Column Ejector	3	30,000	
Sulfuric Acid Decomposer	6	3,552,000	
Sulfuric Acid Decomposer Internals	4	5,376,000	incl. cat.
Reactor Effluent Flash Drum	6	2,063,000	
Recycle Acid HP Flash Drum	3	222,000	
Recycle Acid LP Flash Drum	3	109,000	
Reactor ProductFlash KO Drum	3	351,000	
HP Recycle Acid Vapor KO Drum	3	141,000	
LP SO2 KO Drum	3	35,000	
Vacuum Column Reflux Drum	6	86,000	
Ejector Hotwell	3	22,000	
Reactor Feed Pump	9	7,782,000	
LP SO2 Condensate Pump	6	273,000	
Ejector Condensate Pump	6	74,000	
Vacuum Column Reflux/Ovhd Product Pump	9	544,000	
HP Recycle Acid Flash Condenser	3	123,000	
Reactor Product Condenser	3	289,000	
Reactor Product Trim Cooler	3	178,000	
Recycle Acid Trim Cooler	3	100,000	
EJ-201 Discharge Condenser	3	21,000	
EJ-202 Discharge Condenser	3	21,000	
Vacuum Column Condenser	6	2,886,000	
Vacuum Column Reboiler	6	398,000	
Helium Control Valves	18	3,600,000	
Subtotal Equipment		33,077,000	
<u>Installation</u>			
Construction			
Labor		51,638,000	
Equipment & Supplies		2,548,000	
Construction Equipment		4,557,000	
Vendor Services		150,000	
Sub-subtotal Construction		58,893,000	

Bulk Material	33,219,000
EPC Engineering	17,982,000
Spares	911,000
Freight	3,008,000
Other Costs - Catalyst, Desiccant	1,000,000
Subtotal Installation	115,013,000
SAD system total	148,090,000

FUS System

<u>Equipment</u>	<u>Qty</u>	<u>Cost</u>
Sulfuric Acid Vent Scrubber	1	201,000
Sulfuric Acid Vent Scrubber Internals	1	159,000
Water Pretreatment Filter/Softener System	1	1,000,000
Water Treatment RO/EDI System	1	14,000,000
Waste Water Treatment System	1	1,000,000
Iodine Feedstock Preparation System	1	10,000,000
Sulfuric Acid Degassing Drum	1	44,000
H2SO4 Make-up Pump	2	25,000
H2SO4 Feed Pump	2	51,000
NaOH Make-up Pump	3	37,000
NaOH Solution Supply Pump	2	82,000
Feed Water Pump	4	223,000
H2SO4 Storage Tank	1	41,000
Caustic Storage Tank	1	118,000
H2SO4 Storage Tank Heater/Cooler	1	179,000
NaOH Tank Heater/Cooler	1	4,000
Subtotal Equipment		27,164,000
<u>Installation</u>		
Construction		
Labor		7,480,000
Equipment & Supplies		413,000
Construction Equipment		739,000
Vendor Services		0
Sub-subtotal Construction		8,632,000
Bulk Material		4,864,000
EPC Engineering		3,240,000
Spares		119,000
Freight		387,000
Other Costs - Catalyst, Desiccant		0
Subtotal Installation		17,242,000
FUS system total		44,406,000

PPU System

<u>Equipment</u>	<u>Qty</u>	<u>Cost</u>	
SO2 Scrub Tower	3	283,000	
SO2 Scrub Tower Internals	3	279,000	
Hydrogen Iodine Adsorber	6	1,304,000	ints. & cat.
Hydrogen Drying Bed	6	1,304,000	ints. & cat.
Oxygen H2O Adsorber	6	386,000	ints. & cat.
SO2 Adsorber	6	386,000	ints. & cat.
Hydrogen Compressor Discharge Drum	3	58,000	
Hydrogen Dryer Regen Heater Knockout Drum	3	56,000	
O2 Regen Gas Blower Suction Drum	3	26,000	
NaOH Purge Pump	6	102,000	
Hydrogen Recirculation Blower	3	3,131,000	
Hydrogen Compressor	3	5,244,000	
O2 Regen Gas Recirc. Blower	3	2,528,000	
Oxygen Compressor	3	11,571,000	
Hydrogen Compressor Aftercooler	3	42,000	
Hydrogen Dryer Regen Cooler	3	88,000	
Hydrogen Dryer Regen Heater	3	64,000	
SO2 Adsorber Regen Heater	3	21,000	
Oxygen H2O Absorber Regen Heater	3	24,000	
SO2 Adsorber Regen Cooler	3	21,000	
Oxygen H2O Adsorber Regen Cooler	3	29,000	
O2 Product Cooler	6	231,000	
Subtotal Equipment		27,178,000	
<u>Installation</u>			
Construction			
Labor		46,796,000	
Equipment & Supplies		2,567,000	
Construction Equipment		4,592,000	
Vendor Services		0	
Sub-subtotal Construction		53,955,000	
Bulk Material		32,668,000	
EPC Engineering		13,122,000	
Spares		898,000	
Freight		2,967,000	
Other Costs - Catalyst, Desiccant		2,725,000	
Subtotal Installation		106,335,000	
PPU system total		133,513,000	

Total SI Hydrogen Production System Cost (Carbon Steel)

BUN System Total	175,185,000
HAD System Total	710,111,000
SAD System Total	148,090,000
FUS System Total	44,406,000
PPU System Total	133,513,000

Grand Total**1,211,305,00**

8.2.8 Operating Cost Estimate

Section 8.2.8 - S-I Operating Cost Estimate

8.2.8.1: Overall Plant Operating Costs

Fixed Operation & Maintenance				<u>\$/year</u>	
Total plant staff (Direct labor)					
	HPS	52	FTEs		
	BOP	36	FTEs		
	Total	88	FTEs		
Composite rate		50	\$/hr		
Overhead rate		60	%		
Burdened rate		80			
Annual labor				\$	14,643,200
G&A					
rate		20	%		
G&A				\$	2,928,640
Material costs for maintenance and repairs					
	HPS			\$	11,972,240
	BOP			\$	100,000
	Total			\$	12,172,240
Licenses					
Property Tax & Insurance				\$	61,223,061
Other					
			Subtotal	\$	90,967,141
Heat					
	Use	1583.67	MWt		
	Rate	30	\$/MWt-h		
	Cost			\$	416,188,476
Total Fixed O&M				\$	507,155,617

\$/year

March 2009

Other Material Costs						<u>\$/year</u>	
Decomposer Tubes				\$/hr	in Replacement Capital		
Make-up catalyst				567 \$/hr	\$	4,652,585	
Iodine				17 \$/hr	\$	139,495	
Mol sieves				177 \$/hr	\$	1,452,394	
Make-up acid				242 \$/hr	\$	1,985,759	
Make-up caustic				662 \$/hr	\$	5,432,118	
Total Other Material Costs						\$	13,662,351
Waste treatment costs						\$	34,210,262
q		18.7	kg/s				
C _{S,u}		0.186	\$/kg	÷ 3 =	0.06193	\$/kg	
Solid waste disposal costs						\$	-
q		1.5	kg/hr				
C _{S,u}		0.186	\$/kg				
Total Unplanned Replacement Capital Cost Factor						0.50	%
(% of total direct depreciable costs/year)							
Total Variable O&M						\$	251,420,671

8.2.8.2: Detail, Hydrogen Production System Operating Costs**NGNP HPAS SI Operating Usages and Costs**

[All usages are on a per train basis and multiplied by the number of trains. SI Plant has Three (3) trains]

Number of trains: 3**Staffing:**

Operations: 7 per shift
 Maintenance 4 per shift
 4 additional, day shift only

Supervision & Engineering

Plant Mgr, Assistant, Engineer and Administrative assistant.

Electricity

Per train

Total imported	MW _e /h	226.1	75.4

Steam	kg/h	284,720	94,907

Cooling Water

Plant total	m ³ /h	155,264	51,755

Replacements

RO membranes	(included in process water cost)		

Decomposer tubes	\$	653	\$	23,800	750	82,000	218

Process Water

Usage	55.18 kg/s

Density	999.6 kg/m ³

Blowdown	1%

Ulrich & Vasudevan, "How to estimate Utility Costs," Chem. Eng., Apr 2006, pp. 66-69: Natural Water Pumped and screened.

Supply		201	m ³ /h
Softened	\$	14	181 m ³ /h
RO/EDI	\$	58	143 m ³ /h
			0.079 \$/m ³
			0.403 \$/m ³

Catalyst and Chemicals

Water softening chemicals

(included in process water cost)

	Hourly Cost	per plant as 100%, kg/h	per train, kg/h		Cost, \$ per tonne
Iodine make-up	\$ 17	0.86	0.29		\$ 20,000
Sulfuric Acid make-up	\$ 242	2108	1406	as 50%	\$ 115
Caustic	\$ 662	1720	1146	as 50%	\$ 385
		Cost of a load or unit	Loads or units per train		Life, hours
Decomposition catalyst	\$ 567	\$ 1,888,432	2		20,000
Mol sieves	\$ 177	\$ 283,991	1		4,800
					Cost per train-hour
Subtotal Catalyst & Chemicals	\$ 1,666				\$ 189
					\$ 59

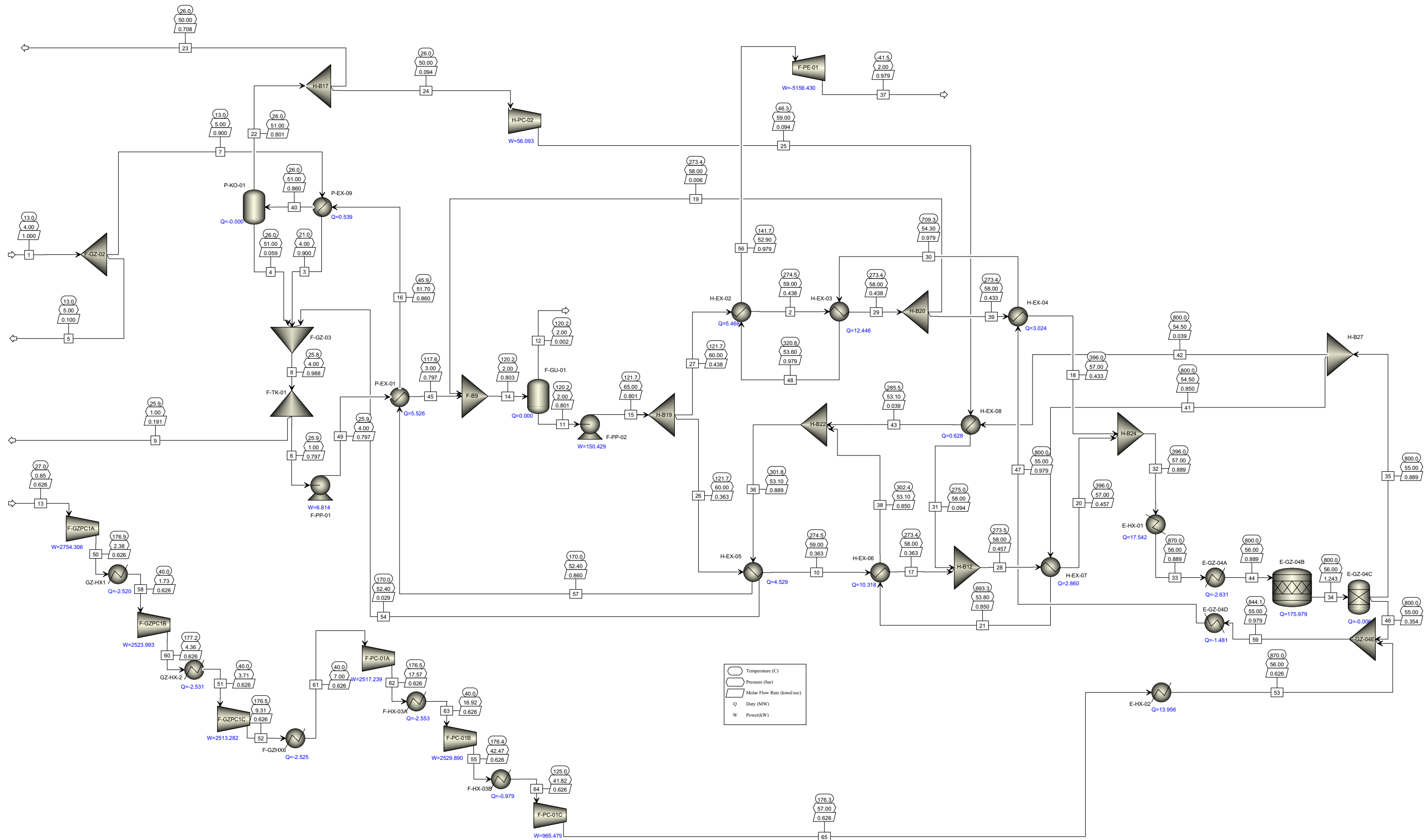
Wastes

Liquid Effluent	From Softening	5.52	kg/s	
	From RO/EDI	10.52	kg/s	
	Sodium sulfite waste	2.63	kg/s	
	Total	18.67	kg/s	
		67,204	kg/h	
		0.186	\$/kg	1/3 of Ulrich, " Conventional Liquid Waste"
Solid Wastes	SiC tubes	1.5	kg/h	
		0.186	\$/kg	Ulrich, " Conventional Solid Waste"

8.3 HIGH TEMPERATURE STEAM ELECTROLYSIS

- 8.3.1 Simulation Diagrams
- 8.3.2 Mass and Energy Balances
- 8.3.3 Process Flow Diagrams
- 8.3.4 Summary Plot Plan Layout
- 8.3.5 Sized Equipment List
- 8.3.6 Preliminary Hazards Analysis
- 8.3.7 Capital Cost Estimate
- 8.3.8 Operating Cost Estimate

8.3.1 Simulation Diagrams



8.3.2 Mass and Energy Balances

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	F-GZ-02	H-EX-03	F-GZ-03	F-GZ-03	0	F-PP-01	P-EX-09	F-TK-01	0	H-EX-06	F-PP-02	0	F-GZPC1A	F-GU-01	H-B19
	0	H-EX-02	P-EX-09	P-KO-01	F-GZ-02	F-TK-01	F-GZ-02	F-GZ-03	F-TK-01	H-EX-05	F-GU-01	F-GU-01	0	F-B9	F-PP-02
	LIQUID	MIXED	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	MIXED	LIQUID	VAPOR	VAPOR	MIXED	LIQUID
Substream: MIXED															
Mole Flow kmol/sec															
HYDROGEN	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OXYGEN	-	-	-	-	-	-	-	-	-	-	-	-	0.308	-	-
WATER	2.347	1.029	2.113	0.138	0.235	1.872	2.113	2.319	0.448	0.852	1.880	0.004	-	1.885	1.880
NITROGEN	-	-	-	-	-	-	-	-	-	-	-	-	1.160	-	-
Total Flow kmol/sec	2.347	1.029	2.113	0.138	0.235	1.872	2.113	2.319	0.448	0.852	1.880	0.004	1.469	1.885	1.880
Total Flow kg/sec	42.288	18.531	38.059	2.481	4.229	33.716	38.059	41.780	8.064	15.349	33.877	0.076	42.369	33.953	33.877
Total Flow cum/sec	0.042	0.024	0.038	0.002	0.004	0.034	0.038	0.042	0.008	0.020	0.036	0.067	43.111	0.103	0.036
Temperature C	13.0	274.5	20.9	26.0	13.0	25.9	13.0	25.8	25.9	274.5	120.2	120.2	27.0	120.2	121.7
Pressure bar	4.0	59.0	4.0	51.0	5.0	1.0	5.0	4.0	1.0	59.0	2.0	2.0	0.9	2.0	65.0
Vapor Frac	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.002	0.000
Liquid Frac	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.998	1.000
Solid Frac	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Enthalpy J/kmol	-2.87E+08	-2.66E+08	-2.86E+08	-2.86E+08	-2.87E+08	-2.86E+08	-2.87E+08	-2.86E+08	-2.86E+08	-2.66E+08	-2.79E+08	-2.39E+08	5.28E+04	-2.79E+08	-2.78E+08
Enthalpy J/kg	-1.59E+07	-1.48E+07	-1.59E+07	-1.59E+07	-1.59E+07	-1.59E+07	-1.59E+07	-1.59E+07	-1.59E+07	-1.48E+07	-1.55E+07	-1.33E+07	1.83E+03	-1.55E+07	-1.55E+07
Enthalpy MW	-673.03	-273.55	-604.46	-39.34	-67.30	-534.80	-605.72	-662.70	-127.90	-226.59	-523.91	-1.01	0.08	-524.92	-523.56
Entropy J/kmol-K	-1.66E+05	-1.15E+05	-1.64E+05	-1.63E+05	-1.66E+05	-1.63E+05	-1.66E+05	-1.63E+05	-1.63E+05	-1.15E+05	-1.42E+05	-4.13E+04	5.91E+03	-1.42E+05	-1.42E+05
Entropy J/kg-K	-9226.9	-6405.0	-9112.6	-9042.3	-9227.2	-9043.0	-9227.2	-9044.0	-9043.0	-6405.0	-7891.6	-2294.7	204.9	-7879.0	-7882.0
Density kmol/cum	55.5	42.1	55.4	55.5	55.5	55.3	55.5	55.3	55.3	42.1	52.3	0.1	0.0	18.3	52.5
Density kg/cum	999.6	758.2	998.2	999.0	999.6	996.8	999.6	997.0	996.8	758.2	943.0	1.1	1.0	329.0	945.0
Average MW	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	28.85	18.02	18.02
Liq Vol 60F cum/sec	4.24E-02	1.86E-02	3.81E-02	2.49E-03	4.24E-03	3.38E-02	3.81E-02	4.19E-02	8.08E-03	1.54E-02	3.39E-02	7.61E-05	7.87E-02	3.40E-02	3.39E-02

Scale-up factor

Plant capacity =
1 lb-mole =
1 kmol =
1 kmol =
Plant capacity =
Plant capacity =
Scale-up factor =

1.20E+08 SCFD (60°F)
379.56 SCF (60°F)
2.2046 lb-moles
836.78 SCF (60°F)
1.43E+05 kmol/day
1.660 kmol/s
2.347

Power Requirement

E-GZ-04A
E-GZ-04B
E-GZ-04C
E-GZ-04D

-6.177E+00
4.132E+02
-9.768E-03
-3.471E+00
403.5 MWe

Thermal Requirement

E-HX-01
E-HX-02

4.119E+01
3.274E+01
73.9 MWth

Heat source rating

Heat available for power generation

Rankine cycle efficiency

Power generated on site

Imported electricity

550 MWth
476.1 MWth
42%
199.9 MWe
203.6 MWe

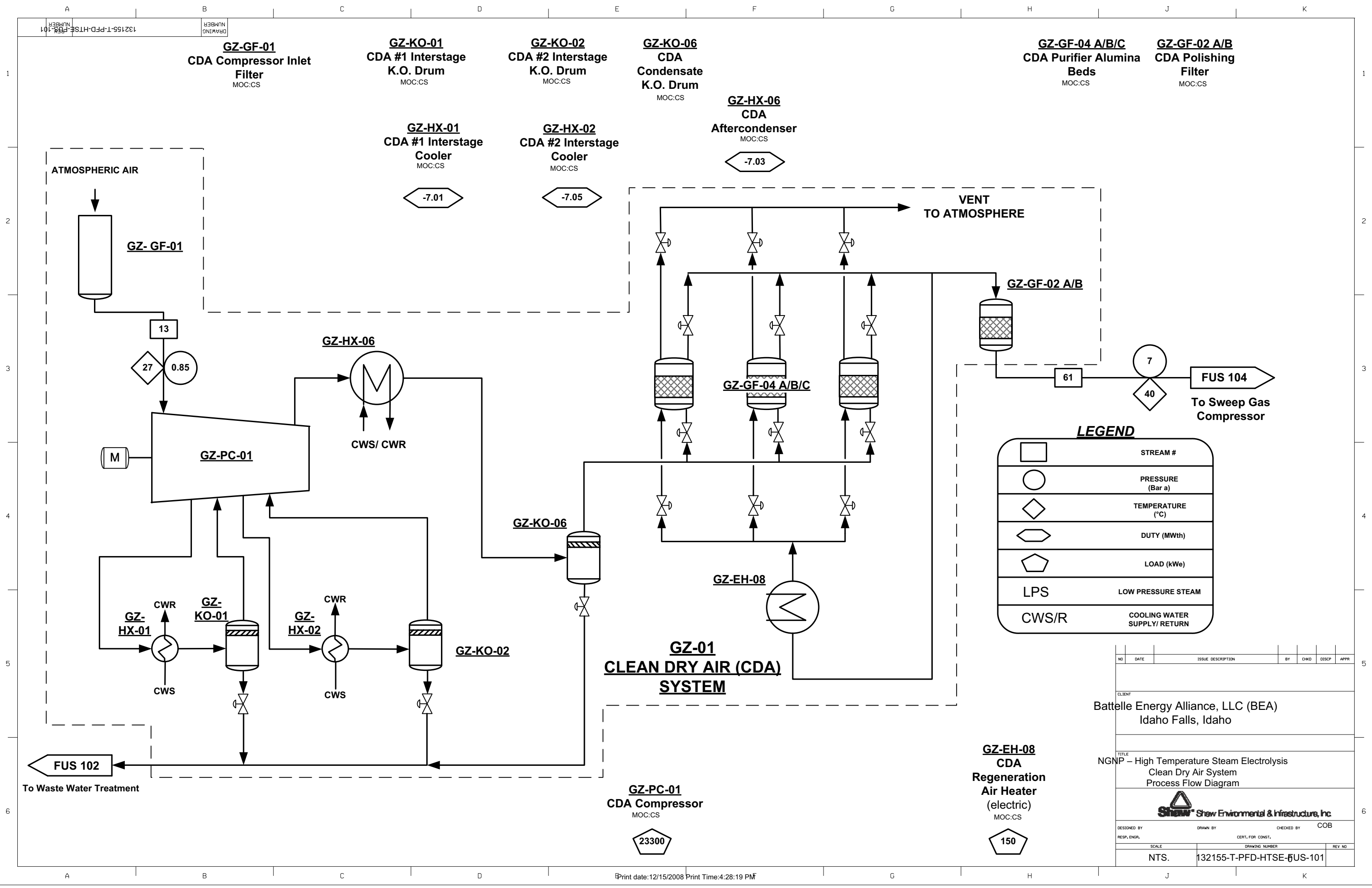
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	P-EX-09	H-B12	H-B24	F-B9	H-B24	H-EX-06	H-B17	0	H-PC-02	H-EX-08	H-EX-05	H-EX-02	H-EX-07	H-B20	H-EX-03
	P-EX-01	H-EX-06	H-EX-04	H-B20	H-EX-07	H-EX-07	P-KO-01	H-B17	H-B17	H-PC-02	H-B19	H-B19	H-B12	H-EX-03	H-EX-04
	MIXED	MIXED	VAPOR	MIXED	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID	LIQUID	VAPOR	MIXED	VAPOR
Substream: MIXED															
Mole Flow kmol/sec															
HYDROGEN	1.880	-	-	-	0.220	1.797	1.880	1.660	0.220	0.220	-	-	0.220	-	-
OXYGEN	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.138
WATER	0.139	0.852	1.015	0.013	0.852	0.198	0.001	0.001	0.000	0.000	0.852	1.029	0.852	1.029	-
NITROGEN	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.160
Total Flow kmol/sec	2.019	0.852	1.015	0.013	1.072	1.996	1.881	1.661	0.220	0.220	0.852	1.029	1.072	1.029	2.299
Total Flow kg/sec	6.289	15.349	18.294	0.236	15.794	7.197	3.806	3.361	0.445	0.445	15.349	18.531	15.794	18.531	68.931
Total Flow cum/sec	1.015	0.517	0.910	0.008	0.981	3.002	1.222	1.095	0.145	0.113	0.016	0.020	0.692	0.623	3.281
Temperature C	45.9	273.4	396.0	273.4	396.0	693.3	26.0	26.0	26.0	46.3	121.7	121.7	273.5	273.4	709.1
Pressure bar	51.7	58.0	57.0	58.0	57.0	53.8	51.0	50.0	50.0	59.0	60.0	60.0	58.0	58.0	58.2
Vapor Frac	0.931	1.000	1.000	0.999	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	1.000	0.999	1.000
Liquid Frac	0.069	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.001	0.000
Solid Frac	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Enthalpy J/kmol	-1.89E+07	-2.38E+08	-2.31E+08	-2.38E+08	-1.81E+08	-3.87E+06	-4.43E+04	-4.43E+04	-4.43E+04	5.54E+05	-2.78E+08	-2.78E+08	-1.87E+08	-2.38E+08	2.16E+07
Enthalpy J/kg	-6.07E+06	-1.32E+07	-1.28E+07	-1.32E+07	-1.23E+07	-1.07E+06	-2.19E+04	-2.19E+04	-2.19E+04	2.74E+05	-1.55E+07	-1.55E+07	-1.27E+07	-1.32E+07	7.20E+05
Enthalpy MW	-38.17	-202.37	-234.13	-3.11	-194.06	-7.72	-0.08	-0.07	-0.01	0.12	-237.22	-286.39	-200.77	-244.34	49.65
Entropy J/kmol-K	-3.95E+04	-6.34E+04	-5.16E+04	-6.34E+04	-3.89E+04	5.04E+02	-3.25E+04	-3.23E+04	-3.23E+04	-3.18E+04	-1.42E+05	-1.42E+05	-4.94E+04	-6.34E+04	8.94E+03
Entropy J/kg-K	-12686.0	-3517.6	-2866.6	-3520.2	-2637.7	139.8	-16066.4	-15982.9	-15982.9	-15727.6	-7880.7	-7880.7	-3353.9	-3520.2	298.2
Density kmol/cum	2.0	1.6	1.1	1.7	1.1	0.7	1.5	1.5	1.5	1.9	52.4	52.4	1.5	1.7	0.7
Density kg/cum	6.2	29.7	20.1	29.7	16.1	2.4	3.1	3.1	3.1	3.9	944.6	944.6	22.8	29.7	21.0
Average MW	3.12	18.02	18.02	18.02	14.73	3.61	2.02	2.02	2.02	2.02	18.02	18.02	14.73	18.02	29.99
Liq Vol 60F cum/sec	1.03E-01	1.54E-02	1.83E-02	2.37E-04	2.72E-02	9.98E-02	1.01E-01	8.89E-02	1.18E-02	1.18E-02	1.54E-02	1.86E-02	2.72E-02	1.86E-02	1.23E-01

	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
	H-B12	E-HX-01	E-GZ-04A	E-GZ-04C	H-B27	H-EX-05	0	H-B22	H-EX-04	P-KO-01	H-EX-07	H-EX-08	H-B22	E-GZ-04B	F-B9
	H-EX-08	H-B24	E-HX-01	E-GZ-04B	E-GZ-04C	H-B22	F-PE-01	H-EX-06	H-B20	P-EX-09	H-B27	H-B27	H-EX-08	E-GZ-04A	P-EX-01
	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	MIXED	MIXED	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID
Substream: MIXED															
Mole Flow kmol/sec															
HYDROGEN	0.220	0.220	0.220	1.880	1.880	1.880	-	1.797	-	1.880	1.797	0.083	0.083	0.220	-
OXYGEN	-	-	-	0.830	-	-	1.138	-	-	-	-	-	-	-	-
WATER	0.000	1.868	1.868	0.208	0.208	0.208	-	0.198	1.015	0.139	0.198	0.009	0.009	1.868	1.872
NITROGEN	-	-	-	-	-	-	1.160	-	-	-	-	-	-	-	-
Total Flow kmol/sec	0.220	2.088	2.088	2.918	2.088	2.088	2.299	1.996	1.015	2.018	1.996	0.092	0.092	2.088	1.872
Total Flow kg/sec	0.445	34.090	34.090	34.090	7.528	7.528	68.931	7.197	18.294	6.287	7.197	0.331	0.331	34.090	33.716
Total Flow cum/sec	0.176	1.891	3.523	4.775	3.410	1.877	21.953	1.797	0.615	1.225	3.290	0.151	0.080	3.299	0.036
Temperature C	275.0	396.0	870.0	800.0	800.0	301.7	(42.8)	302.5	273.4	26.0	800.0	800.0	285.7	800.0	117.6
Pressure bar	58.0	57.0	56.0	55.0	55.0	53.1	2.0	53.1	58.0	51.0	54.5	54.5	53.1	56.0	3.0
Vapor Frac	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.932	1.000	1.000	1.000	1.000	0.000
Liquid Frac	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.068	0.000	0.000	0.000	0.000	1.000
Solid Frac	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Enthalpy J/kmol	7.25E+06	-2.05E+08	-1.85E+08	6.86E+06	-5.07E+05	-1.60E+07	-2.00E+06	-1.60E+07	-2.38E+08	-1.95E+07	-5.07E+05	-5.07E+05	-1.66E+07	-1.88E+08	-2.79E+08
Enthalpy J/kg	3.58E+06	-1.26E+07	-1.14E+07	5.87E+05	-1.40E+05	-4.45E+06	-6.67E+04	-4.44E+06	-1.32E+07	-6.27E+06	-1.40E+05	-1.40E+05	-4.59E+06	-1.15E+07	-1.55E+07
Enthalpy MW	1.60	-428.20	-387.02	20.00	-1.06	-33.47	-4.60	-31.95	-241.22	-39.42	-1.01	-0.05	-1.52	-393.19	-521.81
Entropy J/kmol-K	-1.59E+04	-4.44E+04	-2.20E+04	9.74E+03	3.62E+03	-1.55E+04	-7.49E+03	-1.55E+04	-6.34E+04	-4.14E+04	3.70E+03	3.70E+03	-1.65E+04	-2.47E+04	-1.43E+05
Entropy J/kg-K	-7852.2	-2721.8	-1347.2	833.5	1004.0	-4306.3	-249.8	-4294.7	-3520.2	-13294.6	1025.2	1025.2	-4562.9	-1510.8	-7919.9
Density kmol/cum	1.3	1.1	0.6	0.6	0.6	1.1	0.1	1.1	1.7	1.6	0.6	0.6	1.1	0.6	52.5
Density kg/cum	2.5	18.0	9.7	7.1	2.2	4.0	3.1	4.0	29.7	5.1	2.2	2.2	4.1	10.3	945.1
Average MW	2.02	16.33	16.33	11.68	3.61	3.61	29.99	3.61	18.02	3.11	3.61	3.61	3.61	16.33	18.02
Liq Vol 60F cum/sec	1.18E-02	4.55E-02	4.55E-02	1.49E-01	1.04E-01	1.04E-01	1.23E-01	9.98E-02	1.83E-02	1.03E-01	9.98E-02	4.60E-03	4.60E-03	4.55E-02	3.38E-02

	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
	E-GZ-04E	H-EX-04	H-EX-02	P-EX-01	GZ-HX1	F-GZPC1C	F-GZHX6	E-GZ-04E	F-GZ-03	F-HX-03B	F-PE-01	P-EX-01	F-GZPC1B	E-GZ-04D	GZ-HX-2
	E-GZ-04C	E-GZ-04D	H-EX-03	F-PP-01	F-GZPC1A	GZ-HX-2	F-GZPC1C	E-HX-02	H-EX-05	F-PC-01B	H-EX-02	H-EX-05	GZ-HX1	E-GZ-04E	F-GZPC1B
	VAPOR	VAPOR	VAPOR	LIQUID	VAPOR	VAPOR	VAPOR	VAPOR	LIQUID	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR	VAPOR
Substream: MIXED															
Mole Flow kmol/sec															
HYDROGEN	-	-	-	-	-	-	-	-	-	-	-	1.880	-	-	-
OXYGEN	0.830	1.138	1.138	-	0.308	0.308	0.308	0.308	-	0.308	1.138	-	0.308	1.138	0.308
WATER	-	-	-	1.872	-	-	-	-	0.069	-	-	0.139	-	-	-
NITROGEN	-	1.160	1.160	-	1.160	1.160	1.160	1.160	-	1.160	1.160	-	1.160	1.160	1.160
Total Flow kmol/sec	0.830	2.299	2.299	1.872	1.469	1.469	1.469	1.469	0.069	1.469	2.299	2.019	1.469	2.299	1.469
Total Flow kg/sec	26.562	68.931	68.931	33.716	42.369	42.369	42.369	42.369	1.240	42.369	68.931	6.289	42.369	68.931	42.369
Total Flow cum/sec	1.348	3.738	1.963	0.034	23.109	10.305	5.918	2.576	0.001	1.315	1.467	1.570	22.101	3.938	12.635
Temperature C	800.0	800.0	320.9	25.9	176.9	40.0	176.5	870.0	170.0	176.4	142.0	170.0	40.0	844.0	177.2
Pressure bar	55.7	55.7	59.2	4.0	2.4	3.7	9.3	55.0	52.4	42.5	55.0	52.4	1.7	55.0	4.4
Vapor Frac	1.000	1.000	1.000	0.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000
Liquid Frac	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
Solid Frac	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Enthalpy J/kmol	2.54E+07	2.47E+07	8.89E+06	-2.86E+08	4.46E+06	4.16E+05	4.43E+06	2.67E+07	-2.75E+08	4.38E+06	3.31E+06	-1.25E+07	4.28E+05	2.62E+07	4.46E+06
Enthalpy J/kg	7.93E+05	8.23E+05	2.96E+05	-1.59E+07	1.54E+05	1.44E+04	1.54E+05	9.24E+05	-1.52E+07	1.52E+05	1.10E+05	-4.01E+06	1.48E+04	8.74E+05	1.55E+05
Enthalpy MW	21.05	56.75	20.43	-534.78	6.54	0.61	6.51	39.16	-18.90	6.44	7.60	-25.20	0.63	60.22	6.55
Entropy J/kmol-K	7.56E+03	1.23E+04	-7.62E+03	-1.63E+05	9.24E+03	-5.15E+03	-2.18E+03	1.25E+04	-1.33E+05	-1.50E+04	-1.82E+04	-2.19E+04	1.23E+03	1.38E+04	4.21E+03
Entropy J/kg-K	236.1	410.8	-254.1	-9042.4	320.2	-178.6	-75.4	433.4	-7385.0	-520.4	-606.0	-7033.5	42.5	460.3	146.1
Density kmol/cum	0.6	0.6	1.2	55.3	0.1	0.1	0.2	0.6	50.0	1.1	1.6	1.3	0.1	0.6	0.1
Density kg/cum	19.7	18.4	35.1	997.0	1.8	4.1	7.2	16.5	900.2	32.2	47.0	4.0	1.9	17.5	3.4
Average MW	32.00	29.99	29.99	18.02	28.85	28.85	28.85	28.85	18.02	28.85	29.99	3.12	28.85	29.99	28.85
Liq Vol 60F cum/sec	4.45E-02	1.23E-01	1.23E-01	3.38E-02	7.87E-02	7.87E-02	7.87E-02	7.87E-02	1.24E-03	7.87E-02	1.23E-01	1.03E-01	7.87E-02	1.23E-01	7.87E-02

8.3.3 Process Flow Diagrams

0



NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISCP	APPR
CLIENT						
Battelle Energy Alliance, LLC (BEA) Idaho Falls, Idaho						
TITLE						
NGNP – High Temperature Steam Electrolysis Clean Dry Air System Process Flow Diagram						
 Shaw Environmental & Infrastructure, Inc.						
DESIGNED BY RESP. ENGR.		DRAWN BY		CHECKED BY		COB
SCALE		DRAWING NUMBER				REV NO
NTS.		132155-T-PFD-HTSE-FUS-101				

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2

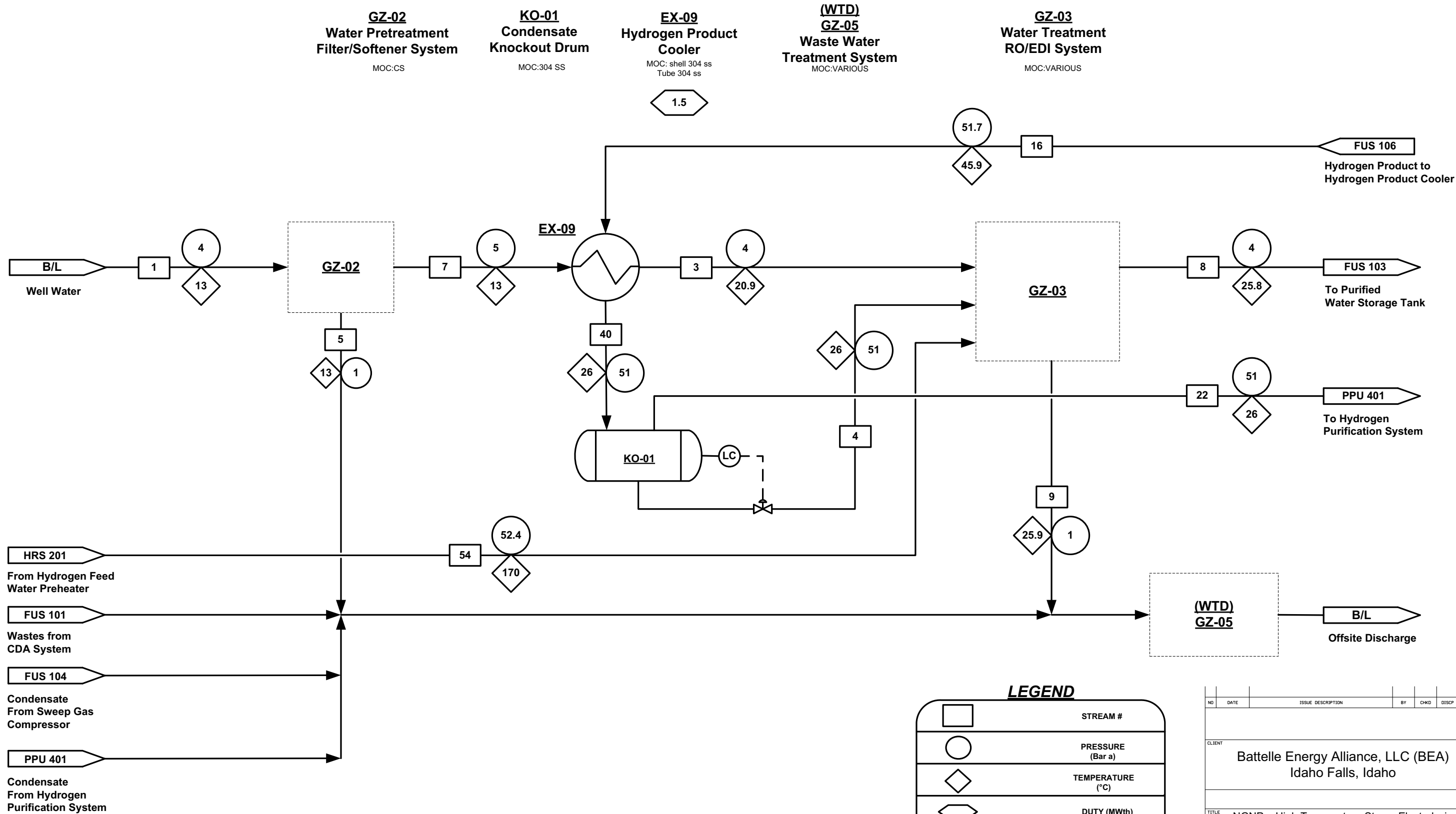
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4

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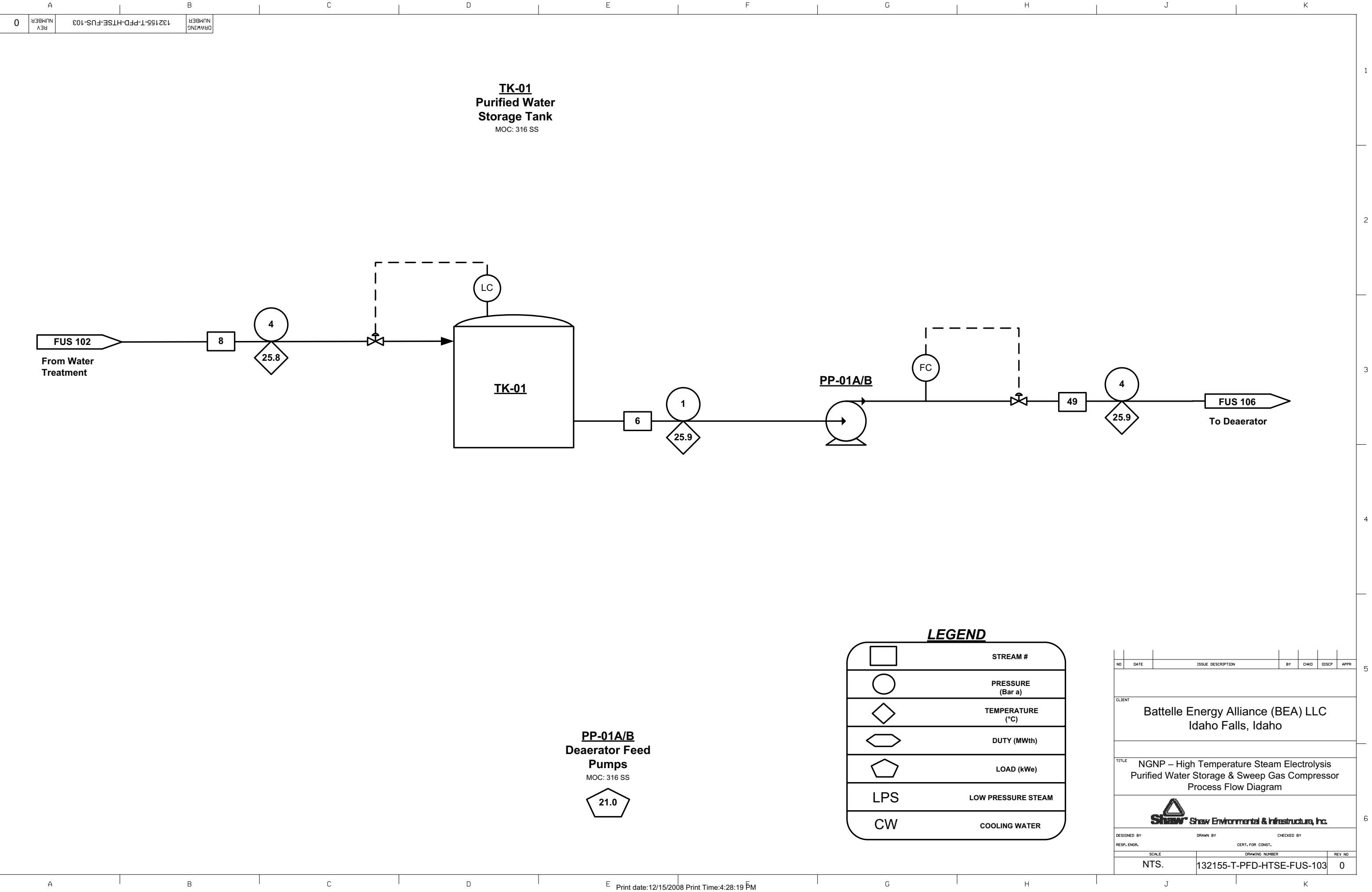
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A		B	
0	REV NUMBER	132155-T-PFD-HTSE-FUS-102	DRAWING NUMBER

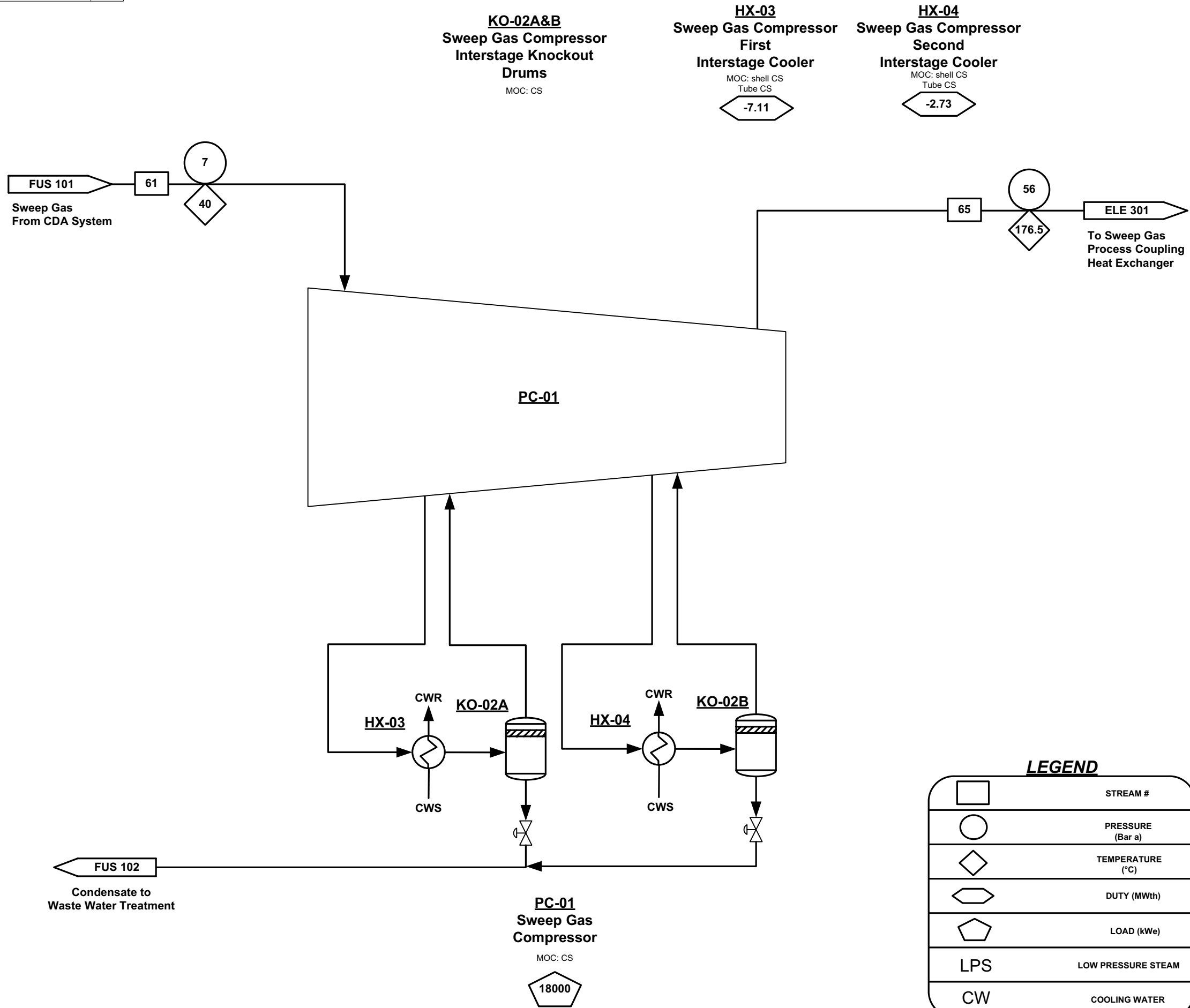


<u>LEGEND</u>	
	STREAM #
	PRESSURE (Bar a)
	TEMPERATURE (°C)
	DUTY (MWth)
	LOAD (kWe)
LPS	LOW PRESSURE STEAM
CW	COOLING WATER

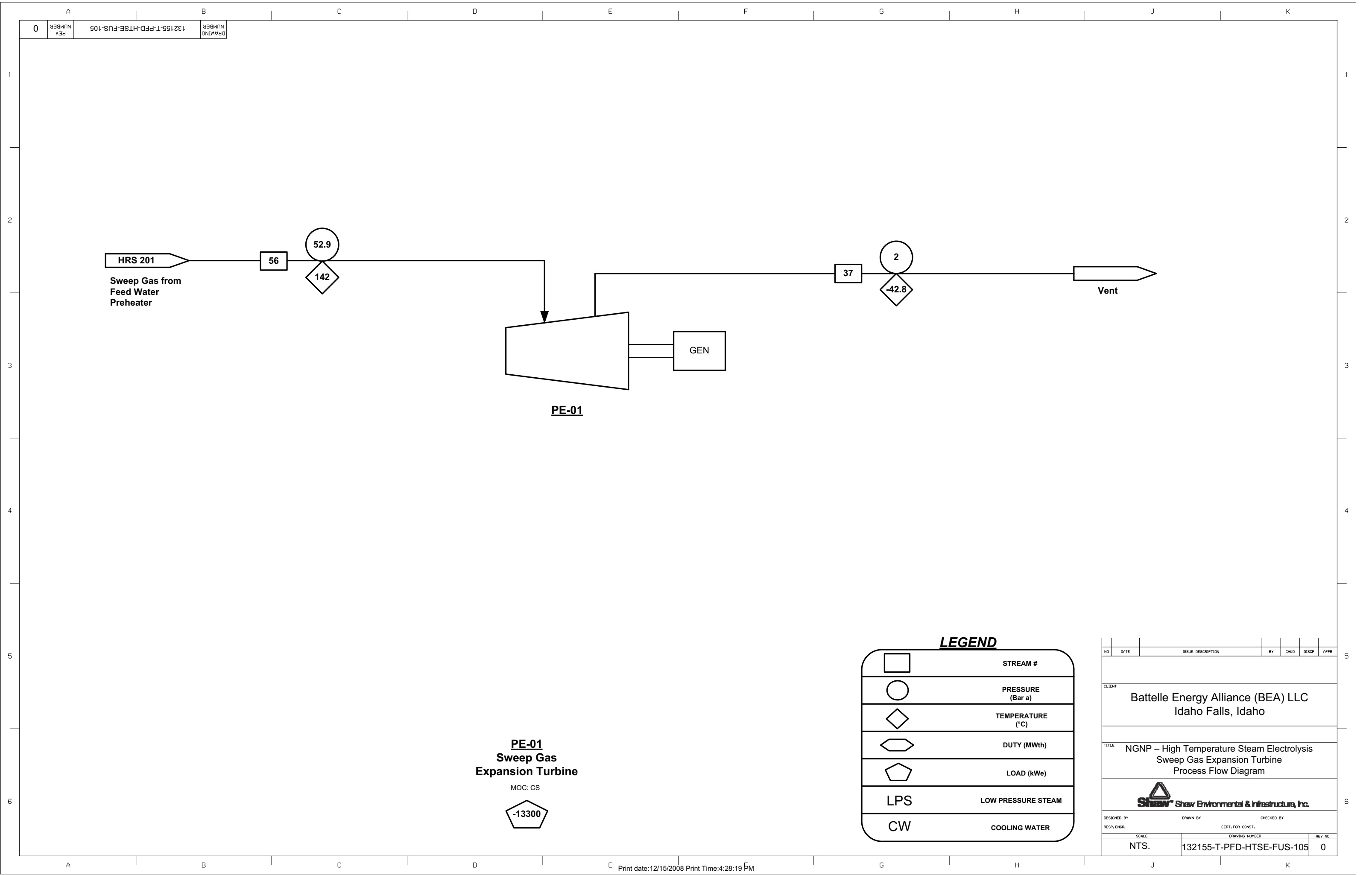
NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISCP	APPR
CLIENT Battelle Energy Alliance, LLC (BEA) Idaho Falls, Idaho						
TITLE NGNP – High Temperature Steam Electrolysis Water & Waste Water Treatment Process Flow Diagram						
 Shaw Environmental & Infrastructure, Inc.						
DESIGNED BY		DRAWN BY		CHECKED BY		
RESP. ENGR.		CERT. FOR CONST.				
SCALE		DRAWING NUMBER			REV NO	
NTS.		132155-T-PFD-HTSE-FUS-102			0	

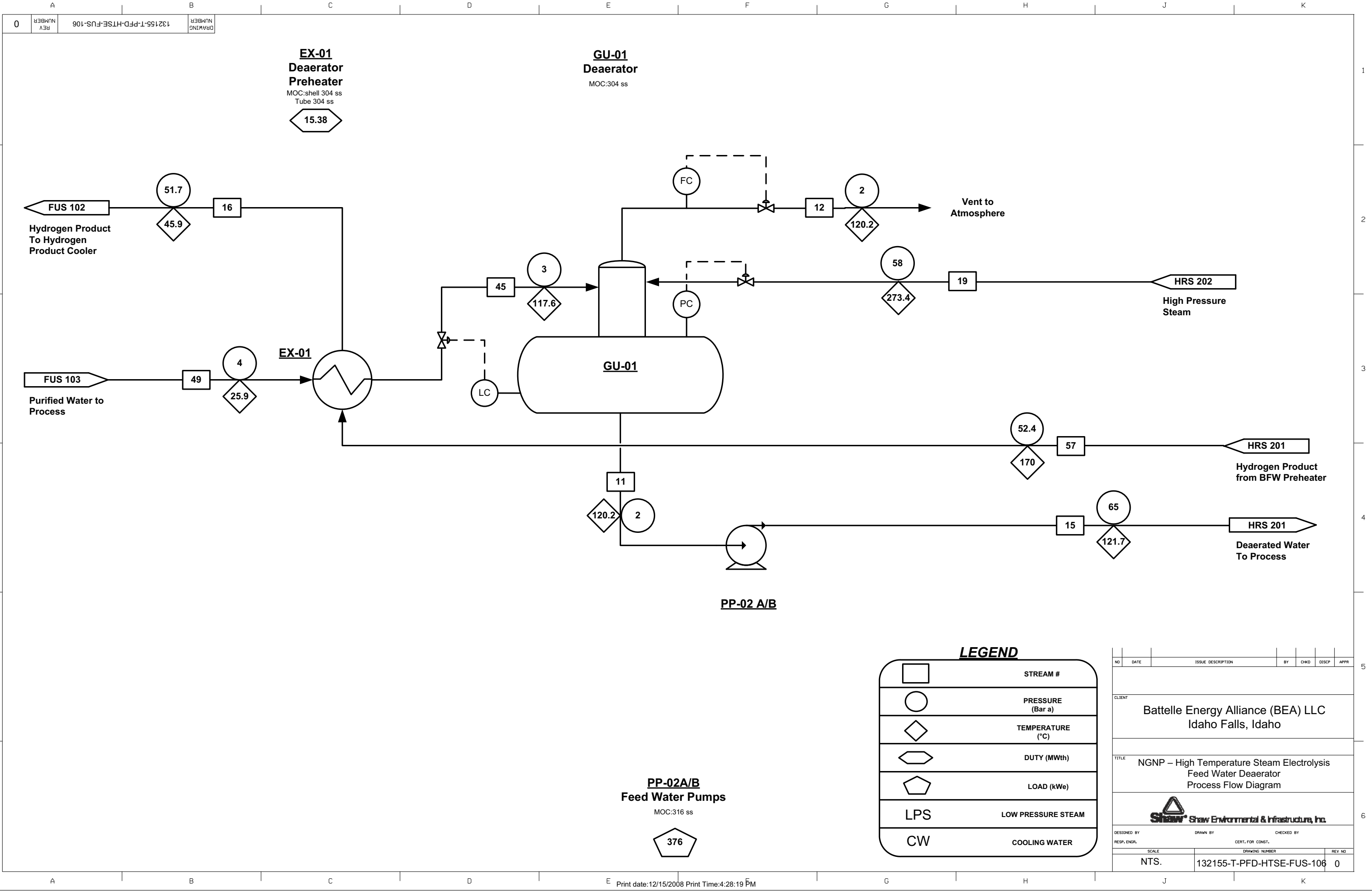


DRAWING NUMBER	132155-T-PFD-HTSE-FUS-104	REV NUMBER	0



NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISCP	APPR
CLIENT Battelle Energy Alliance (BEA) LLC Idaho Falls, Idaho						
TITLE NGNP – High Temperature Steam Electrolysis Purified Water Storage & Sweep Gas Compressor Process Flow Diagram						
 Shaw Environmental & Infrastructure, Inc.						
DESIGNED BY RESP. ENGR.		DRAWN BY		CHECKED BY		
		CERT. FOR CONST.				
SCALE		DRAWING NUMBER			REV NO	
NTS.		132155-T-PFD-HTSE-FUS-104			0	





LEGEND

STREAM #

PRESSURE (Bar a)

TEMPERATURE (°C)

DUTY (MWth)

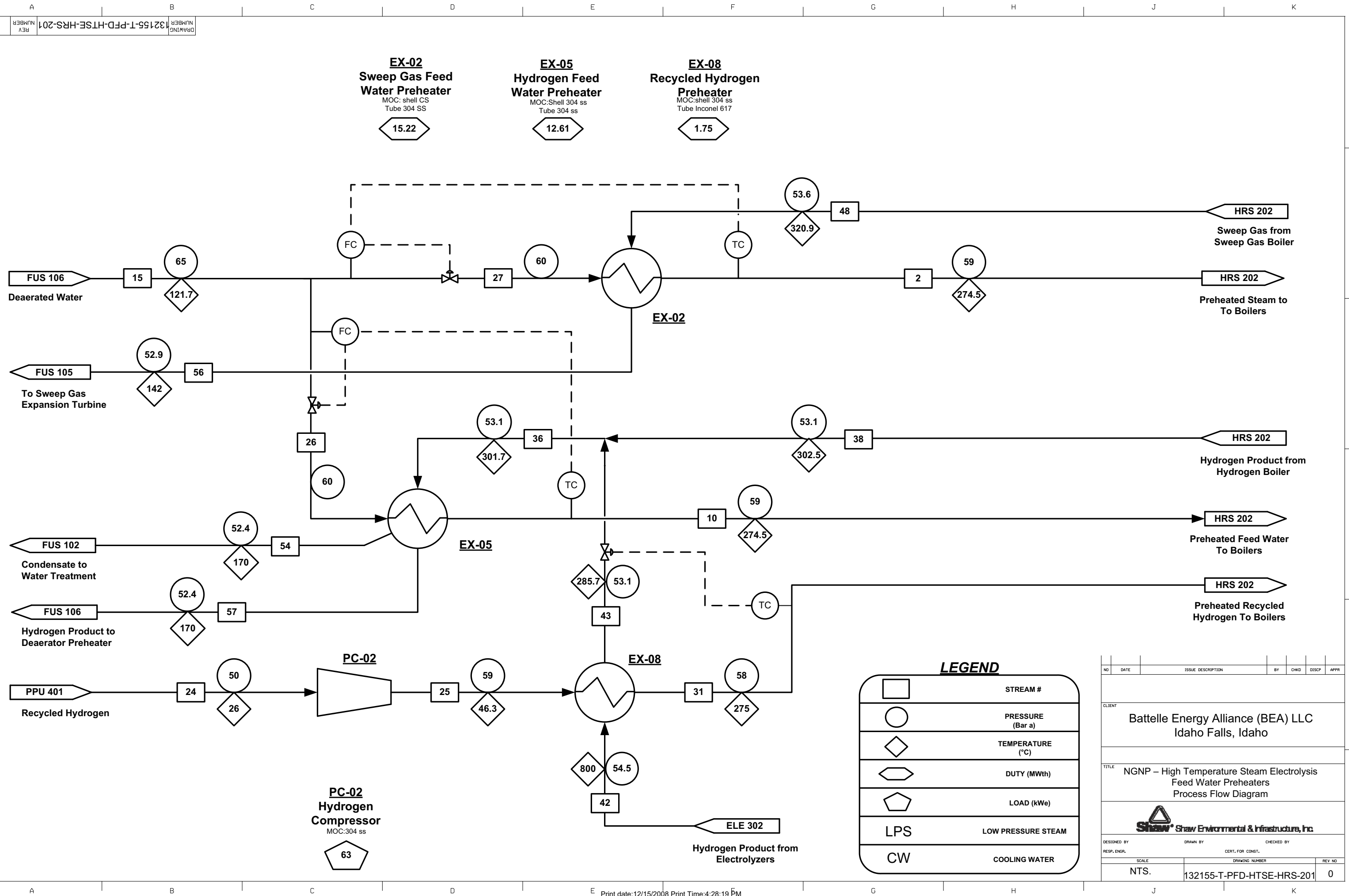
LOAD (kWe)

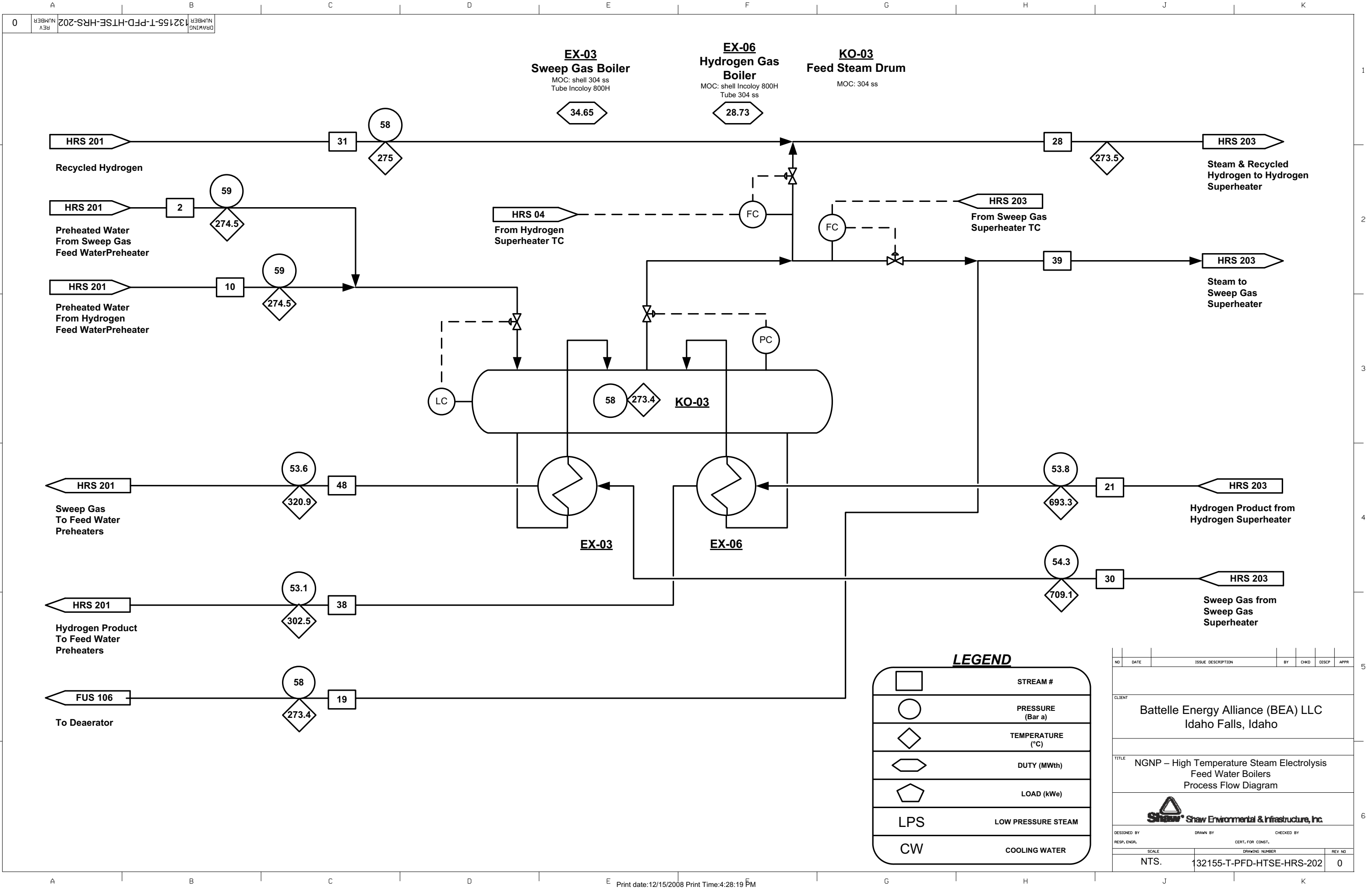
LOW PRESSURE STEAM

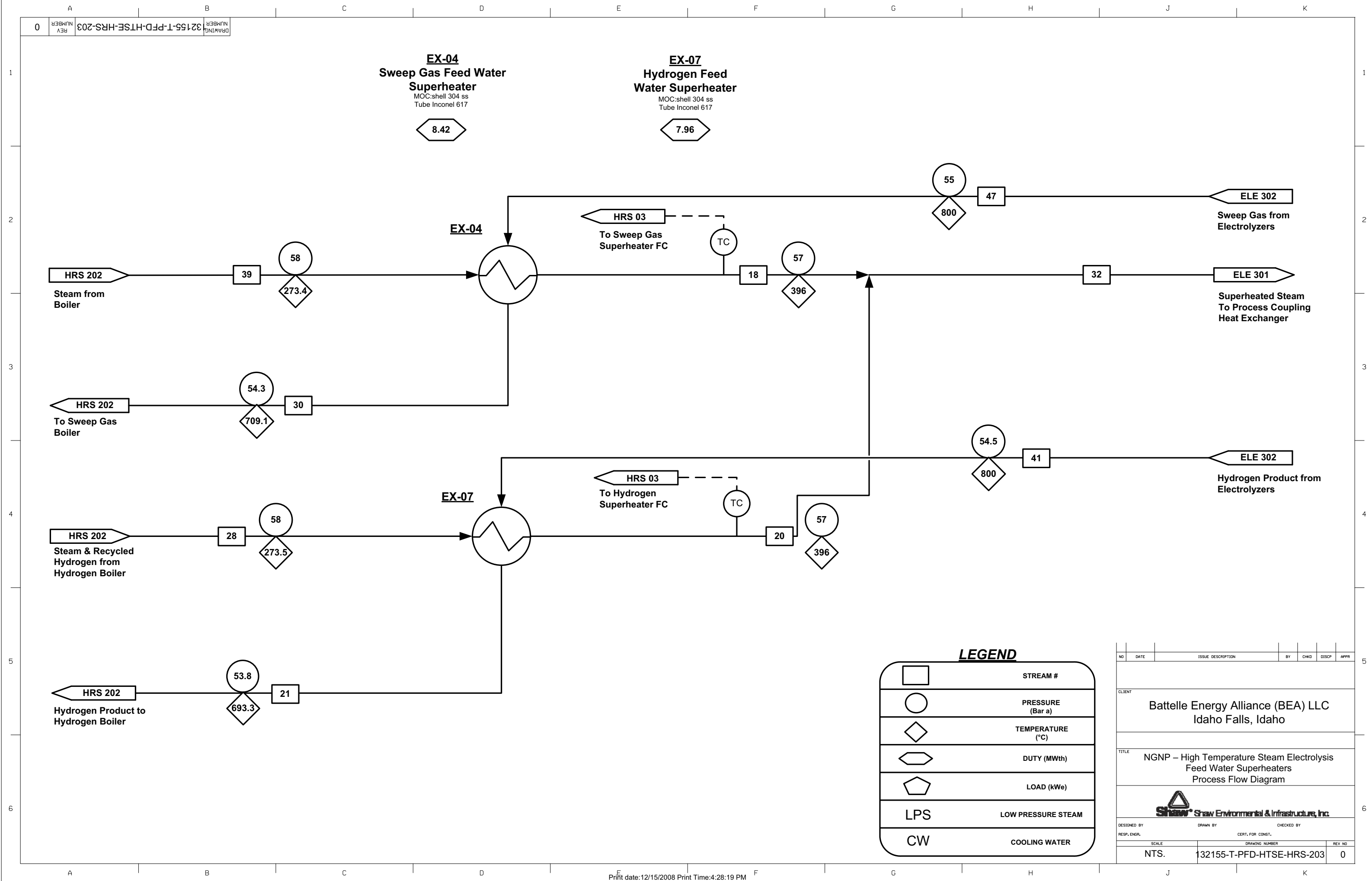
COOLING WATER

NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISCP	APPR
CLIENT Battelle Energy Alliance (BEA) LLC Idaho Falls, Idaho						
TITLE NGNP – High Temperature Steam Electrolysis Feed Water Deaerator Process Flow Diagram						
Shaw Environmental & Infrastructure, Inc.						
DESIGNED BY RESP. ENGR.		DRAWN BY		CHECKED BY CERT. FOR CONST.		REV NO
SCALE NTS.		DRAWING NUMBER 132155-T-PFD-HTSE-FUS-106				REV NO 0

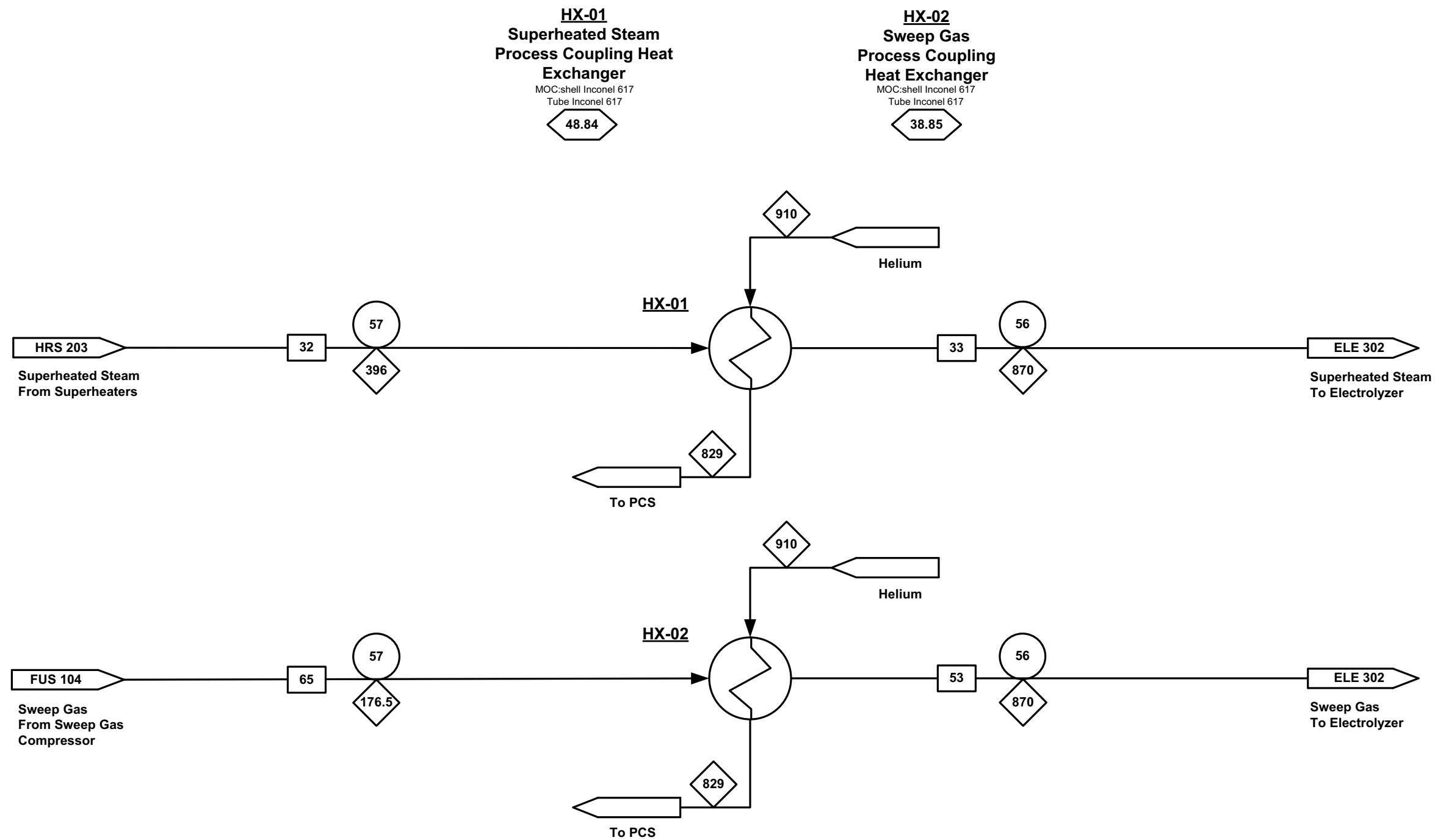
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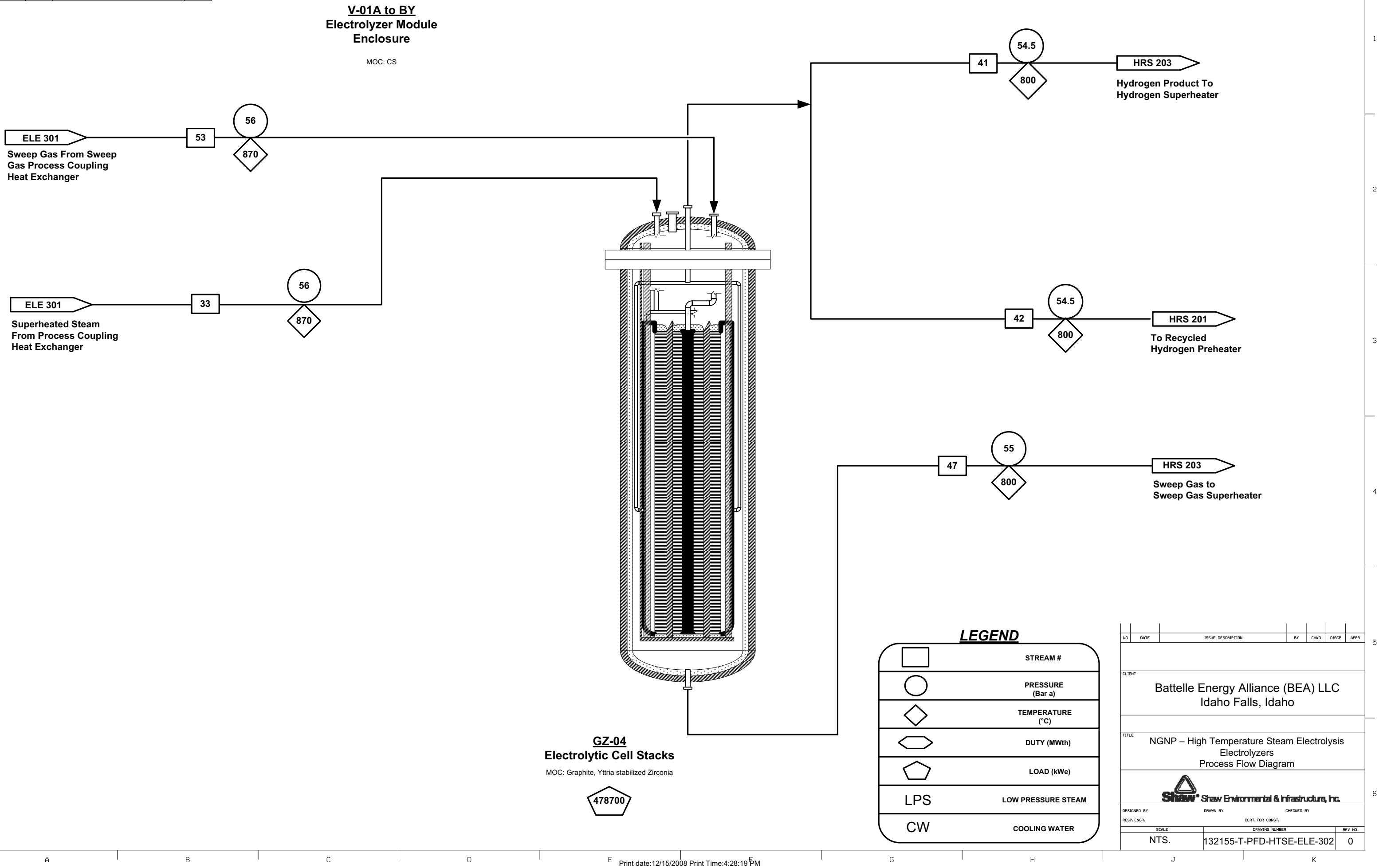
A		B	
0	REV NUMBER	132155-T-PFD-HTSE-ELE-301	DRAWING NUMBER

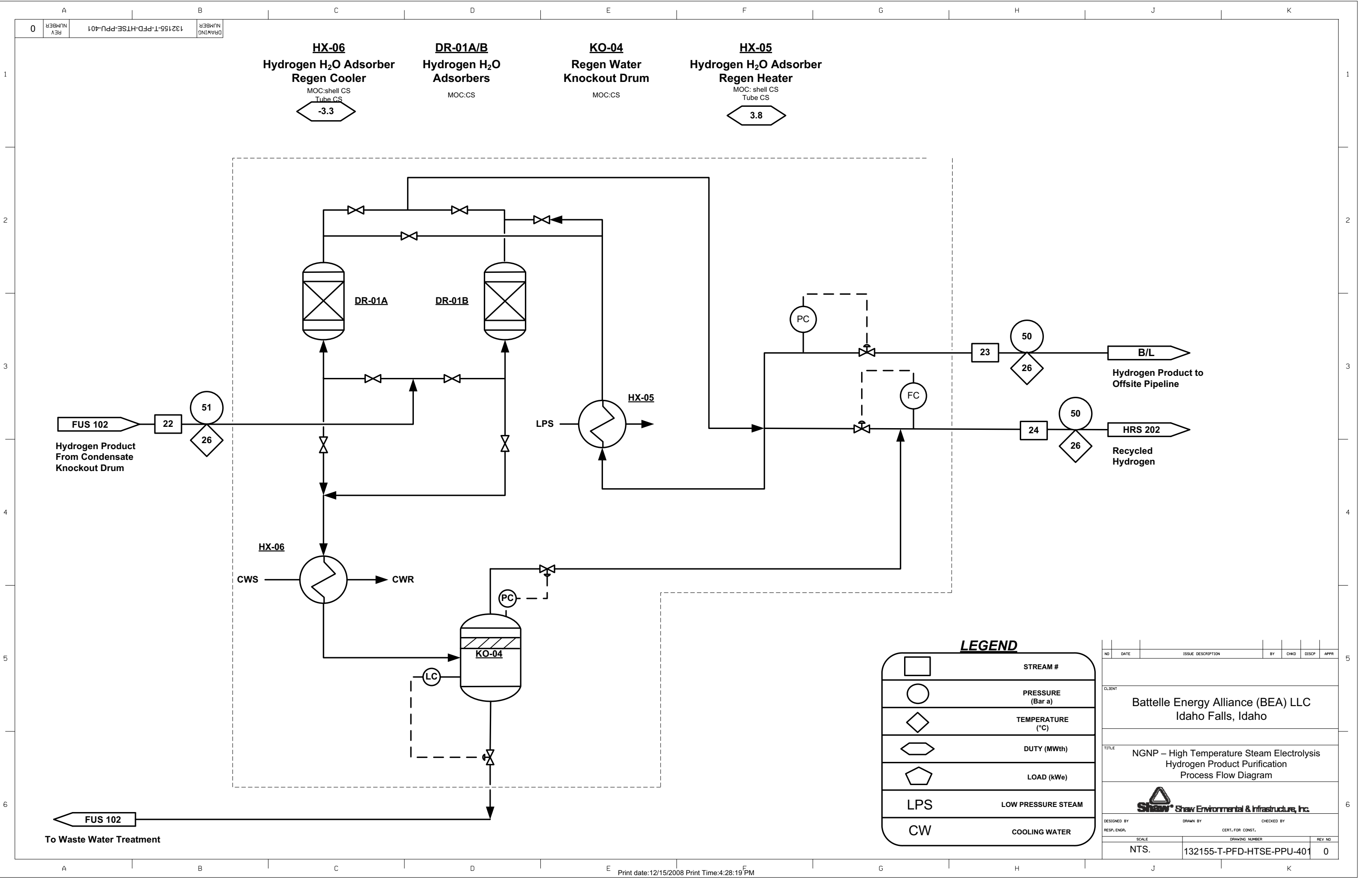


<u>LEGEND</u>	
	STREAM #
	PRESSURE (Bar a)
	TEMPERATURE (°C)
	DUTY (MWth)
	LOAD (kW _e)
LPS	LOW PRESSURE STEAM
CW	COOLING WATER

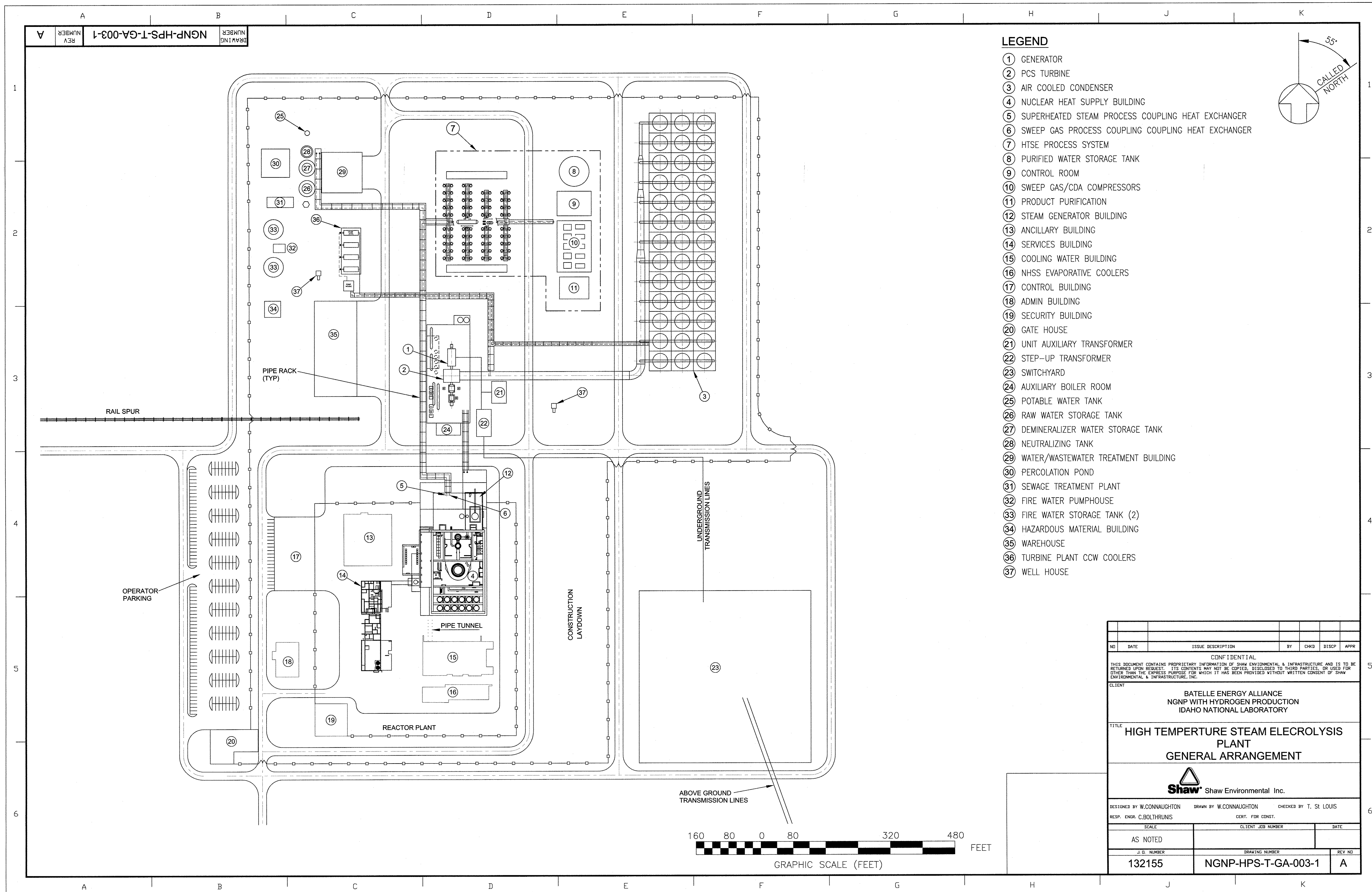
NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISCP	APPR
CLIENT Battelle Energy Alliance (BEA) LLC Idaho Falls, Idaho						
TITLE NGNP – High Temperature Steam Electrolysis Process Coupling Heat Exchangers Process Flow Diagram						
 Shaw Environmental & Infrastructure, Inc.						
DESIGN BY		DRAWN BY		CHECKED BY		
RESP. ENGR.		CERT. FOR CONST.				
SCALE		DRAWING NUMBER			REV NO	
NTS.		132155-T-PFD-HTSE-ELE-301			0	

	A	B	C	D	E	F	G	H	J	K
0	REV	NUMBER	32155-T-PFD-HTSE-ELE-302	DRAWING	NUMBER	32155-T-PFD-HTSE-ELE-302				





8.3.4 Summary Plot Plan Layout



LEGEND

- ① GENERATOR
- ② PCS TURBINE
- ③ AIR COOLED CONDENSER
- ④ NUCLEAR HEAT SUPPLY BUILDING
- ⑤ SUPERHEATED STEAM PROCESS COUPLING HEAT EXCHANGER
- ⑥ SWEEP GAS PROCESS COUPLING COUPLING HEAT EXCHANGER
- ⑦ HTSE PROCESS SYSTEM
- ⑧ PURIFIED WATER STORAGE TANK
- ⑨ CONTROL ROOM
- ⑩ SWEEP GAS/CDA COMPRESSORS
- ⑪ PRODUCT PURIFICATION
- ⑫ STEAM GENERATOR BUILDING
- ⑬ ANCILLARY BUILDING
- ⑭ SERVICES BUILDING
- ⑮ COOLING WATER BUILDING
- ⑯ NHSS EVAPORATIVE COOLERS
- ⑰ CONTROL BUILDING
- ⑱ ADMIN BUILDING
- ⑲ SECURITY BUILDING
- ⑳ GATE HOUSE
- ㉑ UNIT AUXILIARY TRANSFORMER
- ㉒ STEP-UP TRANSFORMER
- ㉓ SWITCHYARD
- ㉔ AUXILIARY BOILER ROOM
- ㉕ POTABLE WATER TANK
- ㉖ RAW WATER STORAGE TANK
- ㉗ DEMINERALIZER WATER STORAGE TANK
- ㉘ NEUTRALIZING TANK
- ㉙ WATER/WASTEWATER TREATMENT BUILDING
- ㉚ PERCOLATION POND
- ㉛ SEWAGE TREATMENT PLANT
- ㉜ FIRE WATER PUMPHOUSE
- ㉝ FIRE WATER STORAGE TANK (2)
- ㉞ HAZARDOUS MATERIAL BUILDING
- ㉟ WAREHOUSE
- ㊱ TURBINE PLANT CCW COOLERS
- ㊲ WELL HOUSE

NO	DATE	ISSUE DESCRIPTION	BY	CHKD	DISCP	APPR
CONFIDENTIAL						
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CLIENT BATELLE ENERGY ALLIANCE NGNP WITH HYDROGEN PRODUCTION IDAHO NATIONAL LABORATORY						
TITLE HIGH TEMPERTURE STEAM ELECROLYSIS PLANT GENERAL ARRANGEMENT						
Shaw Shaw Environmental Inc.						
DESIGNED BY W.CONNAUGHTON		DRAWN BY W.CONNAUGHTON		CHECKED BY T. ST LOUIS		
RESP. ENGR. C.BOLTHRUNIS		CERT. FOR CONST.		DATE		
SCALE AS NOTED		CLIENT JOB NUMBER		DATE		
J. O. NUMBER 132155		DRAWING NUMBER NGNP-HPS-T-GA-003-1		REV NO A		

8.3.5 Sized Equipment List

Battelle Energy Alliance, LLC (BEA)
Next Generation Nuclear Plant
Idaho Falls, Idaho
High Temperature Steam Electrolysis
Equipment List

Stone & Webster Project No. 132155

ISSUE	DATE	DESCRIPTION	ORIGR	CHK'R	SDE	PEM	INTERDISCIPLINE REVIEW		
							DISCIPLINE	REV'R	DATE
							Process		
							Mechanical		
							Civil/Structural		
							Control Systems		
							Power Systems		
C	12/17/08	Revised surface area of HX-01 & 02	TNS			COB	Piping		
B	10/14/08	Revisions for estimate	COB			COB	Material & Corr.		
A		For Estimate	KBG	MM	COB	COB			
FILE NAME			SHEET			DOC.NO.			
2008Dec17_HTSE Equipment List RevC.doc			1 of 10						

EQUIPMENT LIST – VESSELS / REACTORS

Client: Battelle Energy Alliance, LLC (BEA)

Signature: *Charles R. Bottorini*

Unit: HIGH TEMPERATURE STEAM ELECTROLYSIS

Location: Idaho Falls, Idaho (Use USGC for Estimate)

Item No.	Name	Diameter (mm)	Length (mm)	Horizon/ Vertical	Mechanical Design		Material C.A. (mm)	PFD	Remarks
					Pressure (bar g)	Temperature (°C)			
HTSE-FUS KO-01	Condensate Knockout Drum	1500	4500	Horizontal	55	65	304 ss	FUS 102	
HTSE-FUS KO-02A/B	Sweep Gas Compressor Interstage Knockout Drums	3200	9600	Horizontal	46	155	CS	FUS 104	
HTSE-HRS KO-03	Feed Steam Drum	2900	17400	Horizontal	63	305	304 ss	HRS 202	
HTSE-PPU KO-04	Regen Water Knockout Drum	1500	2500	Vertical	55	65	CS	PPU 401	
HTSE-PPU DR-01A/B	Hydrogen H ₂ O Adsorbers	4300	5800	Vertical	55	65	CS	PPU 401	
HTSE-FUS GU-01	Deaerator (Heater) (Storage)	2100 2100	1800 5100	Vertical Horizontal	3	160	304 ss	FUS 106	Kansas City Deaerator quote 10/2/08 : \$ 270,000; Freight: \$6700
HTSE-ELE V-01A to BY	Electrolyzer Module Enclosure	2200	7300	Vertical	61	150	CS	ELE 302	76 units. Full body flange on top head all nozzles enter through top head. Internally insulated: 50 mm Microtherm Slatted Super G and 50 mm Pyrogel 10350 (or equal)

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE B	DATE 14-OCT-08	SHEET 2 of 10	DOC NO

EQUIPMENT LIST – LOW PRESSURE TANKS

Client: Battelle Energy Alliance, LLC (BEA)					Signature: <i>Charles R. Botticini</i>			
Unit: HIGH TEMPERATURE STEAM ELECTROLYSIS					Location: Idaho Falls, Idaho (Use USGC for Estimate)			
Item No.	Name	Diameter (mm)	Height (mm)	Mechanical Design		Material C.A. (mm)	PFD	Remarks
				Pressure	Temperature (°C)			
HTSE-FUS TK-01	Purified Water Storage Tank	24,500	12,800	Ambient	50	316 ss (0)	FUS 103	6,000 m ³ purified water tank, 48 hrs storage. Cost included with HTSE-FUS-GZ-03

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 Shaw Environmental & Infrastructure, Inc.		ISSUE B	DATE 14-OCT-08	SHEET 3 of 10	DOC NO

EQUIPMENT LIST – PUMPS

Client: Battelle Energy Alliance, LLC (BEA)						Signature: <i>Charles R. Bottorini</i>			
Unit: HIGH TEMPERATURE STEAM ELECTROLYSIS						Location: Idaho Falls, Idaho (Use USGC for Estimate)			
Item No.	Name	Type	Rated Flow (m ³ /h)	Differential Pressure bar	Motor kW	Material		PFD	Remarks
						Casing	Impeller		
HTSE-FUS PP-01 A/B	Deaerator Feed Pumps	Horizontal Centrifugal End Suction	146	3.5	25	316ss A-8	316ss A-8	FUS 103	
HTSE-FUS PP-02 A/B	Feed Water Pumps	Multi-Stage Centrifugal	155	58	400	316ss A-8	316ss A-8	FUS 106	

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 Shaw Environmental & Infrastructure, Inc.		ISSUE B	DATE 14-OCT-08	SHEET 4 of 10	DOC NO

EQUIPMENT LIST – COMPRESSORS / BLOWERS / VACUUM PUMPS

Client: Battelle Energy Alliance, LLC (BEA)						Signature: <i>Charles R. Bottani</i>				
Unit: HIGH TEMPERATURE STEAM ELECTROLYSIS						Location: Idaho Falls, Idaho (Use USGC for Estimate)				
Item No.	Name	Type	Capacity (Am ³ /h)	Suction Pressure (bar a)	Differential Pressure (bar)	Driver		Material C.A.(mm)	PFD	Remarks
						Type	Rated Power (kW)			
HTSE-FUS PC-01	Sweep Gas Compressor	Multistage Centrifugal	23,200	7	50	Electric	15,200	CS	FUS 104	Total capacity and power shown. If necessary to divide into separate trains, number should be a multiple of 3
HTSE-HRS PC-02	Hydrogen Compressor	Centrifugal	480	50	59	Electric	195	304 ss	HRS 201	
HTSE-FUS PE-01	Sweep Gas Expansion Turbine	Turbo Expander	6270	53	51	Generator	5160	CS	FUS 105	Note this is a turbo expander. Power is estimated shaft power

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EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance, LLC (BEA)					Signature: <i>Charles R. Bottani</i>		
Unit: HIGH TEMPERATURE STEAM ELECTROLYSIS					Location: Idaho Falls, Idaho (Use USGC for Estimate)		
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HTSE-FUS EX-01	Deaerator Preheater	270	304 ss 56.5 200	304 ss 39 145	BFU	FUS 106	2 shells in series; Area is for total of 2 shells
HTSE-HRS EX-02	Sweep Gas Feed Water Preheater	950	CS 59 350	304 ss 65 350	BFU	HRS 201	3 shells in series; Area is for total of 3 shells
HTSE-HRS EX-03	Sweep Gas Boiler	335	304 ss 64 302	Incoloy 800H 59 737	BEM	HRS 202	
HTSE-HRS EX-04	Sweep Gas Feed Water Superheater	60	304 ss 63 425	Inconel 617 60 830	BFU	HRS 203	2 shells in series; Area is for total of 2 shells
HTSE-HRS EX-05	Hydrogen Feed Water Preheater	965	304 ss 58 330	304 ss 65 305	BFU	HRS 201	2 shells in series; Area is for total of 2 shells
HTSE-HRS EX-06	Hydrogen Gas Boiler	335	Incoloy 800H 58 721	304 ss 64 305	BEM	HRS 202	

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 Shaw Environmental & Infrastructure, Inc.		ISSUE B	DATE 14-OCT-08	SHEET 6 of 10	DOC NO

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance, LLC (BEA)				Signature: <i>Charles R. Bottum</i>			
Unit: HIGH TEMPERATURE STEAM ELECTROLYSIS				Location: Idaho Falls, Idaho (Use USGC for Estimate)			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HTSE-HRS EX-07	Hydrogen Feed Water Superheater	55	304 ss 63 425	Inconel 617 59 830	BFU	HRS 203	2 shells in series; Area is for total of 2 shells
HTSE-HRS EX-08	Recycled Hydrogen Preheater	15	304 ss 64 305	Inconel 617 60 830	BFU	HRS 201	2 shells in series; Area is for total of 2 shells
HTSE-FUS EX-09	Hydrogen Product Cooler	45	304 ss 56 75	304 ss 39 66	BEU	FUS 102	Feed water used to cool hydrogen product gas before Hydrogen Purification System
HTSE-ELE HX-01	Superheated Steam Process Coupling Heat Exchanger	590	Inconel 617 68 900	Inconel 617 98 940	BFU	ELE 301	2 shells in series; Area is for total of 2 shells
HTSE-ELE HX-02	Sweep Gas Process Coupling Heat Exchanger	430	Inconel 617 68 900	Inconel 617 98 940	BFU	ELE 301	2 shells in series; Area is for total of 2 shells
HTSE-FUS HX-03	Sweep Gas Compressor First Interstage Cooler	460	CS 18.5 205	CS 13 65	BEU	FUS 104	

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 Shaw Environmental & Infrastructure, Inc.		ISSUE B	DATE 14-OCT-08	SHEET 7 of 10	DOC NO

EQUIPMENT LIST – HEAT EXCHANGERS

Client: Battelle Energy Alliance, LLC (BEA)				Signature: <i>Charles R. Bottum</i>			
Unit: HIGH TEMPERATURE STEAM ELECTROLYSIS				Location: Idaho Falls, Idaho (Use USGC for Estimate)			
Item No.	Name	Area (m ²) (Total)	Mechanical Design		Type	PFD	Remarks
			Shell	Tube			
			Material Pressure (bar g) Temperature (°C)	Material Pressure (bar g) Temperature (°C)			
HTSE-FUS HX-04	Sweep Gas Compressor Second Interstage Cooler	55	CS 46 205	CS 32 65	BEU	FUS 104	
HTSE-PPU HX-05	Hydrogen H ₂ O Adsorber Regen Heater	75	CS 38 200	CS 55 110	BEU	PPU 401	
HTSE-PPU HX-06	Hydrogen H ₂ O Adsorber Regen Cooler	135	CS 38 65	CS 55 65	BEU	PPU 401	

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.		ISSUE B	DATE 14-OCT-08	SHEET 8 of 10	DOC NO

EQUIPMENT LIST – MISCELLANEOUS

Client: Battelle Energy Alliance, LLC (BEA)

Signature: 

Unit: HIGH TEMPERATURE STEAM ELECTROLYSIS

Location: Idaho Falls, Idaho (Use USGC for Estimate)

Item No.	Name	Material	PFD	Duty - Description - Remarks
HTSE-FUS GZ-01	Clean Dry Air (CDA) System	CS	FUS 101	53.85 kg/s (150,200 Nm ³ /hr) at 10.4 bara. The purity specification is the standard -40°C dew point. 6 parallel units, each unit with a 2 bed systems. Each unit includes a 5 stage compressor (2800 KW) and a 100 KW heater that operates about 50% of the time. Total Installed Cost: \$36.6 Million (including compressors, beds, heaters, controls)
HTSE-FUS GZ-02	Water Pretreatment Filter/Softener System	Various	FUS 102	Water treatment multimedia and zeolite softener system. System consist of two trains, each train having a capacity of 136 m ³ /hr (600 gpm). Vessels are plasite lined carbon steel. System consists of skid mounted feed pumps (2 x 100%), skid mounted backwash pumps (2 x 100%), skid mounted regeneration pumps (2 x 100%), two multi-media filter vessels (12 ft diameter each), two zeolite vessels (10 ft diameter each), and one salt dissolving tank. Total equipment cost: \$1.37 Million for equipment described above plus PLC controls. Quote from Aquatech via email dated 10/3/08.
HTSE-FUS GZ-03	Water Treatment RO/EDI System	Various	FUS 102	Reverse Osmosis, Electric Deionization System, 8 x 120 gpm RO/EDI trains. System capacity 720 gpm, with 240 gpm installed spare capacity. RO/EDI equipment pricing based on Jan 2008 estimate for Duke Buck combined cycle plant. 6,000 m ³ purified water tank, 48 hrs storage, \$528/m ³ installed cost. Water Purification Building, 836 m ² , \$3122/m ² installed. Total Installed System Cost: \$28.6 Million (including tank, building and foundations and electrical)
HTSE-ELE GZ-04 A to BY	Electrolytic Cell Stack Modules	Graphite, Ytria stabilized Zirconia	ELE 302	76 modules each with 4 stacks of 2500 cells. Cells are 50 cm by 50 cm area. 2500 m ² cell area per module. Cost provided by others: Later DC conversion, cables and electrical controls and connections: (Later, by others)

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE B	DATE 14-OCT-08	SHEET 9 of 10	DOC NO

EQUIPMENT LIST – MISCELLANEOUS

Client: Battelle Energy Alliance, LLC (BEA)

Signature: 

Unit: HIGH TEMPERATURE STEAM ELECTROLYSIS

Location: Idaho Falls, Idaho (Use USGC for Estimate)

Item No.	Name	Material	PFD	Duty - Description - Remarks
HTSE- WTD-GZ- 05	Waste Water Treatment System	Various	FUS 102	Corrugated inclined plate oil/water separator, 200 gpm capacity. Equipment includes tank, separation media, pumps and control panel. Total Equipment Cost for tank, media, controls, sludge pumps and oil transfer pumps: \$32,100 (does not include freight, or interconnecting piping, foundations etc...) Quoted price from Pan America Environmental for Model OF-80 separator

Note: Above data (except for Item No. and name) shall not be used for design purposes. For this purpose the data on the relevant specification/data sheets shall be used

 Shaw Environmental & Infrastructure, Inc.	ISSUE B	DATE 14-OCT-08	SHEET 10 of 10	DOC NO

8.3.6 Preliminary Hazards Analysis

Section 8.3.6: NGNP HTSE Preliminary Hazard Assessment

Item	Risk	Comments
Electrolytic Cell	Leak between H ₂ and O ₂ -enriched streams resulting in a fire	Need to consider the safety consequences of a crack in the solid electrolyte or at any of the seals within the electrolyzer. Since the H₂ is above its auto-ignition temperature, one would expect a leak in either direction to result in an immediate fire. As the fire raised the temperature of the contained gas, equipment rupture could occur if the relief devices were not sized for an internal fire. Fortunately, the leak rate should be low due to the lack of significant pressure difference between the H₂ and sweep streams. Since routine inspection of the electrolyzer internals will be difficult, a means of leak detection should be considered (perhaps a high temperature alarm) and a means devised for shutting down appropriate sections. The minimization of non-ceramic materials in the design of the electrolyzer will minimize the fuel present in the case of a fire.
Sweep gas turbine	Fire resulting from rotating machinery acting on an O ₂ -enriched stream	Expansion turbines are routinely used within the industrial gases industry with streams of 50 - 70% O₂. There is no industrial experience of fires in such equipment. The inlet temperature and pressure in the present application, however, are both higher than normally seen. The use of a fire barrier around this equipment, as is used with O₂ compressors, should be considered. 50% O₂ at 53 bara is at the upper limit of streams that can be treated as "oxygen enriched" rather than "oxygen". The classification affects design criteria including materials of construction, seal configuration and cleaning/inspections specifications.

Item	Risk	Comments
Sweep gas- 50% O ₂ at high T & P	The enhanced flammability of materials in O ₂ -enriched air resulting in an equipment fire	All piping, fittings and equipment exposed to > 25% oxygen must be oxygen-clean before start up. Fittings that are O₂-cleaned at the factory must be shipped sealed. At 56 bar and < 300°C, carbon steel might be used but velocity limits would need to be imposed to minimize the impact energy of any particles carried by the gas stream. The pipe should have a minimum thickness of 4.8 mm to minimize flammability. Special attention must be given to the material of construction of thin metal items such as filters and strainers and items in high velocity regions such as valve stems. 50% O₂ at 870°C and 56 bar is far outside of the range of industrial experience. Certainly a Ni alloy would be required. At 50% oxygen, stainless steel may be acceptable with velocity limits. Testing would be recommended before final specification. The Marshall Space Flight Center has appropriate equipment for such testing. The electrical connections and wiring within the electrolyzer must be designed for exposure to the O₂-enriched sweep gas within the electrolyzer vessel. The use of soft materials and lubricants should be minimized with oxygen-enriched streams. Fluorinated compounds such as Teflon™ and Viton™ are normally used for seals and per-fluorinated materials as lubricants. Temperature limits must of course be considered when using these materials..
H ₂	Loss of containment of a flammable gas at high pressure and temperature resulting in a fire or explosion	Materials of construction: Per API Publication 941, steel cannot be used with H₂ at 56 bar above about 600°C. More exotic materials such as Inconel will need to be identified for the higher temperature equipment. Due to the flammability of H₂, mechanical joints should be avoided in this piping system. The identification of appropriate seals may be an issue. The possibilities of a jet fire or a confined vapor cloud explosion in the region of potential leak points should be considered in the development of the plant layout.

Item	Risk	Comments
Processing Coupling Heat Exchangers	Loss of containment of high pressure air, steam or He. Contamination of He stream due to tube leaks and materials incompatibility.	Keeping the pressure of the He stream above that of the electrolyzer feed should prevent leakage into the He.
Steam generation Heat recuperation and Steam generation equipment	Equipment fires, vessel failures, hydrogen leaks resulting in fire	Aside from the H ₂ and O ₂ -enriched air materials of construction issues noted above, this system should be composed of standard equipment routinely used in industry with standard safety measures.
Water treatment	No extra ordinary risk	This system should be standard equipment routinely used in industry with standard safety measures.
Air Compressor	No extra ordinary risk	This system should be standard equipment routinely used in industry with standard safety measures.
CDA system	No extra ordinary risk	This system should be standard equipment routinely used in industry with standard safety measures.
H ₂ compressor	Hydrogen leaks resulting in fire	This design is within industrial gases industry experience. Standard safety measures should be incorporated into the design.
H ₂ Driers	Hydrogen leaks resulting in fire	This system should be standard equipment routinely used in industry with standard safety measures.

8.3.7 Capital Cost Estimate

Section 8.3.7 – HTSE Capital Cost Estimate

ELE System

	<u>Qty</u>	<u>Cost</u>
<u>Equipment</u>		
Electrolyzers		
Electrolytic Cell Stacks		1,881,579
Cell Stack Assembly		184,211
Electrolyzer Module Enclosure		151,500
Electrolyzer Module Enclosure Insulation		120,408
each module		2,337,697
total	76	177,665,000
Superheated Steam Process Coupling Exch	2	1,014,000
Sweep Gas Process Coupling Exch	2	748,000
Helium Control Valves	12	2,400,000
Subtotal Equipment		181,827,000
<u>Installation</u>		
Construction		
Labor		35,425,000
Equipment & Supplies		1,949,000
Construction Equipment		3,485,000
Vendor Services		300,000
Sub-subtotal Construction		41,159,000
Bulk Material		81,613,000
EPC Engineering		33,696,000
Spares		3,706,000
Freight		12,339,000
Other Costs - Catalyst, Desiccant		0
Subtotal Installation		172,513,000
ELE System Total		354,340,000

HRS System

	<u>Qty</u>	<u>Cost</u>
<u>Equipment</u>		
Feed Steam Drum	1	2,651,000
Deaerator	1	63,000
Deaerator	2	1,013,000
Hydrogen Compressor	1	5,760,000
Deaerator Preheater	2	155,000
Sweep Gas Feed Water Preheater	3	382,000
Sweep Gas Boiler	1	405,000
Sweep Gas Feed Water Superheater	2	285,000
Hydrogen Feed Water Preheater	2	331,000
Hydrogen Gas Boiler	1	322,000
Hydrogen Feed Water Superheater	2	274,000
Recycled Hydrogen Preheater	2	149,000
Subtotal Equipment		11,790,000
<u>Installation</u>		
Construction		
Labor		9,321,000
Equipment & Supplies		416,000
Construction Equipment		747,000
Vendor Services		150,000
Sub-subtotal Construction		10,634,000
Bulk Material		8,676,000
EPC Engineering		6,480,000
Spares		307,000
Freight		1,020,000
Other Costs - Catalyst, Desiccant		1,000,000
Subtotal Installation		28,117,000
HRS System Total		39,907,000

FUS System

	<u>Qty</u>	<u>Cost</u>
<u>Equipment</u>		
Clean Dry Air System	1	36,600,000
Water Pretreatment Filter/Softener System	1	1,370,000
Water Treatment RO/EDI System & Tank	1	28,600,000
Waste Water Treatment System	1	1,000,000
Condensate KO Drum	1	134,000
Sweep Gas Compressor Interstage KO Drums	4	1,125,000
Deaerator Feed Pumps	2	106,000
Sweep Gas Compressor	1	6,883,000
Sweep Gas Turbine	1	3,234,000
Hydrogen Product Cooler	1	43,000
Sweep Gas Compressor 1st Interstage Cooler	1	73,000
Sweep Gas Compressor 2nd Interstage Cooler	1	27,000
Subtotal Equipment		79,195,000
<u>Installation</u>		
Construction		
Labor		8,946,000
Equipment & Supplies		497,000
Construction Equipment		890,000
Vendor Services		0
Sub-subtotal Construction		10,333,000
Bulk Material		5,218,000
EPC Engineering		4,590,000
Spares		289,000
Freight		953,000
Other Costs - Catalyst, Desiccant		0
Subtotal Installation		21,383,000
FUS System Total		100,578,000

PPU System

	<u>Qty/Train</u>	<u>Cost</u>
<u>Equipment</u>		
Hydrogen H2O Adsorbers	2	1,234,000
Regen Water KO Drum	1	40,000
Hydrogen H2O Adsorber Regen Heater	1	32,000
Hydrogen H2O Adsorber Regen Cooler	1	43,000
Subtotal Equipment		1,349,000
<u>Installation</u>		
Construction		
Labor		3,034,000
Equipment & Supplies		169,000
Construction Equipment		303,000
Vendor Services		0
Sub-subtotal Construction		3,506,000
Bulk Material		2,428,000
EPC Engineering		1,620,000
Spares		57,000
Freight		187,000
Other Costs - Catalyst, Desiccant		4,879,000
Subtotal Installation		12,677,000
PPU system total		14,026,000

Total HTSE Hydrogen Production System Cost

ELE System Total	354,340,000
HRS System Total	39,907,000
FUS System Total	100,578,000
PPU System Total	14,026,000

Grand Total	508,851,000

8.3.8 Operating Cost Estimate

Section 8.3.8 – HTSE Operating Cost Estimate

8.3.8.1: Overall Plant Operating Costs

Fixed Operation & Maintenance				<u>\$/year</u>
Total plant staff (Direct labor)				
	HPS	40	FTEs	
	PCS	25	FTEs	
	BOP	36	FTEs	
	Total	101	FTEs	
	Composite rate	50	\$/hr	
	Overhead rate	60	%	
	Burdened rate	80		
	Annual labor			\$ 16,806,400
	G&A			
	rate	20	%	
	G&A			\$ 3,361,280
	Material costs for maintenance and repairs			
	HPS			\$ 772,555
	PCS			\$ 100,000
	BOP			\$ 100,000
	Total			\$ 972,555
	Licenses			
	Property Tax & Insurance			\$ 18,055,779
	Other			
		Subtotal		\$ 39,196,014
Heat				
	Use	527.89	MWt	
	Rate	30	\$/MWt-h	
	Cost			\$ 138,729,492
	Total Fixed O&M			\$ 177,925,506

Variable Operation & Maintenance
\$/year

Electric power consumption									\$ 224,887,754
rate	75	\$/MWe-h							
annual cost									
Cooling water consumption									\$ 563,958
q	2664	m ³ /hr	=	49.17	gal/kg H ₂				
trains	2			0.37	m ³ /sec				
C _{S,u}	0.026	\$/m ³							
Process water									
supply - natural									
water									
q	184	m ³ /hr	=	3.40	gal/kg H ₂				
C _{S,u}	0.069	\$/m ³						\$ 103,766	
softening									
q	166	m ³ /hr							
	0.079	\$/m ³						\$ 107,608	
RO/EDI									
q	132	m ³ /hr							
	0.403	\$/m ³						\$ 436,506	
Total Unit Cost			0.002	\$/gal					
								Total Water Cost	\$ 647,881
Other Material Costs									
Electrolyzer refurbishment								in Replacement Capital	
Mol sieves	109	\$/hr						\$ 894,412	
								Total Other Material Costs	\$ 894,412
Waste treatment costs									\$ 28,502,454
q	15.58	kg/s							
C _{S,u}	0.248	\$/kg	÷ 4 =	0.06193	\$/kg				

Solid waste disposal costs	\$	-
Total Unplanned Replacement Capital Cost Factor (% of total direct depreciable costs/year)	0.50	%
Total Variable O&M	\$ 255,496,458	

8.3.8.2: Detail, Hydrogen Production System Operating Costs**NGNP HPAS HTSE Operating Usages**

[All usages are on a per train basis. HTSE Plant has One (1) train]

Operating hours per year 8200**Staffing:**

Operations:	3	per shift
Maintenance	5	per shift
	4	additional, day shift only (these should cover the electrolyzer replacement labor)
Supervision & Engineering		

Plant Mgr, Assistant, Engineer and Administrative assistant.

Electricity

Electrolysis total	MW _e h/h	478.7

Steam

none

Cooling Water

Plant total	m ³ /h	2,664

Catalyst and ChemicalsHourly costs

Water softening chemicals	(included in process water cost)

Mole sieves	\$ 109

Replacements

	per module costs	Annual Replacements	Hourly costs	
Electrolyzers				
Cell stacks	\$1,880,000	4	\$917	
Stack assembly/Refurbishing	\$184,000	7	\$157	
Enclosure	\$270,000	2	\$66	
Installation: Stack (replacement or refurbishing)		40 effort hours		Included in maintenance hours
Installation: Enclosure		50 effort hours		hours
RO membranes				(included in process water cost)

Process Water

Usage	50.16	kg/s
Density	999.6	kg/m ³
Boiler blowdown	2%	
Supply	184	m ³ /h
Softened	166	m ³ /h
RO/EDI	132	m ³ /h

Costs	Supply	0.069	\$/m ³
	Softening	0.079	\$/m ³
	RO/EDI	0.403	\$/m ³

Ulrich & Vasudevan, "How to estimate Utility Costs," Chem. Eng., Apr 2006, pp. 66-69: Natural Water Pumped and screened.

Wastes

Liquid Effluent	From Softening	5.02	kg/s
	From RO/EDI	9.56	kg/s
	Blowdown	1.00	kg/s
	Total	15.58	kg/s
		56,102	kg/h

	0.248	\$/kg	1/4 of Ulrich, "Conventional Liquid Waste"
Solid Wastes	Damaged stacks	no cost	Assumed damaged stacks are returned to the manufacturer for recycle

Vapor Effluent	Sweep gas:	no cost

8.4 TECHNOLOGY DEVELOPMENT

- 8.4.1 Technology Readiness Levels
- 8.4.2 Design Data Needs
- 8.4.3 Design Tasks

8.4.1 Technology Readiness Levels

Sulfuric Acid Decomposition TRLs (Page 1)

Sulfur Dioxide Electrolysis TRLs (Page 12)

Bunsen Reaction and HI Decomposition TRLs (Page 22)

High Temperature Steam Electrolysis TRLs (Page 32)

Sulfuric Acid Decomposition TRLs

TRL Rating Sheet			
Document Number:		009	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: H ₂ SO ₄ Decomposer Tubes and Tube Array			
Description: an SSE of the H ₂ SO ₄ Decomposer of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS			
Facility: ☐ NHSS ☐ HTS ☒ HPS ☐ PCS ☐ BOP			
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Proof-of concept	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.
TRL	3	4	5
Basis for Rating (Attach additional sheets as needed)			
The silicon carbide bayonet tube H ₂ SO ₄ Decomposer has been demonstrated as a separate component, as documented in reports by Sandia Laboratories [Ref. Parma, E., <i>et al.</i> "Modeling the Sulfuric Acid Decomposition Section for Hydrogen Production," ANS Topical Meeting, June 24-28, 2007, Boston] and has functioned in the S-I ILS.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
DDN(s) supported: HPS-SAD-01 through HPS-SAD-13			
Subject Matter Expert Making Determination: meeting, Denver, 20NOV08			
Date: 20NOV08	Originating Organization: - -		

Rev. AUG08, DTA

TRL Rating Sheet						
Document Number:		031	Revision:			
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component			
Title: H ₂ SO ₄ Decomposer Internal Manifolds and Seals						
Description: an SSE of the H ₂ SO ₄ Decomposer of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS						
Facility: ☐ NHSS ☐ HTS ☒ HPS ☐ PCS ☐ BOP						
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 33%; height: 20px;"></td> <td style="width: 33%; height: 20px;"></td> <td style="width: 33%; height: 20px;"></td> </tr> </table>						
Technology Readiness Level						
	Next Lower Rating Level	Rating	Next Higher Rating Level			
Generic Definitions (<i>abbreviated</i>)	Proof-of concept	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.			
TRL	3	4	5			
Basis for Rating (Attach additional sheets as needed)						
The silicon carbide bayonet tube H ₂ SO ₄ Decomposer has been demonstrated as a separate component, as documented in reports by Sandia Laboratories [Ref. Parma, E., <i>et al.</i> "Modeling the Sulfuric Acid Decomposition Section for Hydrogen Production," ANS Topical Meeting, June 24-28, 2007, Boston] and has functioned in the S-I ILS.						
Outline of a plan to get from current level to next level (Attach additional sheets as needed)						
Actions (list all)		Schedule	Cost (k\$)			
DDN(s) supported: HPS-SAD-01 through HPS-SAD-13						
Subject Matter Expert Making Determination: meeting, Denver, 20NOV08						
Date: 20NOV08	Originating Organization: - -					

Rev. AUG08, DTA

TRL Rating Sheet						
Document Number:		032	Revision:			
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component			
Title: H ₂ SO ₄ Decomposer Vessel						
Description: an SSE of the H ₂ SO ₄ Decomposer of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS						
Facility: ☐ NHSS ☐ HTS ☒ HPS ☐ PCS ☐ BOP						
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 33%; height: 30px;"></td> <td style="width: 33%;"></td> <td style="width: 33%;"></td> </tr> </table>						
Technology Readiness Level						
	Next Lower Rating Level	Rating	Next Higher Rating Level			
Generic Definitions (<i>abbreviated</i>)	Proof-of concept	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.			
TRL	3	4	5			
Basis for Rating (Attach additional sheets as needed)						
The silicon carbide bayonet tube H ₂ SO ₄ Decomposer has been demonstrated as a separate component, as documented in reports by Sandia Laboratories [Ref. Parma, E., <i>et al.</i> "Modeling the Sulfuric Acid Decomposition Section for Hydrogen Production," ANS Topical Meeting, June 24-28, 2007, Boston] and has functioned in the S-I ILS.						
Outline of a plan to get from current level to next level (Attach additional sheets as needed)						
Actions (list all)		Schedule	Cost (k\$)			
DDN(s) supported: HPS-SAD-01 through HPS-SAD-13						
Subject Matter Expert Making Determination: meeting, Denver, 20NOV08						
Date: 20NOV08	Originating Organization: - -					

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		030	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Decomposer Catalyst			
Description: an SSE of the H ₂ SO ₄ Decomposer of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology concept and application formulated	Proof-of concept	Technology or component is tested at bench scale.
TRL	2	3	4
Basis for Rating (Attach additional sheets as needed)			
Performance and candidate catalytic materials have been identified, but not fully defined. Lab tests (SNL) have been performed, but one of the critical performance issues, catalyst life, has not been proven. Therefore all critical functions have not been proven in the laboratory. Candidate catalytic materials that have a reasonable operating life must be identified before the catalyst can be properly designed.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
DDN(s) supported: HPS-SAD-2			
Subject Matter Expert Making Determination: Charles O. Bolthrunis			
Date: 08AUG07	Originating Organization: Shaw Stone & Webster		
Modified: Daniel Allen	Changed TRL 1 to TRL 3, consequence of review meeting in Denver, 07NOV08.		
Date: 07NOV08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		010	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Decomposer Product Handling Equipment			
Description: an SSE of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at experimental scale in relevant environment	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment
TRL	5	6	7
Basis for Rating (Attach additional sheets as needed)			
The design will be typical of standard technology. However, there need to be testing of compatibility with materials of construction. TRL 6 assigned because technology is definitely beyond demonstration of feasibility and functionality and has operated in relevant environments, but adequate scale of demonstration is unclear. Could be TRL 7 but needs demonstration in the operational environment to get to TRL 8.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
DDN(s) supported: HPS-SAD-1, HPS-SAD-12, HPS-SAD-13, HPS-SAD-14			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 29OCT08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		011	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: H ₂ SO ₄ Concentrator Vacuum Column			
Description: an SSE of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at experimental scale in relevant environment	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment
TRL	5	6	7
Basis for Rating (Attach additional sheets as needed) Vapor-liquid equilibrium data is needed as well as adequate mass and heat transfer data. TRL 6 assigned because technology is definitely beyond demonstration of feasibility and functionality. Once the design concept has been defined, sub-scale testing will confirm readiness for the prototype system test (TRL 8).			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
DDN(s) supported: HPS-SAD-15			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 29OCT08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		012	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Feed Acid Handling and Concentrating Equipment			
Description: an SSE of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at experimental scale in relevant environment	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment
TRL	5	6	7
Basis for Rating (Attach additional sheets as needed) Vapor-liquid equilibrium data is needed as well as compatibility testing of materials. TRL 6 assigned because technology is definitely beyond demonstration of feasibility and functionality. Then once the design concept has been defined, sub-scale testing will confirm readiness for the prototype system test (TRL 8).			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule		Cost (k\$)
DDN(s) supported:			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 29OCT08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		013	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Steam Ejectors and Vacuum Pump			
Description: an SSE of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at experimental scale in relevant environment	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment
TRL	5	6	7
Basis for Rating (Attach additional sheets as needed) The design will be typical of standard technology. However, there need to be testing of compatibility with materials of construction. TRL 6 assigned because technology is definitely beyond demonstration of feasibility and functionality.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule		Cost (k\$)
DDN(s) supported: HPS-SAD-1, HPS-SAD-10 through HPS-SAD-14			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 29OCT08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		033	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Helium Control Valves			
Description: an SSE of Sulfuric Acid Decomposition Section of the S-I and HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Proof-of concept	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.
TRL	3	4	5
Basis for Rating (Attach additional sheets as needed) The feasibility of a valve is not in question but qualification testing will be required. Valves of this size in the high-temperature helium environment may require development.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
Subject Matter Expert Making Determination: Daniel Allen			
Date: 28NOV07	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		034	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Sensors and Instruments			
Description: an SSE of the Sulfuric Acid Decomposition Section of the S-I and HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at experimental scale in relevant environment	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment
TRL	5	6	7
Basis for Rating (Attach additional sheets as needed)			
Chief concerns in this sub-system are control valves (process side), sensors and other instruments in contact with aggressive environments. Previous experience applicable but not sufficient. TRL 6 assigned because technology is beyond demonstration of feasibility and functionality.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Actions (list all)	Actions (list all)	
DDN(s) supported: HPS-PCN-01, HPS-PCN-02, HPS-PCN-03			
Subject Matter Expert Making Determination: Charles O. Bolthrunis			
Date: 08AUG07	Date: 08AUG07		
Modified: Daniel Allen	Modified: Daniel Allen		
Date: 28NOV08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

Sulfur Dioxide Electrolysis TRLs

TRL Rating Sheet			
Document Number:		023	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: SO ₂ Electrolysis Cells			
Description: an SSE of the Electrolyzer System (ELE) of the HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology concept and application formulated	Proof-of concept	Technology or component is tested at bench scale.
TRL	2	3	4
Basis for Rating (Attach additional sheets as needed) Tests completed at SRNL constitute proof-of-principle. Testing at expected pressures has not been accomplished. All acceptable materials have not been identified and materials issues have not been quantified. A multicell stack has been demonstrated at bench-scale (3 cell stack, 160 sq. cm per cell) but suitable catalyst and membrane materials have not been determined to allow the individual components to work with suitable performance at the laboratory scale. Based on information available from the labs, Westinghouse, and industry, a basic cell configuration selection must be made shortly. .			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule	Cost (k\$)	
A number of membranes tested show formation of a sulfur-rich layer that degrades cell performance. Effects of membrane materials, fabrication methods, and operating conditions on transport of SO ₂ through the membranes have been hypothesized but are not fully understood at this time. Development and testing of candidate membranes must continue until a suitable membrane can be demonstrated. Electrocatalytic activity shown in testing to-date is not sufficient for target operating conditions: 0.5 A/cm ² at			

0.6 V at 50 wt% sulfuric acid. Development and testing of candidate catalysts must continue until suitable activity can be achieved. Define operating conditions and conduct electrolyzer testing using the final selected Membrane-Electrode Assembly (MEA) at true process conditions (temperature, pressure, reactant concentration). This can only be completed after membrane selection and catalyst development are complete. Complete longevity tests using final selected MEA at true process conditions. This can only be completed after membrane selection and catalyst development are complete.		
DDN(s) supported: HPS-ELE-01A through HPS-ELE-06		
Subject Matter Expert Making Determination: Kathleen McHugh		
Date: 10/20/08	Originating Organization: MPR	
Modified: Daniel Allen	Changed TRL 2 to TRL 3, basis discussion modified; DDNs added	
Date: 29OCT08	Originating Organization: Technology Insights	

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		024	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Electrolyzer Module Internals			
Description: an SSE of the Electrolyzer System (ELE) of the HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Basic principles observed	Technology concept and application formulated	Proof-of concept
TRL	1	2	3
Basis for Rating (Attach additional sheets as needed)			
An intermediate scale multicell stack will be needed before going to larger scale. R&D is needed to fabricate larger area cells and refine the design of electrical distribution within the multicell stack. Further advancement beyond concept requires design.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule	Cost (k\$)	
An intermediate scale multicell stacks and electrolyzer module demonstrations will be needed before going to 1 sq. meter cell size for NNGP. R&D is needed to fabricate larger area cells and refine the design of electrical distribution within the multicell stack. This can be completed only after selecting final Membrane-Electrode Assembly (MEA) and demonstrating performance and longevity in true process conditions.			
DDN(s) supported:			
Subject Matter Expert Making Determination: Kathleen McHugh			

Date: 10/20/08	Originating Organization: MPR
Modified: Daniel Allen	Changed TRL 3 to TRL 2, basis discussion and actions list modified
Date: 29OCT08	Originating Organization: Technology Insights

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		025	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Electrolyzer Module Pressure Boundary			
Description: an SSE of the Electrolyzer System (ELE) of the HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.	SSC demonstrated at pilot scale in relevant environment
TRL	4	5	6
Basis for Rating (Attach additional sheets as needed) Once the requirement for an electrolyzer container is established, no further testing is required. A commercial vessel can be designed. Selection of the configuration of the Electrolyzer will determine the need for a container.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule		Cost (k\$)
DDN(s) supported:			
Subject Matter Expert Making Determination: Charles O. Bolthrunis			
Date: 08AUG07	Originating Organization: Shaw Stone & Webster		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		026	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: SO ₂ Absorber			
Description: an SSE of the Sulfuric Acid Decomposition System (SAD) of the HyS HPS			
Facility: ☐ NHSS ☐ HTS ☒ HPS ☐ PCS ☐ BOP			
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at experimental scale in relevant environment	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment
TRL	5	6	7
Basis for Rating (Attach additional sheets as needed)			
Absorption operations are used commonly throughout industry. Packed columns are available for use at all scales. Preliminary process parameters for the HyS process have been defined in a conceptual design flowsheet. Further flowsheet optimization for pilot scale is expected, which may impact key process parameters for separation equipment. This absorption column accepts streams containing SO₂, H₂O, H₂SO₄, and trace amounts of O₂; a corrosion-resistant material will be needed. Pressure in the current flow sheet is too high for use of a glass-lined column; fabrication from a corrosion resistant metal (e.g., Hastelloy B3) may be needed. Equipment scaling and manufacturing processes for packed columns are well understood in industry, but the selected material will need to be tested in the operating environment for corrosion resistance.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule	Cost (k\$)	
Identify suitable materials of construction and test in process conditions. Complete optimization and prepare a design specification considering final operating conditions for the column for procurement at the pilot scale.			

DDN(s) supported: HPS-SAD-16		
Subject Matter Expert Making Determination: Kathleen McHugh		
Date: 10/20/08	Originating Organization: MPR	
Modified: Daniel Allen	Revised from TRL 4 to TRL 6, as per meeting, Denver, 20NOV08	
Date: 20NOV08	Originating Organization: Technology Insights	

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		028	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Water Treatment System			
Description: an SSE of the Feed and Utility System (FUS) of the HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)			
TRL		U	
Basis for Rating (Attach additional sheets as needed)			
Feed purification is critical to all water splitting technologies. Preliminary work on critical component tolerance has not yet been done. Commercially available feed water purification may not be adequate; process fluid purification may be required. TRL for this cannot be assigned until the requirements are known.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
DDN(s) supported: HPS-FUS-01, HPS-FUS-02, HPS-FUS-03			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 27OCT08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		029	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Instrument and Controls System			
Description: an SSE of the HyS HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at experimental scale in relevant environment	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment
TRL	5	6	7
Basis for Rating (Attach additional sheets as needed)			
Chief concerns in this sub-system are control valves (process side), sensors, and other instruments in contact with aggressive environments. Previous experience applicable but not sufficient. TRL 6 assigned because technology is beyond demonstration of feasibility and functionality.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
.			
DDN(s) supported: HPS-PCN-01, HPS-PCN-02, HPS-PCN-03			
Subject Matter Expert Making Determination: Charles O. Bolthrunis			
Date: 08AUG07	Originating Organization: Shaw Stone & Webster		
Modified: Daniel Allen	Revised from TRL 2 to TRL 6, basis discussion modified; DDNs added		
Date: 27OCT08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

Bunsen Reaction and HI Decomposition TRLs

TRL Rating Sheet			
Document Number:		014	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Bunsen Reactor			
Description: an SSE of the Bunsen Reaction Section of the S-I HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology concept and application formulated.	Proof-of concept	Technology or component is tested at bench scale.
TRL	2	3	4
Basis for Rating (Attach additional sheets as needed)			
General feasibility is supported by laboratory bench-scale tests and the initial operation of the S-I ILS. Bunsen reactors were operated successfully at GA in the 1980s, in France and more recently in Japan (for a period of a week). These experiments meet the required proof-of-concept. The critical functions have been proven. To advance, Basic thermodynamic data is needed. Compatibility with materials of construction uncertain, particularly with seals. Hydraulic, kinetic, and thermal design and analyses are needed.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
Successful completion of the ILS and its operation in integrated mode for X,XXX hours with no more than Y% degradation in output will advance the Bunsen Reactor to TRL 4.			
DDN(s) supported: HPS-BUN-01 through HPS-BUN-06			
Subject Matter Expert Making Determination: meeting, Denver, 20NOV08			
Date: 20NOV08	Originating Organization: - -		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		015	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Three-phase Separator			
Description: an SSE of the Bunsen Reaction Section of the S-I HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology concept and application formulated.	Proof-of concept	Technology or component is tested at bench scale.
TRL	2	3	4
Basis for Rating (Attach additional sheets as needed) General feasibility is supported by laboratory bench-scale tests and the initial operation of the S-I ILS.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
Successful completion of the ILS and its operation in integrated mode for X,XXX hours with no more than Y% degradation in output will advance the Three-phase Separator to TRL 4.			
DDN(s) supported:			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 28NOV08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		016	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Reactive Still			
Description: an SSE of the HI Decomposition Section of the S-I HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Basic principles observed	Technology concept and application formulated	Proof-of concept
TRL	1	2	3
Basis for Rating (Attach additional sheets as needed)			
Although results are unpublished, GA has done batch experiments in glass that produced relatively high H ₂ yield in I ₂ -lean experiments. Independent ongoing experiments at ENEA (Italy) support this result. These experiments go beyond “Basic principles observed and reported in ... research without well-defined application.” (TRL-1), but they are short of “critical function ... proven” (TRL-4).			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
Verification of kinetic and thermodynamic data will advance the Reactive Still to TRL 3.			
DDN(s) supported: HPS-HID-01 through HPS-HID-08			
Subject Matter Expert Making Determination: meeting, Denver, 20NOV08			
Date: 20NOV08	Originating Organization: - -		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		018	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Process Coupling Heat Exchanger			
Description: an SSE of the HI Decomposition Section of the S-I HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.	SSC demonstrated at pilot scale in relevant environment
TRL	4	5	6
Basis for Rating (Attach additional sheets as needed)			
The extreme high temperature would require testing of potential heat exchanger materials of construction to validate their ability to operate in those conditions. Current compact heat exchangers are made of materials capable of process temperatures and pressures, but the compatibility of the material with the process fluids needs to be tested. RL-5 assigned because technology is beyond demonstration of feasibility and functionality but has not operated in relevant environments.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Actions (list all)	Actions (list all)	
The level can be increased to TRL 6 when materials are tested for the relevant environment, because at that point components will have been defined, acceptable technologies identified and technology issues quantified.			
DDN(s) supported:			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 27OCT08	Originating Organization: Technology Insights		

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TRL Rating Sheet			
Document Number:		031	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Reactor Product Handling Equipment			
Description: an SSE of the Balance of the S-I HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at experimental scale in relevant environment	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment
TRL	5	6	7
Basis for Rating (Attach additional sheets as needed)			
Reactor product handling equipment (both Bunsen and HI Decomposition reactors) are pumping and handling very large streams of iodine and hydroiodic acid is a problem that has not been dealt with commercially. The large flows required are beyond the experience of chemical plants. The possibility of very large spills has to be considered. Economic solutions need to be found.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule		Cost (k\$)
DDN(s) supported: HPS-BUN-07, HPS-HID-09			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 31OCT08	Originating Organization: Technology Insights		

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TRL Rating Sheet			
Document Number:		020	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Feed Purification System			
Description: an SSE of the Balance of the S-I HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)			
TRL		U	
Basis for Rating (Attach additional sheets as needed)			
The concept purification for feed streams (water and air) and the application are established. Requirements are not resolved and require operation of test loops. Until then the feasibility can't be determined. .			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
DDN(s) supported: HPS-FUS-01 through HPS-FUS-03			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 16OCT08	Originating Organization: Technology Insights		

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TRL Rating Sheet			
Document Number:		021	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Product Purification System			
Description: an SSE of the Balance of the S-I HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)			
TRL		U	
Basis for Rating (Attach additional sheets as needed) Can not rate without requirements.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule	Cost (k\$)	
DDN(s) supported: HPS-PPU-01, HPS-PPU-02			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 29OCT08	Originating Organization: Technology Insights		

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TRL Rating Sheet			
Document Number:		022	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Instrument and Controls System			
Description: an SSE of the Balance of the S-I HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at experimental scale in relevant environment	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment
TRL	5	6	7
Basis for Rating (Attach additional sheets as needed)			
Chief concerns in this sub-system are control valves (process side), sensors, and other instruments in contact with aggressive environments. Previous experience applicable but not sufficient. TRL 6 assigned because technology is beyond demonstration of feasibility and functionality.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
.			
DDN(s) supported: HPS-PCN-01, HPS-PCN-02, HPS-PCN-03			
Subject Matter Expert Making Determination: Charles O. Bolthrunis			
Date: 08AUG07	Originating Organization: Shaw Stone & Webster		
Modified: Daniel Allen	Revised from TRL 2 to TRL 6, basis discussion modified; DDNs added		
Date: 27OCT08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		035	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Helium Control Valves			
Description: an SSE of the Balance of the S-I HPS			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Proof-of concept	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.
TRL	3	4	5
Basis for Rating (Attach additional sheets as needed) The feasibility of a valve is not in question but qualification testing will be required. Valves of this size in the high-temperature helium environment may require development.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
Subject Matter Expert Making Determination: Daniel Allen			
Date: 28NOV07	Originating Organization: Technology Insights		

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High Temperature Steam Electrolysis TRL_s

TRL Rating Sheet			
Document Number:		001	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Solid Oxide Electrolyzer (SOE) Cells			
Description: an SSE of the Electrolyzer Modules of the HTSE Electrolyzer System (ELE)			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology concept and application formulated.	Proof-of concept	Technology or component is tested at bench scale.
TRL	2	3	4
Basis for Rating (Attach additional sheets as needed) The required environment requires the cells to operate under pressure and temperature. The cells have never been operated in a pressurized environment. The manufacturing process for the cells is still being identified. Currently the process is to hand-make each cell, which would not be effective for a pilot scale component which requires far more cells than are currently available. The cells currently have a high rate of degradation at operating temperature. This does not meet functionality requirements for this component. Reference: O'Brien, J.E., "Documentation of Short Stack and Button Cell Experiments Performed at INL and Ceramtec during FY-07," September 2007.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule	Cost (k\$)	
More research must be accomplished to determine a suitable manufacturing method for the electrolyzer cells. More research must be accomplished to increase cell longevity. Testing of the cells concurrently at the process temperature (800°C) and pressure (50 bar) must be accomplished.			

DDN(s) supported: HPS-ELE-01B through HPS-ELE-6, HPS-ELE-10, HPS-ELE-11		
Subject Matter Expert Making Determination: Demetrius Siachames		
Date: 09SEP08	Originating Organization: MPR Associates	
Modified: Daniel Allen	Revised from TRL 2 to TRL 3, as per meeting, Denver, 20NOV08	
Date: 20NOV08	Originating Organization: Technology Insights	

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		002	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Electrolyzer Manifolds			
Description: an SSE of the Electrolyzer Modules of the HTSE Electrolyzer System (ELE)			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.	SSC demonstrated at pilot scale in relevant environment
TRL	4	5	6
Basis for Rating (Attach additional sheets as needed)			
The basic design of the manifolds is still being determined for the pilot scale. Design adequacy is supported by the CFD analyses done at INL on flow distribution and by the experimental results in cell stack tests where operation was satisfactory over a wide range of flow conditions.			
Reference: O'Brien, J.E., "Documentation of Short Stack and Button Cell Experiments Performed at INL and Ceramatec during FY-07," September 2007.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
More research must be accomplished to determine a suitable solution for the electrolyzer manifold.			
A manifold system must be tested at operating pressure and temperature.			
DDN(s) supported:			
Subject Matter Expert Making Determination: Demetrius Siachames			
Date: 09SEP08	Originating Organization: MPR Associates		

Modified: Daniel Allen	Revised from TRL 3 to TRL 5, per 20NOV08 meeting in Denver
Date: 28NOV08	Originating Organization: Technology Insights

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		039	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Seals			
Description: an SSE of the Electrolyzer Modules of the HTSE Electrolyzer System (ELE)			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Proof-of concept	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.
TRL	3	4	5
Basis for Rating (Attach additional sheets as needed) Basis is the stack demonstrations done at INL. Concern about the adequacy of the response to leaks and internal combustion were ameliorated in discussion.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule		Cost (k\$)
DDN(s) supported:			
Subject Matter Expert Making Determination: 20NOV08 meeting in Denver			
Date: 20NOV08	Originating Organization: - -		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		003	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Sweep Gas Coupling Heat Exchanger			
Description: an SSE of the HTSE Electrolyzer System (ELE)			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.	SSC demonstrated at pilot scale in relevant environment
TRL	4	5	6
Basis for Rating (Attach additional sheets as needed)			
The extreme high temperature would require testing of potential heat exchanger materials of construction to validate their ability to operate in those conditions. Current compact heat exchangers are made of materials capable of process temperatures and pressures, but the compatibility of the material with the process fluids needs to be tested. Reference: UNLV, "Crack Growth Rate of Structural Materials for Heat Exchanger Applications," August 2007; UCB, "Composite Heat Exchanger Fabrication Methods and Test Results," February 2007; Ceramtec, "FY-07a Annual Report – Heat Exchanger Scale-up," July, 2007; Xiuqing Li, Meggit Ltd., "Heat Exchangers for the Next Generation of Nuclear Reactors," June, 2006.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule	Cost (k\$)	
Determine industry available materials capable of high temperatures (800°C) and suitable for fluids considered.			
Test heat exchanger materials to determine their feasibility for continuous operation.			
DDN(s) supported: HPS-ELE-07 through HPS-ELE-09			

Subject Matter Expert Making Determination: Demetrius Siachames		
Date: 09SEP08	Originating Organization: MPR Associates	
Modified: Daniel Allen	Revised from TRL 2 to TRL 5; removed requirement to test complete heat exchanger and left testing materials.	
Date: 27OCT08	Originating Organization: Technology Insights	

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		004	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Process Coupling Heat Exchanger			
Description: an SSE of the HTSE Electrolyzer System (ELE)			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.	SSC demonstrated at pilot scale in relevant environment
TRL	4	5	6
Basis for Rating (Attach additional sheets as needed) The high temperature would require testing of potential heat exchanger materials of construction to validate their ability to operate in those conditions. Current compact heat exchangers are made of materials capable of process temperatures and pressures, but the compatibility of the material with the process fluids needs to be tested. Reference: UNLV, "Crack Growth Rate of Structural Materials for Heat Exchanger Applications," August 2007; UCB, "Composite Heat Exchanger Fabrication Methods and Test Results," February 2007; Ceramtec, "FY-07a Annual Report – Heat Exchanger Scale-up," July, 2007; Xiuqing Li, Meggit Ltd., "Heat Exchangers for the Next Generation of Nuclear Reactors," June, 2006.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule	Cost (k\$)	
Determine industry available materials capable of high temperatures (800°C) and suitable for fluids considered. Test heat exchanger materials to determine their feasibility for continuous operation.			
DDN(s) supported: HPS-ELE-07 through HPS-ELE-09			

Subject Matter Expert Making Determination: Demetrius Siachames		
Date: 09SEP08	Originating Organization: MPR Associates	
Modified: Daniel Allen	Revised from TRL 2 to TRL 5; removed requirement to test complete heat exchanger and left testing materials.	
Date: 27OCT08	Originating Organization: Technology Insights	

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		005	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Piping and Manifolds			
Description: an SSE of the HTSE Electrolyzer System (ELE)			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)			
TRL		U	
Basis for Rating (Attach additional sheets as needed)			
Manufacturing of required piping is technically possible, but has not been manufactured or tested in a laboratory setting to validate feasibility for the temperatures and pressures required. It is uncertain without further study and design work whether new technology is needed to accommodate pipe thermal expansion.			
Reference: INEEL, "High Temperature Electrolysis System Configuration Study."			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule	Cost (k\$)	
An engineering solution requiring a pipe-in-pipe design will have to be developed and manufactured that can withstand 50 bar and 800°C.			
The engineering solution for a pipe-in-pipe will have to be tested at the required conditions.			
DDN(s) supported: HPS-ELE-10 through HPS-ELE-13			
Subject Matter Expert Making Determination: Demetrius Siachames			
Date: 09SEP08	Originating Organization: MPR Associates		

Modified: Daniel Allen	Revised from TRL 2 to TRL U, as per 20NOV08 meeting in Denver
Date: 28NOV08	Originating Organization: Technology Insights

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		006	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Heat Exchangers			
Description: SSEs of the HTSE Heat Recovery System (HRS)			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.	SSC demonstrated at pilot scale in relevant environment
TRL	4	5	6
Basis for Rating (Attach additional sheets as needed)			
The extreme high temperature would require testing of potential heat exchanger materials of construction to validate their ability to operate in those conditions. Current compact heat exchangers are made of materials capable of process temperatures and pressures, but the compatibility of the material with the process fluids needs to be tested. Reference: UNLV, "Crack Growth Rate of Structural Materials for Heat Exchanger Applications," August 2007; UCB, "Composite Heat Exchanger Fabrication Methods and Test Results," February 2007; Ceramtec, "FY-07a Annual Report – Heat Exchanger Scale-up," July, 2007; Xiuqing Li, Meggit Ltd., "Heat Exchangers for the Next Generation of Nuclear Reactors," June, 2006.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Actions (list all)	Actions (list all)	
Determine industry available materials capable of high temperatures (800°C) and suitable for fluids considered. Test heat exchanger materials to determine their feasibility for continuous operation.			
DDN(s) supported: HPS-ELE-07 through HPS-ELE-09			

Subject Matter Expert Making Determination: Demetrius Siachames	
Date: 09SEP08	Originating Organization: MPR Associates
Modified: Daniel Allen	Revised from TRL 2 to TRL 5
Date: 27OCT08	Originating Organization: Technology Insights

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		007	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Feed Purification System			
Description: an SSE of the HTSE Feed and Utility System (FUS)			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)			
TRL		U	
Basis for Rating (Attach additional sheets as needed)Can not rate without requirements.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule	Cost (k\$)	
DDN(s) supported: HPS-FUS-01 through HPS-FUS-03			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 27OCT08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		008	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Sweep Gas Turbine			
Description: an SSE of the HTSE Feed and Utility System (FUS)			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment	Integrated prototype demonstrated in operational environment.
TRL	6	7	8
Basis for Rating (Attach additional sheets as needed) Such as standard turbogenerator requires only design verification testing, presumably by the vendor to his standards in the design environment.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
DDN(s) supported:			
Subject Matter Expert Making Determination: Daniel Allen			
Date: 02OCT08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		037	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Helium Control Valves			
Description: an SSE of the HTSE			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	Proof-of concept	Technology or component is tested at bench scale.	SSC demonstrated at experimental scale in relevant environment.
TRL	3	4	5
Basis for Rating (Attach additional sheets as needed) The feasibility of a valve is not in question but qualification testing will be required. Valves of this size in the high-temperature helium environment may require development.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)		Schedule	Cost (k\$)
Subject Matter Expert Making Determination: Daniel Allen			
Date: 28NOV07	Originating Organization: Technology Insights		

Rev. AUG08, DTA

TRL Rating Sheet			
Document Number:		038	Revision:
☐ Facility	☒ System	☐ Subsystem	☐ Structure ☐ Component
Title: Instrumentation and Control			
Description: an SSE of the HTSE			
Facility:	☐ NHSS	☐ HTS	☒ HPS ☐ PCS ☐ BOP
Technology Readiness Level			
	Next Lower Rating Level	Rating	Next Higher Rating Level
Generic Definitions (<i>abbreviated</i>)	SSC demonstrated at experimental scale in relevant environment	SSC demonstrated at pilot scale in relevant environment	SSC demonstrated at engineering scale in relevant environment
TRL	5	6	7
Basis for Rating (Attach additional sheets as needed) Chief concerns in this sub-system are control valves (process side), sensors, and other instruments in contact with aggressive environments. Previous experience applicable but not sufficient. TRL 6 assigned because technology is beyond demonstration of feasibility and functionality.			
Outline of a plan to get from current level to next level (Attach additional sheets as needed)			
Actions (list all)	Schedule	Cost (k\$)	
.			
DDN(s) supported: HPS-PCN-01, HPS-PCN-02, HPS-PCN-03			
Subject Matter Expert Making Determination: Charles O. Bolthrunis			
Date: 08AUG07	Originating Organization: Shaw Stone & Webster		
Modified: Daniel Allen	Revised from TRL 2 to TRL 6, basis discussion modified; DDNs added		
Date: 27OCT08	Originating Organization: Technology Insights		

Rev. AUG08, DTA

8.4.2 Design Data Needs

8.4.2 Design Data Needs

DDNs are formally prepared descriptions of the needed data for design calculations and design decisions that are identified on the level of the SSCs. Below are tabulations of the summary titles of DDNs that apply to the three water splitting-based hydrogen production technologies identified for HTGR applications. The three hydrogen production technologies are Sulfur-Iodine (S-I), Hybrid Sulfur (HyS) and High Temperature Steam Electrolysis (HTSE).

These DDNs are keyed to the respective critical SSCs through entries on the TRL Summary Sheets for each SSC (see Section 8.4.1).

The table has descriptive titles only. Complete DDNs were prepared for the Hybrid Sulfur production technology as part of the Preconceptual Design [Ref. “NGNP and Hydrogen Production Preconceptual Design Report, Section 7: Hydrogen Production System,” NGNP-07-RPT-001, May 2007.], but those are in need of updating as a result of this study. That update and preparation of the other complete DDNs is beyond the present scope.

DDN	Title
Design Data Needs for Sulfuric Acid Decomposition (SAD)	
HPS-SAD-01	Confirm Thermodynamic Data for the Sulfuric Acid Decomposition Process
HPS-SAD-02	Develop a Commercial Sulfuric Acid Decomposition Catalyst
HPS-SAD-03	Gather Decomposition Reaction Kinetics Data
HPS-SAD-04	Test Silicon Carbide and other Ceramic Material in Decomposition Service
HPS-SAD-05	Test Alloy 230 and Alloy 617 in a High Temperature Sulfuric Acid, Sulfur Dioxide, and Oxygen Atmosphere.
HPS-SAD-06	Develop a Method to Bond Alloy 230 or Alloy 617 or Similar Materials to Silicon Carbide and other Ceramics.
HPS-SAD-07	Develop Materials to Seal the Joints between Ceramic Decomposer Elements and the Metallic Tube Sheet or Vessel.
HPS-SAD-08	Test a Pilot-Scale Decomposer.
HPS-SAD-09	Provide Data Supporting a Design Code Case
HPS-SAD-10	Develop Gasket Materials and Design
HPS-SAD-11	Develop Seal Materials and Design
HPS-SAD-12	Develop Welding Materials
HPS-SAD-13	Develop Cladding and Coating Materials
HPS-SAD-14	Develop Piping Materials and Design Methods
HPS-SAD-15	Measure the Height Equivalent to a Theoretical Plate (HETP) for the Concentrator (Vacuum Tower)
HPS-SAD-16	Measure the Height Equivalent to a Theoretical Plate (HETP) for the SO ₂ Absorber

Design Data Needs for Feed Purification (FUS)	
HPS-FUS-01	Identify Critical Impurities and Determine Critical Component Tolerance
HPS-FUS-02	Develop Feed Water Purification Methods
HPS-FUS-03	Develop Process Fluid Purification Methods
Design Data Needs for Bunsen Reaction (BUN)	
HPS-BUN-01	Confirm Thermodynamic Data for the Bunsen Reaction Process including Phase Equilibria
HPS-BUN-02	Gather Kinetic and Mass Transfer Data for the Bunsen Reaction in the proposed reactor configuration
HPS-BUN-03	Develop Gasket Materials and Design for Bunsen Reaction Environment
HPS-BUN-04	Develop Seal Materials and Design for Bunsen Reaction Environment
HPS-BUN-05	Develop Welding Materials for Bunsen Reaction Environment
HPS-BUN-06	Develop Cladding and Coating Materials for Bunsen Reaction Environment
HPS-BUN-07	Develop Piping Materials and Design Methods for Bunsen Reaction Environment
Design Data Needs for Hydroiodic Acid Decomposition (HID)	
HPS-HID-01	Demonstrate Hydroiodic Acid Reactive Distillation Decomposition in Principle
HPS-HID-02	Confirm Thermodynamic Data for the Hydroiodic Acid Decomposition Process including Phase Equilibria
HPS-HID-03	Develop commercial HI Decomposition Catalyst
HPS-HID-04	Gather Kinetic and Mass Transfer Data for the Hydroiodic Acid Decomposition in the proposed reactor configuration based on the commercial catalyst
HPS-HID-05	Develop Gasket Materials and Design for Hydroiodic Acid Decomposition Environment
HPS-HID -06	Develop Seal Materials and Design for Hydroiodic Acid Decomposition Environment
HPS-HID -07	Develop Welding Materials for Hydroiodic Acid Decomposition Environment
HPS-HID -08	Develop Cladding and Coating Materials for Hydroiodic Acid Decomposition Environment
HPS-HID-09	Develop Piping Materials and Design Methods for Hydroiodic Acid Decomposition Environment
Design Data Needs for the Electrolyzers (including PCHX) (ELE)	
HPS-ELE-01A	Develop a Cell Membrane
HPS-ELE-01B	Develop a Cell with a commercially acceptable activity and life
HPS-ELE-02	Optimize Catalyst Loading in the Electrodes
HPS-ELE-03	Develop a Cell Configuration and Materials
HPS-ELE-04	Build and Test a Laboratory-scale Cell
HPS-ELE-05	Build and Test Pilot-scale Cells
HPS-ELE-06	Build and Test a Stack of Cells at Engineering Scale

HPS-ELE-07	Test Alloy 230 and Alloy 617 in High Temperature Helium and Air/Oxygen and Steam/Hydrogen Mixtures
HPS-ELE-08	Test a Pilot-Scale PCHX
HPS-ELE-09	Provide Data Supporting a Design Code Case
HPS-ELE-10	Develop Gasket Materials and Design
HPS-ELE-11	Develop Seal Materials and Design
HPS-ELE-12	Develop Welding Materials
HPS-ELE-13	Develop Piping Materials and Design Methods
Design Data Needs for Product Purification (PPU)	
HPS-PPU-01	Identify Product Impurities
HPS-PPU-02	Test Product Purification Methods
Design Data Needs for Instrument and Controls (PCN)	
HPS-PCN-01	Test Sensors in the Pilot Plant
HPS-PCN-02	Develop Valves for High-Temperature Acid Service
HPS-PCN-03	Test Valves in the Pilot Plant
HPS-PCN-04	Develop and Test High Temperature Helium Control Valves

8.4.3 Design Tasks

8.4.3 Design Tasks

Table 8.4.3-1: Design Tasks: Hybrid Sulfur

DTs	Title
HPS-HYS-DT-01	Analyze Data and Improve Process Simulation
HPS-SAD-DT-02	Develop additional alternatives for the decomposition reactor
HPS-SAD-DT-03	Complete thermal and hydraulic analyses of the alternatives using equilibrium data only
HPS-SAD-DT-04	Complete a conceptual mechanical design of each of the alternative concepts
HPS-SAD-DT-05	Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from bench scale testing
HPS-SAD-DT-06	Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from engineering or pilot scale testing
HPS-SAD-DT-07	Develop a preliminary piping spec and materials selections for equipment
HPS-SAD-DT-08	Size conceptual equipment and track economics as technology develops
HPS-FUS-DT-09	Design a feed water purification system including equipment sizing and economics
HPS-FUS-DT-10	Design a process fluid purification system including equipment sizing and economics
HPS-ELE-DT-11	Design an electrolysis system based on the electrolyzer design and track economics
HPS-PCN-DT-12	Identify appropriate valve materials and sensing devices for the aggressive environments of the process technology
HPS-HYS-DT-13	Develop P&IDs and operating outline including normal and abnormal transients
HPS-HYS-DT-14	Perform appropriate hazard and operability reviews at designated stages in process development

Table 8.4.3-2: Design Tasks: Sulfur Iodine

DTs	Title
HPS-SI-DT-01	Analyze Data and Improve Process Simulation
HPS-SAD-DT-02	Develop additional alternatives for the decomposition reactor
HPS-SAD-DT-03	Complete thermal and hydraulic analyses of the alternatives using equilibrium data only
HPS-SAD-DT-04	Complete a conceptual mechanical design of each of the alternative concepts
HPS-SAD-DT-05	Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from bench scale testing
HPS-SAD-DT-06	Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from engineering or pilot scale testing
HPS-SAD-DT-07	Develop a preliminary piping spec and materials selections for SAD equipment
HPS-SI-DT-08	Track equipment size and cost as development progresses
HPS-FUS-DT-09	Design a feed water purification system including equipment sizing and economics

DTs	Title
HPS-FUS-DT-10	Design a process fluid purification system including equipment sizing and economics
HPS-PCN-DT-12	Identify appropriate valve materials and sensing devices for the aggressive environments of the process technology
HPS-SI-DT-13	Develop P&IDs and operating outline including normal and abnormal transients
HPS-SI-DT-14	Perform appropriate hazard and operability reviews at designated stages in process development
HPS-BUN-DT-15	Design Alternative Bunsen Reactors
HPS-BUN-DT-16	Complete thermal and hydraulic analyses of the alternatives using equilibrium data only
HPS-BUN-DT-17	Complete a conceptual mechanical design of each of the alternative concepts
HPS-BUN-DT-18	Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from bench scale testing
HPS-BUN-DT-19	Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from engineering or pilot scale testing
HPS-BUN-DT-20	Develop a preliminary piping spec and materials selections for BUN equipment
HPS-HID-DT-21	Design Alternative HI Decomposition Reactors
HPS-HID-DT-22	Complete thermal and hydraulic analyses of the alternatives using equilibrium data only
HPS-HID-DT-23	Complete a conceptual mechanical design of each of the alternative concepts
HPS-HID-DT-24	Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from bench scale testing
HPS-HID-DT-25	Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from engineering or pilot scale testing
HPS-HID-DT-26	Develop a preliminary piping spec and materials selections for HID equipment
HPS-PPU-DT-27	Develop a preconceptual design for a product purification system

Table 8.4.3-3: Design Tasks: High Temperature Steam Electrolysis

DDN	Title
HPS-FUS-DT-01	Design a feed water purification system including equipment sizing and economics
HPS-FUS-DT-02	Design a process fluid purification system including equipment sizing and economics
HPS-ELE-DT-03	Design a cell stack suitable for operation at high temperature in a high pressure, oxygen-rich environment
HPS-ELE-DT-04	Design an economical stack enclosure that minimizes heat loss, sealing and stack handling and maximizes safety
HPS-ELE-DT-05	Design a conceptual plant layout and piping arrangement that accommodates expected thermal expansion
HPS-ELE-DT-06	Design and rate conceptual PCHXs

8.5 ECONOMIC MODEL

8.5. Economic Model

8.5.1 The Modeling Tool

The DOE has sponsored and published a specific tool for the comparison of hydrogen production technologies. This is a result of the H2A Production Analysis Program, which is part of the national Hydrogen Fuel Initiative, and which was conducted by a team from the various DOE divisions, the national laboratories, and industrial participants.

The primary objectives of the H2A Production Analysis Program have been as follows:

- Improve the consistency and transparency of the ground rules and assumptions for the economic analyses of hydrogen systems within the DOE hydrogen programs, as well as within related industry programs.
- Develop a tool for consistent analyses and reporting of the economics of hydrogen production and delivery systems, as well as for R&D direction and portfolio analyses.
- Validate the consistent ground rules, assumptions, and analyses methodology through deliberations with a select group of key industrial collaborators, including nuclear utility and vendor representatives.

The H2A model is a spreadsheet-based (Microsoft Excel) calculation tool that gives the required selling price of hydrogen for the input capital and operating cost factors for a hydrogen production plant and for the specified economic parameters, including the rate of return on investment. The units of the resultant price are dollars per kilogram, which serves to normalize the comparisons and happens to be approximately equal to the price of gasoline with the same energy content on a lower heating value basis. The results of H2A have been published on the DOE website [http://www.hydrogen.energy.gov/h2a_analysis.html].

While the tool includes agreed-upon H2A reference values for several financial parameters, the user is also given the opportunity to vary parameters such as internal rate of return, plant life, feedstock costs, and tax rate, to examine the technology using their own basis. The calculation part of the tool uses a standard discounted cash flow rate of return analysis methodology to determine the hydrogen selling cost for the desired internal rate of return.

Inflation can be input to the model, but in the discounted cash flow analysis the effect of inflation is nullified except for a small impact on the tax depreciation. For this reason, the calculated selling price for hydrogen is the fixed or leveled price over the plant life in reference year dollars.

There are two versions of the tool – one formatted for central production of hydrogen and one for “forecourt” production. The latter is for analysis of smaller-scale hydrogen plants that would be integrated with dispensing of the hydrogen product to fuel cell vehicles. This study concerns large central production with transport to a relatively distant set of users, and so for these analyses only the former version applies.

In 2007, DOE reconvened the H2A participants to review and refine the modeling tools and update the cases to be modeled. Refinements to the modeling tools have been based on improvements for convenience and correction of small errors found in the interim by users and by the original developers. The analyses in this report utilize the latest (2007-2008) tool, which are referred to as H2A Production Model, version 2.0.

8.5.2. Summary of Economic Assumptions and Analysis Ground Rules

The following are the ground rules for the comparative H2A modeling for nuclear high-temperature hydrogen production technologies evaluated in this report. The H2A program not only produced an analysis tool for the comparison of costs for hydrogen technologies, but it also developed a set of assumptions for economic and financial factors that by general consensus could be applied to assure that the comparisons are on a reasonable basis. The H2A modeling tool as published [http://www.hydrogen.energy.gov/h2a_analysis.html.] is populated with these economic factors, which can be accepted or modified. For the most part the economic factors are the commonly agreed upon “default” values for future central hydrogen production plants developed in the H2A Production Analysis.

These are in general also the same ground rules used by Technology Insights for analyses of hydrogen costs for nuclear hydrogen technologies done previously for the H2A project and for the DOE Nuclear Hydrogen Initiative program.

- Use H2A modeling tool.
- All HPS alternatives assumed to be commercially mature and evaluated for a consistent 2030 to 2070 service timeframe.
- Generic HTR heat sources (NHSSs) at 550MWt core power, modeled for all cases as a fixed operating cost of 30 \$/MW_{th}-h, based on the nuclear reactor core heat generation, but factored for reactor outlet temperature variation from the reference value. This cost is developed from the NHSS capital and operating costs for a commercial NNGP as part of the NNGP Preconceptual Design.
- Number of reactor modules determined by reference HPS output (142 million SCFD Hydrogen) with appropriate sharing factors for multiple modules.
- Capacity factor of overall plant is 8,200 hours per year (94%)
- 100% equity financing with an after income tax internal rate of return (IRR) of 10%, which is equivalent to financing at 25% equity and 75% debt with 20% IRR and 10% debt rate. Sensitivities to cover a range of IRR.
- Capital cost contingency adjustment is made to the total initial capital cost such that the resulting cost represents a mean or expected value. This cost is the baseline value from which hydrogen price sensitivity can be calculated. Periodic replacement capital includes the same contingency.
- Periodic capital replacements are added to the capital cash flow and depreciated over the useful lives. In addition, an allowance for an annual capital replacement of 0.5%/year is included.
- Facility lives of 30 years of operation. Any shorter life limiting components are replaced at designated intervals.

- Accelerated depreciation facility lives of 20 years and the MACRS schedule are applied for the energy source plants, as well as the hydrogen production plants.
- An effective income tax rate of 38.9 % is applied based on a federal tax rate of 35% and a state tax rate of 6%.
- Property tax and business insurance each 1% per year of the total initial overnight capital cost.
- Reference year dollars are 3rd Quarter 2008.
- General inflation is zero. In H2A analyses one can apply a general inflation rate, but in the model the results are deflated back to reference year dollars so inflation is nominally irrelevant.
- A nominal three year construction period is applied with 25%, 40% and 35% of the costs incurred respectively.
- A Gulf Coast site is assumed with an average burdened operating labor rate of 50 \$/hour, plus a 20% G&A adder, applied consistently for the plant staffs, which are estimated separately for the different options along with the respective maintenance cost estimates.
- Plant startup is considered to occur over one year. In that period, revenues are assumed to be 50% of subsequent full-year revenues and variable costs are assumed to be 50% likewise. Fixed annual costs are taken at 100% in the startup year.
- The hydrogen delivery pressure at all production plant gates is consistently 50 bar (710 psig). If a lower pressure is supplied by the process, compression costs are added.
- Deficit or surplus electric power priced at 75 \$/MW-h import and 60\$/MW-h export before escalation. These are representative of today's industrial electricity prices with the addition of a factor for increased overall electricity market cost due to future carbon penalty. This is a cost driving parameter that is varied in the sensitivity analyses.
- No central hydrogen storage is included at the production plants other than buffer storage, as required for efficient operations.
- A constant site size of 400 acres has been applied for all options at an assumed unit cost of 5,000 \$/acre.
- Oxygen byproduct credit is included in the analysis. The reference credit is to be applied at 40 \$/MT, which is about today's industrial oxygen price.

8.6 COMPONENT COST DEVELOPMENT

8.6 Component Cost Development

The capital costs in Appendices 8.1.7, 8.2.7 and 8.3.7 are in general for process plant components that are developed and available or that can be estimated based on components used in the process industry for which estimating algorithms are in hand. However, there are components of the hydrogen process systems that are unique and developmental at this stage, for which cost estimates are based on data from technology developers, as follows. These were prepared as costs for a mature plant excluding development and first-of-a-kind costs, although further development effort could lead to equipment cost changes.

8.6.1 Sulfuric Acid Decomposer Cost

The cost used for the Sulfuric Acid Decomposer are scaled with heat transfer area from the design by Westinghouse as published in Lahoda, E.J., *et al.*, “Optimization and Costs of the Westinghouse Hybrid Sulfur Process with the PBMR for the Production of Hydrogen,” 16th Pacific Basin Nuclear Conference (16PBNC), Aomori, Japan, Oct. 13-18, 2008, Paper ID P16P1241. The design of that Acid Decomposer is summarized in the first table below. The costs in the following table are further developed from that design considering learning factors and other cost reduction considerations, such as bulk purchases. The data are from the author, and initial catalyst cost is included.

Physical Parameters of the Decomposition Reactor

	Material	Length (m)	Inner Diameter (m)	Outer Diameter (m)	Thickness (m)	Required per Tube		Total Required, Units	
Gas Riser Tube	SiC	0.75	0.034	0.042	0.004	4		3000	
Concentrator Packing	13 mm Berl Saddle	0.23		0.103		1.92E-03	m ₃	1.44	m ³
Bayonet Tube	SiC	7.24	0.103	0.144		1		750	
Support Tube (inner)	SiC	6.7	0.02	0.028	0.004	1		750	
Support Tube (outer)	SiC	6.7	0.048	0.056	0.004	1		750	
Gas Downflow Tube	SiC	6.7	0.061	0.073	0.0061	1		750	
Catalyst		1.20	0.073	0.103		0.005	m ₃	3.75	m ³
Support Demister Packing	Flexera mic	5.50				2.28E-02	m ₃	17.14	m ³
Liquid Catch Ring	SiC	0.05	0.020	0.103	0.005	1		750	
Gas Distributing Plate	SiC	0.01		0.103	0.01	1		750	
Supporting Insulation	ZirCar Ceramics	6.7	0.028	0.048	0.01	1		750	

Cost Estimate for the Decomposition Reactor

Bayonet Tube	Total Required, Unit		Price Per Unit (USD)	Price (USD)
Gas Riser Tube	3000		\$185.67	\$557,000
Concentrator Packing	1.44	m ³	\$46.95	\$2,385
Bayonet Tube	750		\$12,379.19	\$9,284,394
Support Tube (inner)	750		\$943.66	\$707,746
Support Tube (outer)	750		\$2,988.26	\$2,241,197
Gas Downflow Tube	750		\$11,457.00	\$8,592,750
Catalyst	3.75	m ³	\$696,580.00	\$2,612,175
Support Demister Packing	17.14	m ³	\$132.24	\$2,266
Liquid Catch Ring	750		\$259.00	\$194,250
Gas Distributing Plate	750		\$679.25	\$509,438
Supporting Insulation	750		\$863.83	\$647,874
Estimated Labor Hour	28,800	hr	\$60.00	\$1,728,000
construction rental				\$400,000
Vessel	Total Required, Unit			
Gasket	7.50E+02		\$4.17	\$3,130
Vessel Hemispherical Head	8.84E+04	kg		\$2,341,400
Vessel Plenum	2.90E+04	kg		included
Supporting Flanged Plate	2.30E+04	kg		included
Vessel Shell	1.65E+05	kg		included
Vessel Insulation	28.45	m ³	\$1,400.00	\$39,832
Teflon Coating				\$190,400
Metal Supporting Spring	220			\$10,511
Supporting Plate	15,862.93	kg		included
Cost Total (USD)				\$30,064,748

8.6.2 Sulfur Dioxide Electrolysis Module Cost

The cost used for the Sulfur Dioxide Electrolysis (SOE) module is as developed in the following tables. Note that costs are per square meter. The data is from Gorensek, M.B., et al., “Hybrid Sulfur Process Reference Design and Cost Analysis, Final Report,” Savannah River National Laboratory, unpublished.

SOE Cell Cost by Component

Item	Description	Cost Basis	\$/m ²
Membrane	Nafion® 117 or equiv	\$300/m ²	300
Gas diffusion layers	Porous carbon	\$75/m ² (2 layers req'd)	150
Electrocatalyst	1 mg/cm ² Pt (total)	\$1500/troy oz	480
Bipolar plates	3/8-in graphite	\$200/m ²	200
Seals, gaskets, etc.	PEEK or equiv	50/m ²	50
Cell assembly	Automated	1 man-hr @\$50/man-hr	50
Single cell cost basis			1,230

SOE Module Cost

Item	Description	Cost Basis	\$/m ²
Individual cells	200 units	SOE Cell Cost less 20% for NOAK improvements	984
End plates, tie rods, & other pressure comp.	Carbon steel	\$20,000 total	100
Current collectors & connection to DC bus	Copper	\$8,000 total	40
Supply lines to cells	4 lines; every 10 cells	\$100 per line x 80	N/A
Other piping connect.		\$4,000	N/A
Instruments and misc.		\$2,000	N/A
Module supports	Weight = 8 t	\$10,000 total	N/A
Module assembly	Off-site assembly	64 man-hr @\$50/man-hr	16
Module installation		64 man-hr @\$50/man-hr	N/A
Subtotal			1,140
Overhead	Electrolyzer mfg.	20% of matls & labor	228
Total SDE Module cost basis			1,368

8.7 HPAS STUDY 90% REVIEW SLIDES

Hydrogen Plant Alternative Study
90% Technical Review Slides
November, 20, 2008

76 pages

Hydrogen Plant Alternatives Study (HPAS) 90% Review

Shaw Offices
Denver, Colorado
November 6, 2008

NGNP TEAM



1. Welcome

NGNP TEAM



2. Review Agenda

NGNP TEAM



Agenda

- Welcome; clarify expectations
- Review Summary Agenda
- Study Purpose & Objectives
- Review Study Products (Deliverables)
- Review Evaluation Criteria
- Technical issues and progress
 - HTSE
 - HyS (including sulfuric acid decomposition)
 - SI (Bunsen reaction and HI decomposition)
 - Flow Diagram
 - Preliminary hazards review
 - Life-cycle costs
 - Technical risk assessment
 - Technology development roadmap

Agenda (Continued)

- Technology comparison
 - Cost of production
 - Sensitivity analyses
 - Capital cost
 - Hazards reviews
 - Technical risk
- Conclusions
- Deliverable schedule

3. Purpose & Objectives

Purpose & Objectives

- Provide basis for further development
 - Commercial Potential
 - Technology Readiness
- For three technologies
 - High temperature steam electrolysis (HTSE)
 - Hybrid sulfur (HyS)
 - Sulfur iodine (SI)

4. Study Products

NGNP TEAM

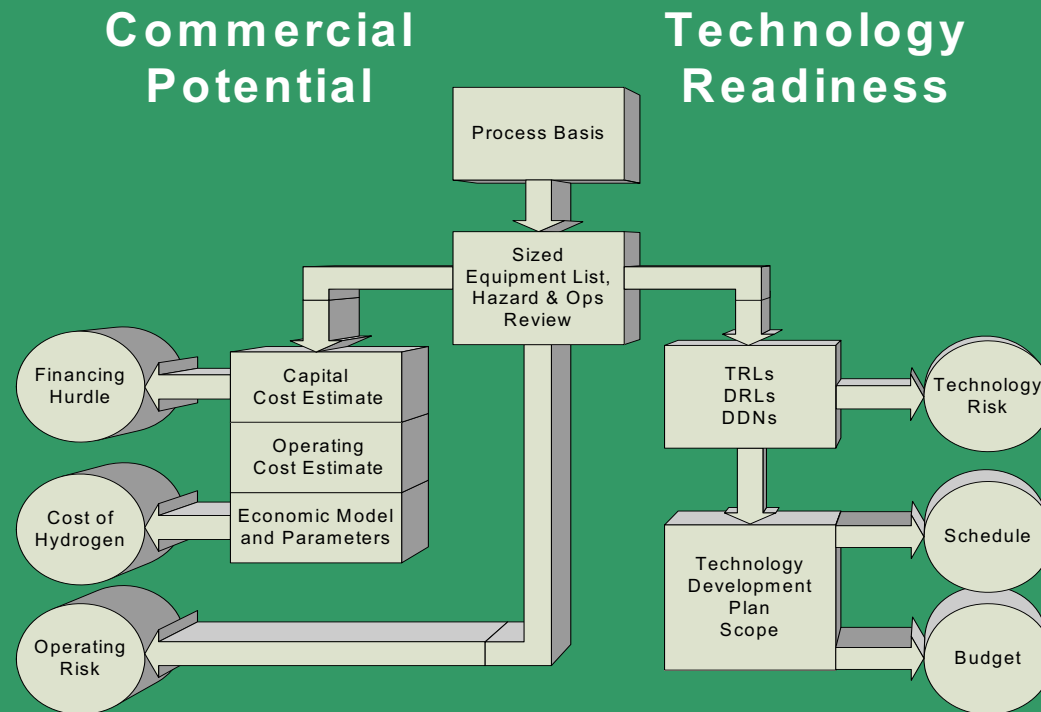


Study Deliverables

- Process flow sheets
- Sized equipment lists
- Capital cost estimates
- Operating cost estimates
- Economic model
- Life-cycle cost of hydrogen
- Sensitivity analyses
- Preliminary hazards analysis and operability review
- Technology readiness level scores (TRLs)
- Design readiness level scores (DRLs)
- Design data needs (DDNs)
- Technology development plan (technology maturation plan)
 - Scope
 - Schedule
 - Budget

5. Evaluation Criteria

Study Process: Development of Criteria



Study Basis

- Study Basis is for the base case for each technology
- Sensitivity analyses are carried out around these base cases
- Technologies studied
 - HTSE; HyS & SI
 - Not Reactor technologies
 - Not specific combinations
- System energy balance
 - Baseline price for nuclear thermal energy
 - Excess heat used to generate electricity via a Rankine cycle, with variable efficiency based on available temperature
 - Electricity deficit or surplus is balanced by the grid at a set price and charged with a carbon penalty

Study Basis (continued)

- Plant size: 142 million SCFD (343 MT/day) hydrogen product
- Plant baseline availability: 8200 hours per year average
- Reactor thermal rating: 550 MW_{th}
- Operating temperatures
 - Max Process side temperature: 870°C (Reactor Outlet Temperature [ROT] = 950°C)
 - The helium return temperature to the IHX is set by process requirements
- Reactor Inlet Temperature limits
 - Max is 500°C
 - Min is 350°C.

Study Basis: Plant Capacity

- Optimal use of process heat means using as much high temperature heat from the helium as possible consistent with the heat recovery scheme.
- Heat use is set by the minimum return temperature of helium from the PCHX.
- HTSE optimal use of process heat requires a plant capacity too large to be considered as a comparative baseline:
 - 820 million SCFD
 - About 7 times the capacity of a large world-scale hydrogen plant today
 - Uses one HTGR and about 2800 MW_e imported.
- Hybrid Sulfur and Sulfur Iodine optimum use requires 2 HTGRs to produce 142 million SCFD hydrogen
- 142 million SCFD selected as baseline capacity; optimal use for HTSE will be investigated in sensitivity analysis

6. Technologies

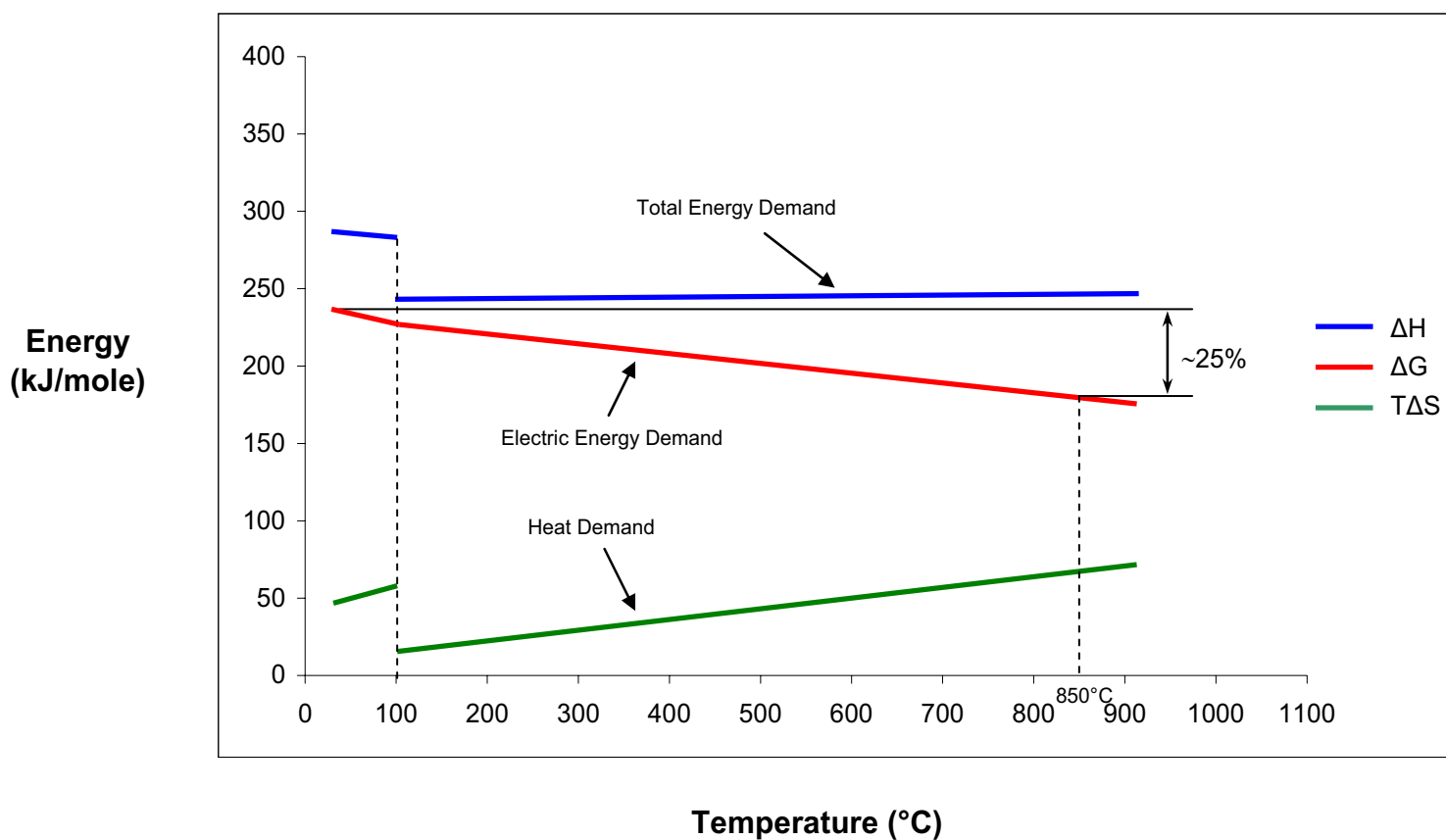
NGNP TEAM



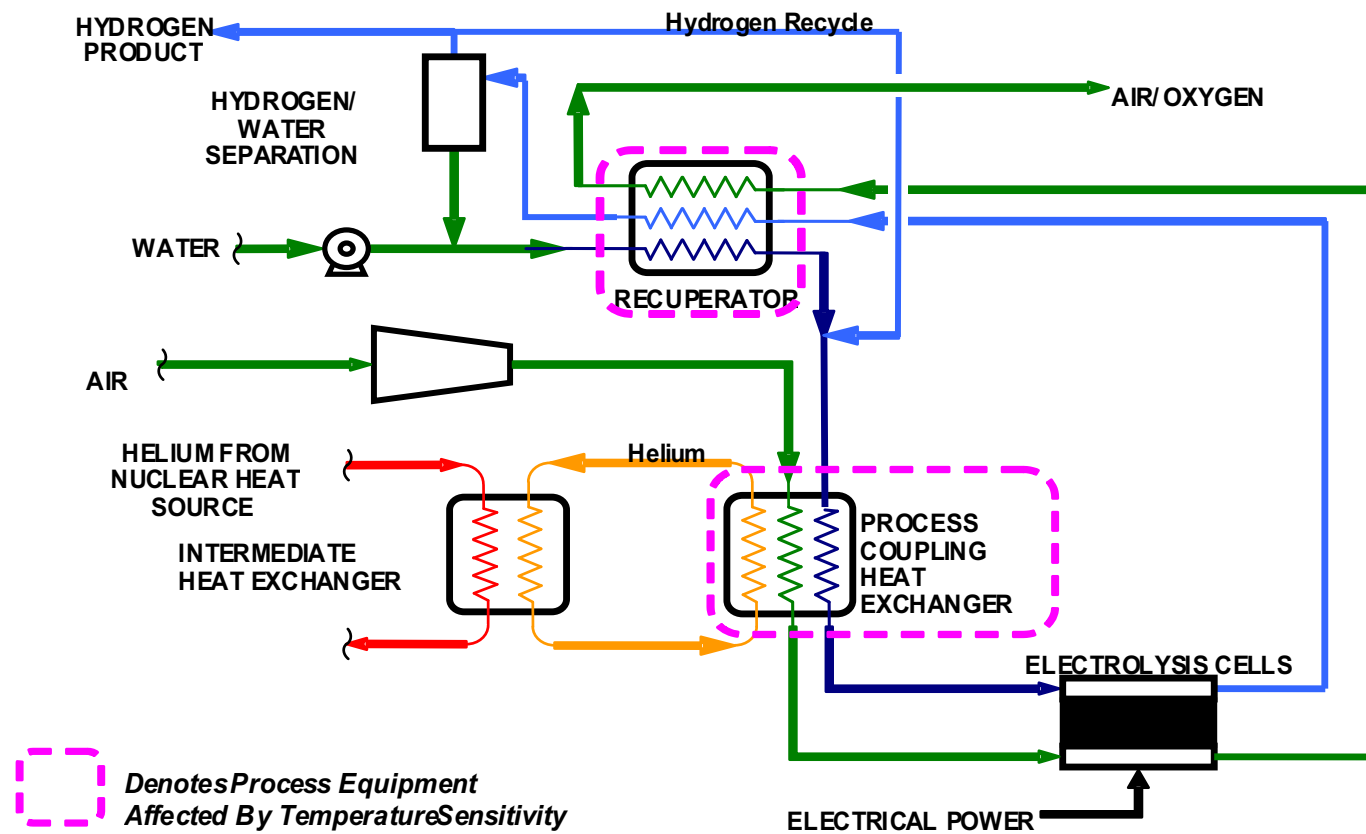
6.1 HTSE

Heat and Electricity Requirements for HTSE

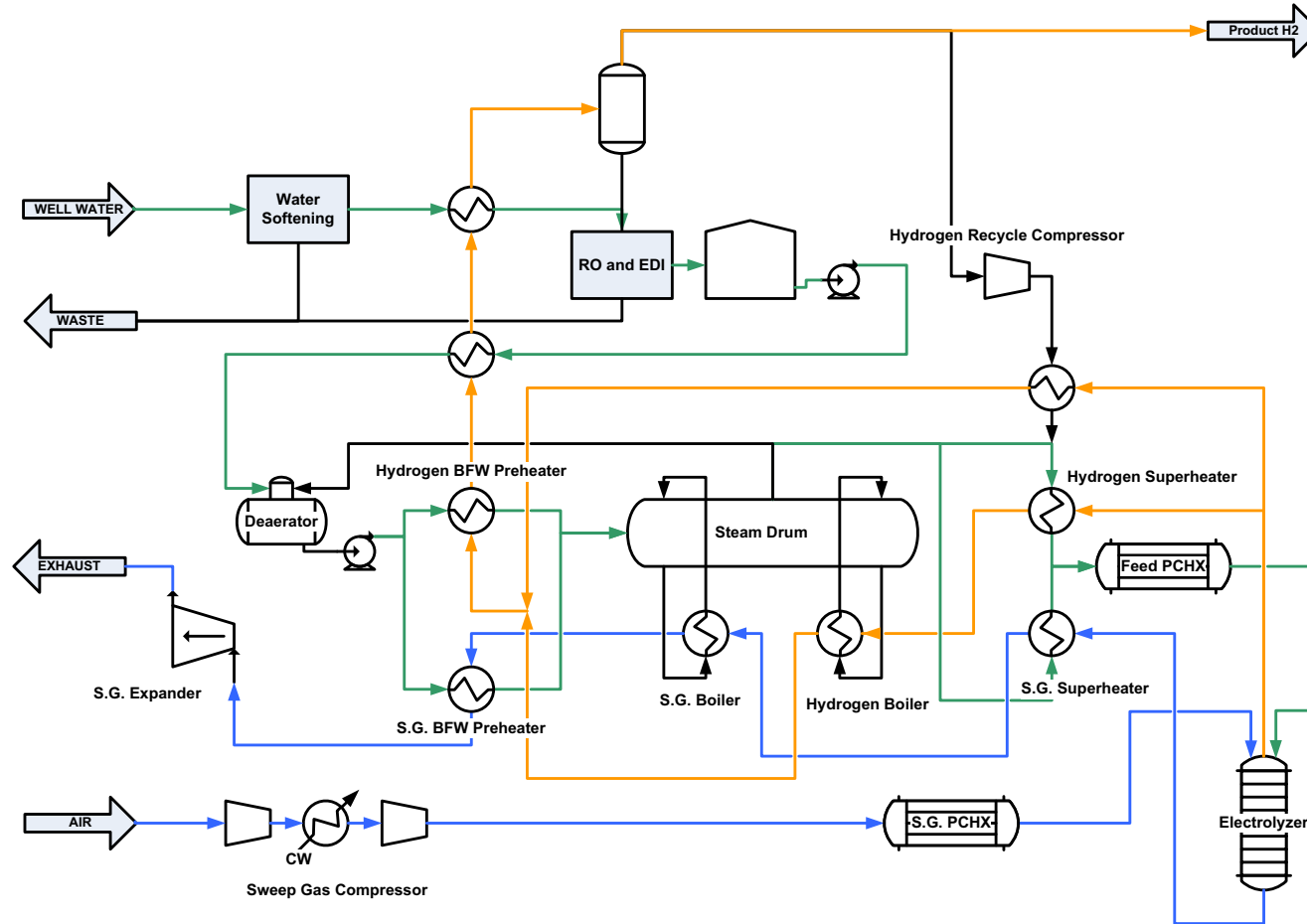
THERMODYNAMIC POTENTIALS OF HTSE VS. TEMPERATURE



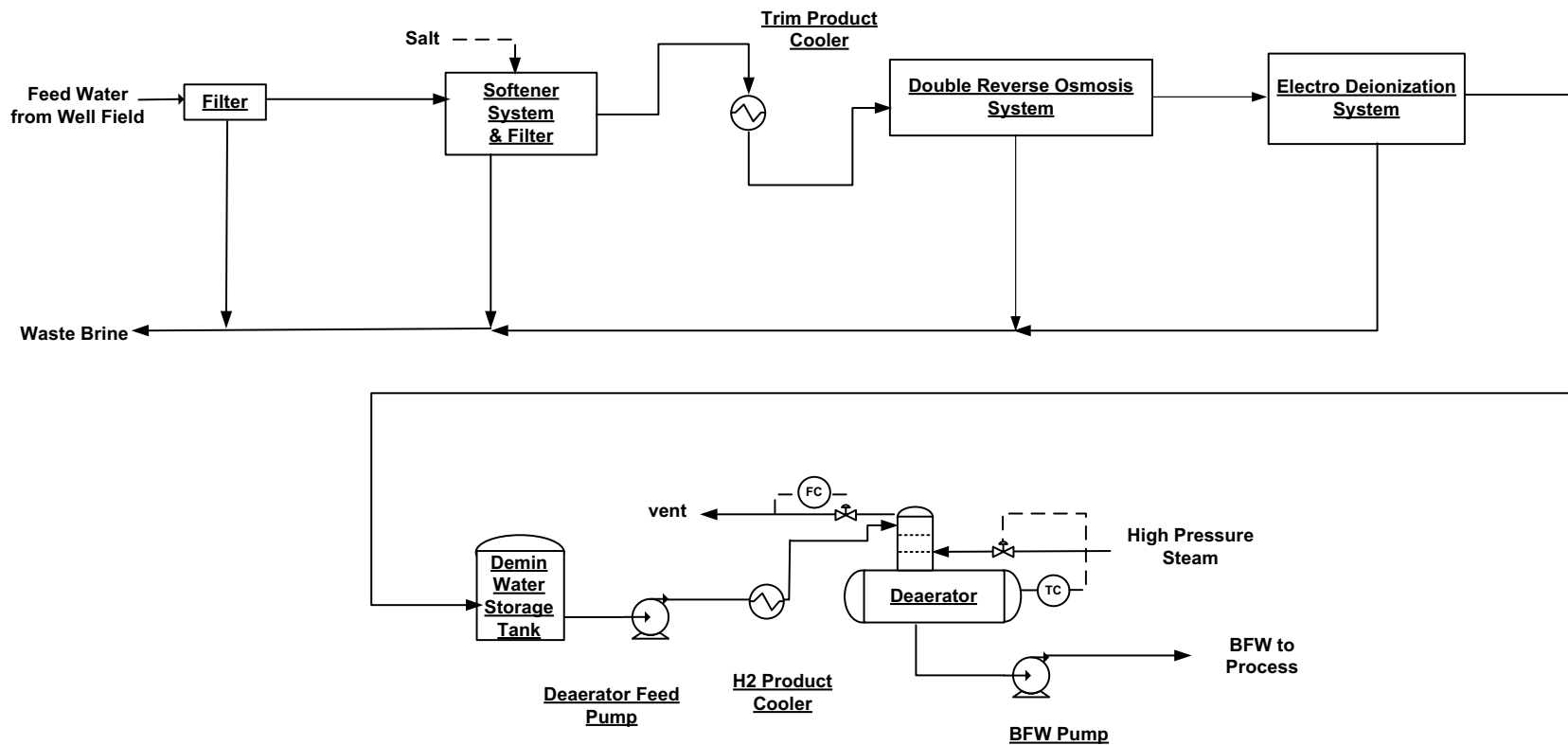
Simplified HTSE Flow Diagram



HTSE Flow Diagram

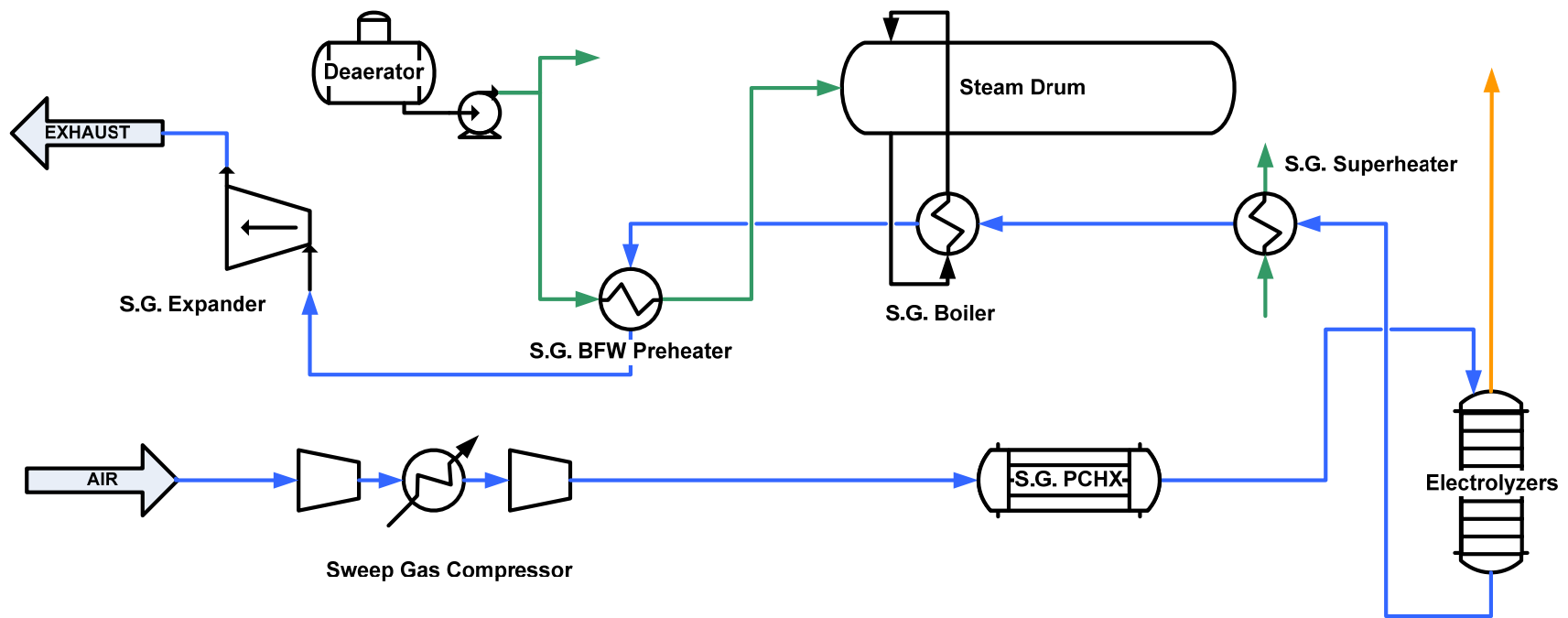


HTSE Water Treatment System

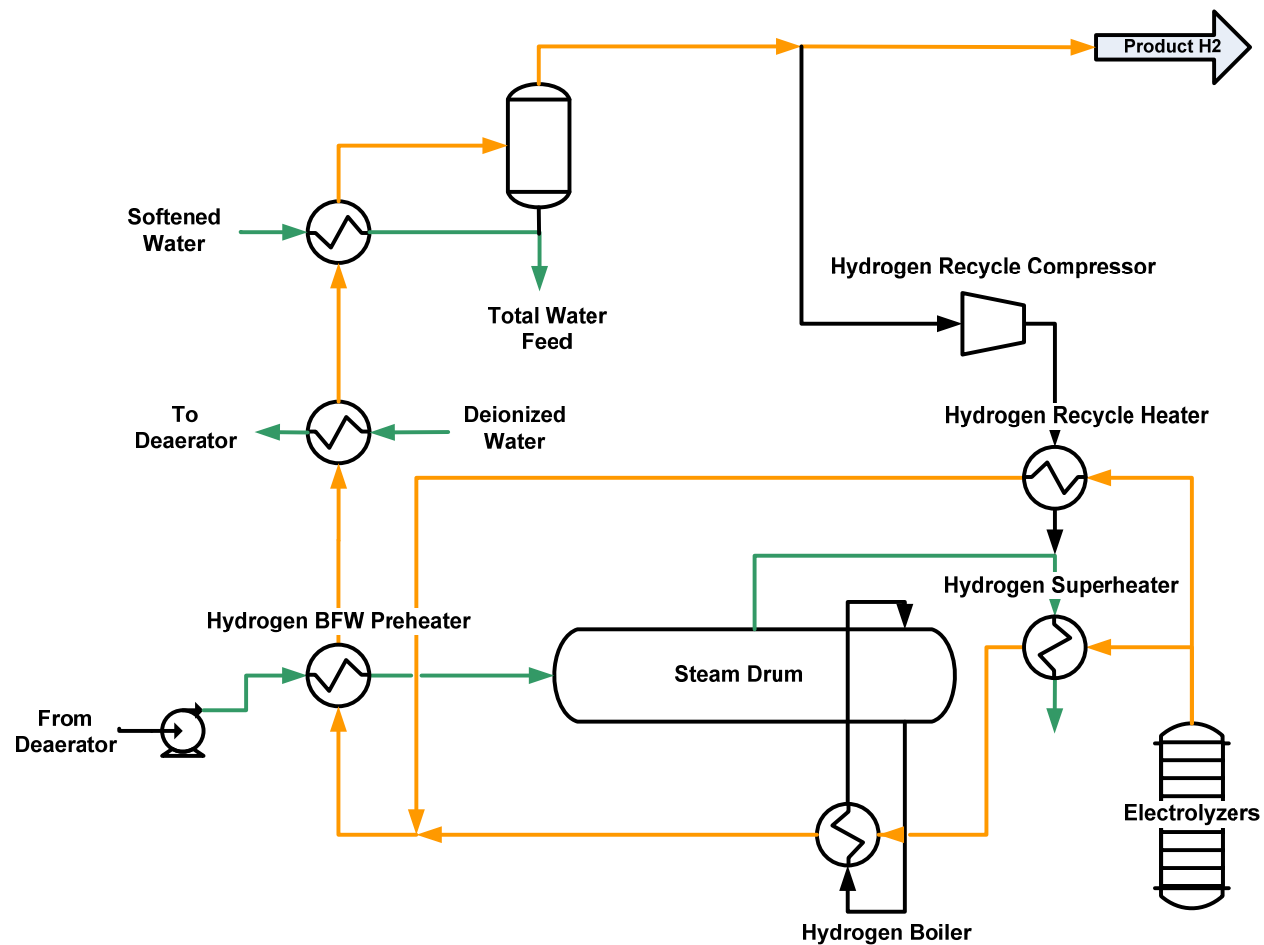


The diagram illustrates a hydrogen production process. It begins with 'WELL WATER' entering a 'Water Softening' unit. The output of the softening unit goes to a pump, then through a heat exchanger, and finally to an 'RO and EDI' unit. The 'RO and EDI' unit produces 'Product H2' and 'Return Water'. The 'Return Water' is pumped back to the 'Water Softening' unit. The 'RO and EDI' unit also feeds into a 'Steam Drum'. The 'Steam Drum' is connected to a 'Deaerator' and a 'BFW Preheaters' unit. The 'Deaerator' feeds into the 'BFW Preheaters'. The 'BFW Preheaters' feed into the 'Steam Drum'. The 'Steam Drum' also feeds into a 'Superheaters' unit. The 'Superheaters' feed into a 'Feed PCHX' unit. The 'Feed PCHX' unit feeds into the 'Electrolyzers'. The 'Electrolyzers' produce 'Product H2' and 'Return Water'. The 'Return Water' is pumped back to the 'Water Softening' unit. The 'Superheaters' also feed into the 'Steam Drum'.

HTSE Sweep Gas System



HTSE Product System

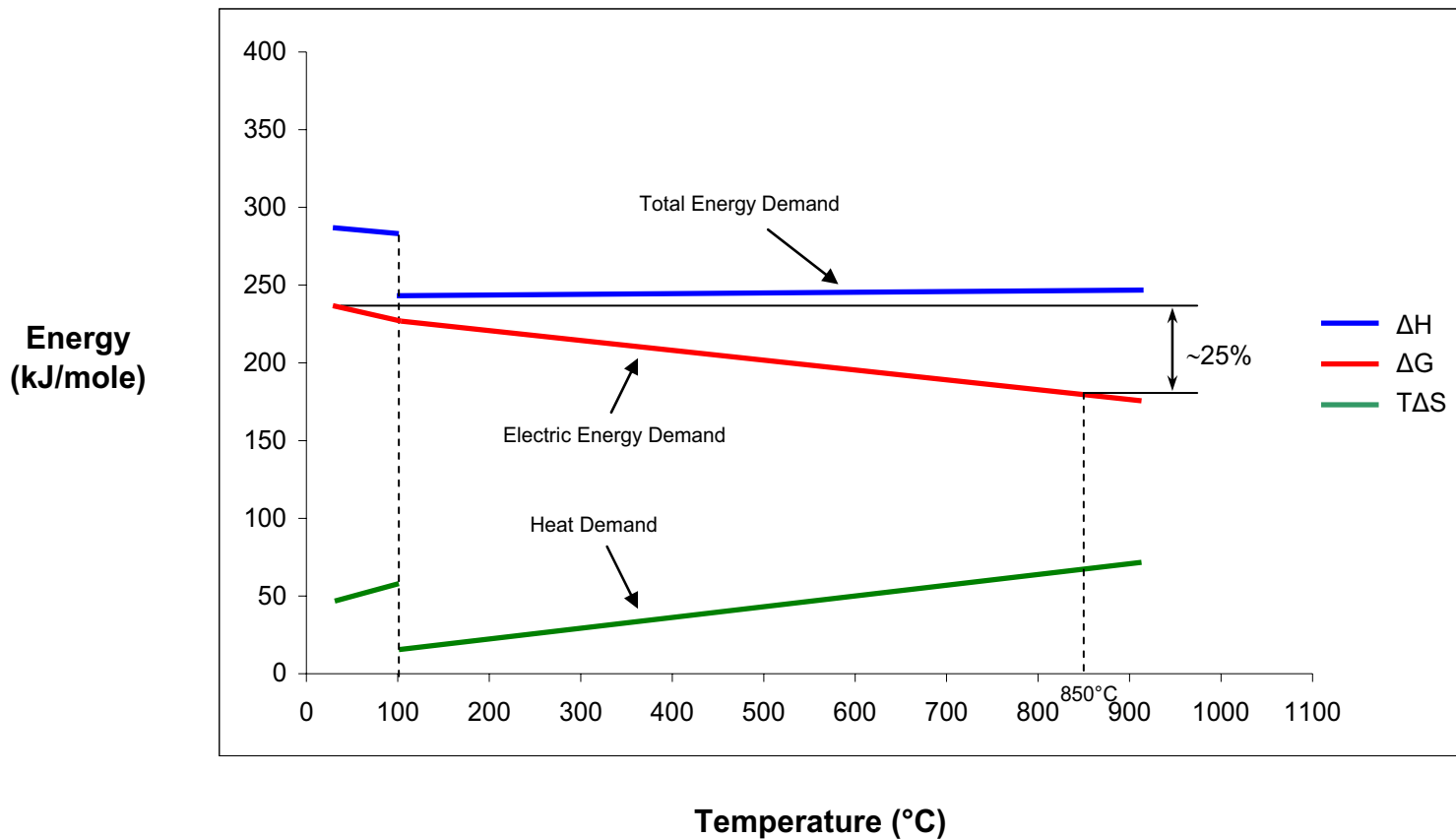


HTSE Flowsheet

- Nothing in the flowsheet is extraordinary upstream of the superheaters
- Technology is available to produce ultra-pure water feed
 - Requirements of the system are not clear
 - In-process treatment may be required
- Purity requirements of the sweep gas are not clear
- High temperature materials are an issue
- To use heat from an HTGR effectively with this technology, high temperature helium valves are required
- Process uses proportionately very little process heat; practical delivery of the heat restricts it further
 - Sensible heat in feed and sweep gas provides some heat
 - Balance is made up by electricity
 - **ASSUMPTION:** No impact on current density

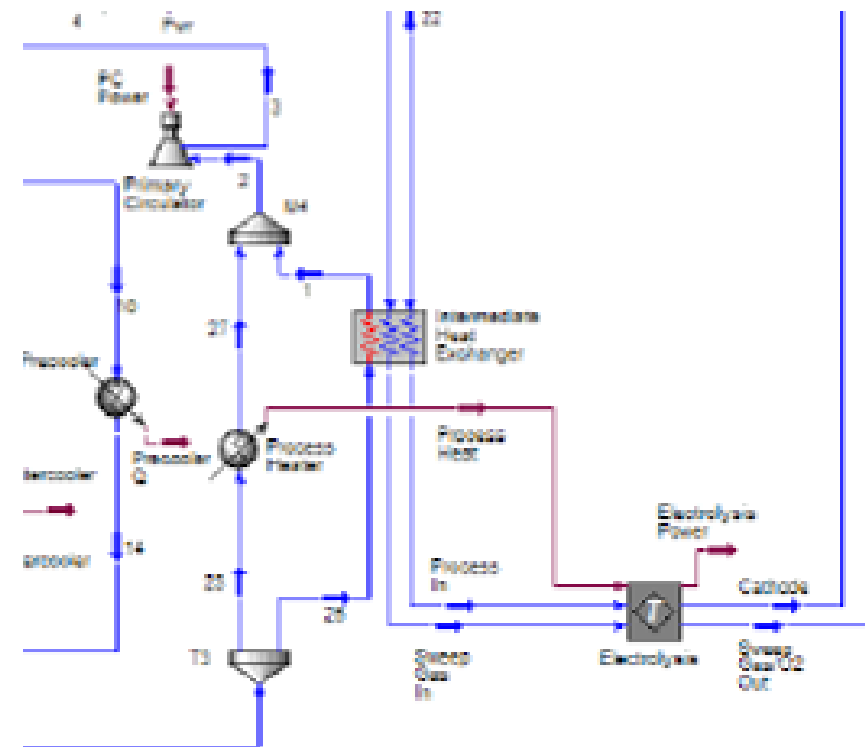
Heat and Electricity Requirements for HTSE

THERMODYNAMIC POTENTIALS OF HTSE VS. TEMPERATURE



HTSE Process Heat

- Process Heat assumed to be supplied at 800°C
- Only sensible heat in feed and sweep gas ABOVE 800°C can realistically be used to supply this heat.
- Max process temperature is set at 870°C
- Only 70K delta T is available to provide process heat
- The remainder is supplied by electricity used for heating rather than electrolysis
- For 142 million SCFD hydrogen
 - 88 MWth process heat
 - 479 MWe for electrolysis and remainder of process heat



HTSE Life Cycle Costs: Capital and Reliability

- Capital cost:
 - Total Installed Cost: Pending
 - Cell Stacks: \$143 million (including in-place spares)
 - Stack assembly: \$ 14 million (allow 10% for labor, seals, frame assembly, tension bars, installation into enclosures, etc.)
 - Power supply: \$ 87 million (including in-place spares)
- Reliability:
 - High temperature equipment will have a foreshortened life: Allow 10 years
 - Lower temperature equipment will be as reliable as any others handling pure water and steam: 30 year life
 - Stacks will require frequent maintenance and replacement: 20 km of seals per module; 76 modules in the plant = 1520 km of seals: Allow 7 year life; 11 module replacements per year.

HTSE Life Cycle Costs: Operating Costs

- Raw Material
 - Availability not an issue
- Maintenance
 - Seals and electrical connections
 - Water treatment facilities
 - Helium valves
- Inspection
 - Seal leaks
 - Internal insulation faults
- Waste disposal
 - Water treatment wastes
- Staff requirements:
 - Maintenance staff requirements:
 - » 5 maintenance personnel per shift plus
 - » 5 day shift only
 - Operating staff requirements:
 - Water treatment: 1 operator per shift
 - Heat recovery: 1 operator per shift
 - Electrolysis: 1 operator per shift
 - Management: 1 Plant manager; 1 Assistant; 1 Engineer and Administrative staff

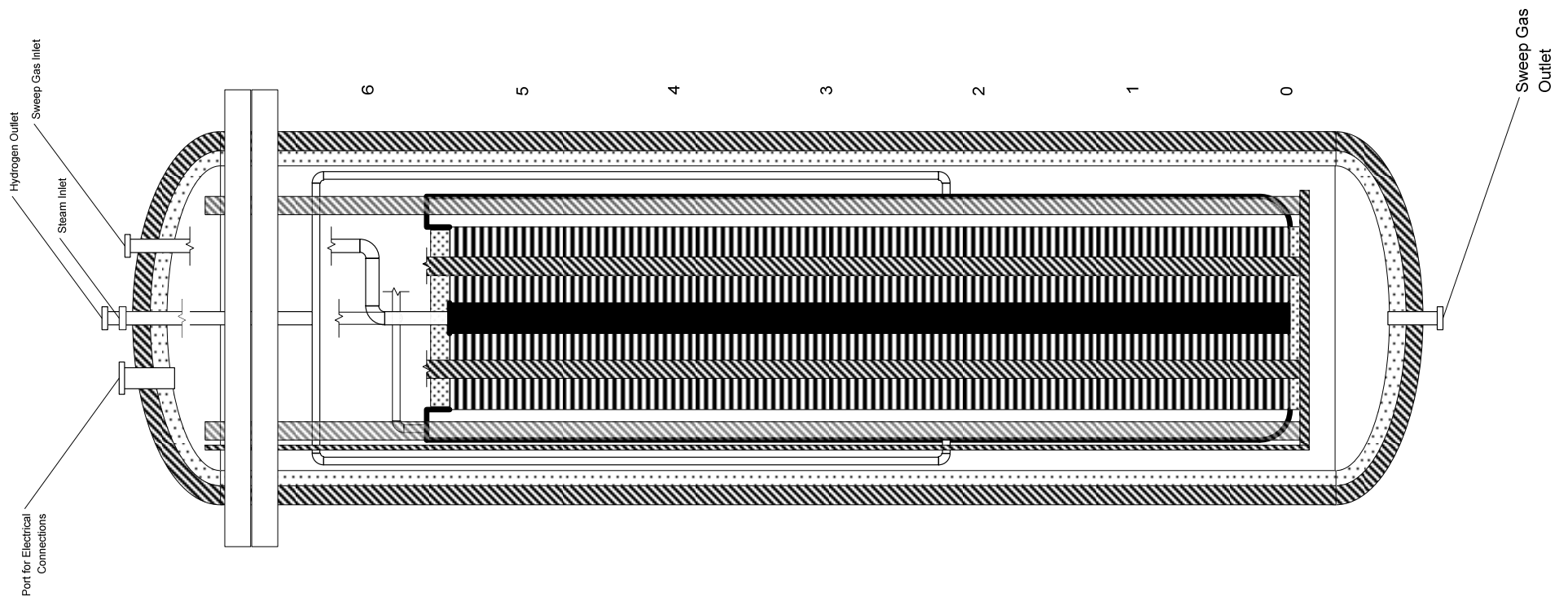
HTSE Life Cycle Costs: Utilities, Catalyst and Chemicals

- Electrical usage
 - Electrolyzers: 478.7 MW_e
 - Other users: 28.6 MW_e
 - Generated on site: 194.2 MW_e
 - Imported electricity: 313.1 MW_e
- Thermal usage
 - Hot helium: 87.7 MW_{th}
- Other utilities
 - Water treatment chemicals:
 - Cooling Water: 34.2 MW_{th}

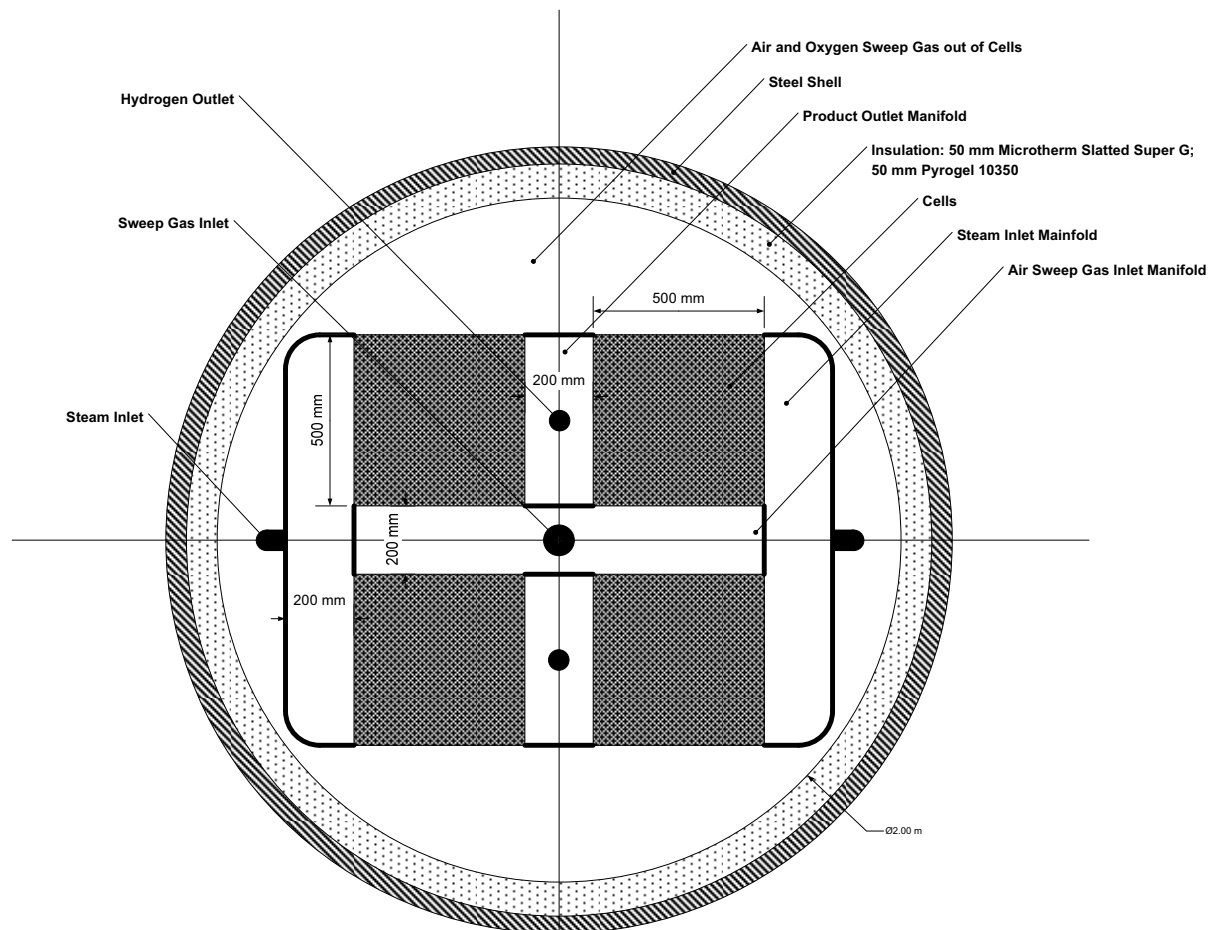
HTSE Preliminary Hazard and Operability Review

- Leak between H₂ and O₂-enriched streams in the electrolyzers resulting in a fire
- Enhanced flammability of materials in O₂-enriched air resulting in an equipment fire
- Fire resulting from rotating machinery acting on an O₂-enriched stream
- Loss of containment of a flammable gas (hydrogen) at high pressure and temperature resulting in a fire or explosion
- Loss of containment of high pressure He
- Higher pressure in He should prevent steam and H₂ leak into the He stream

Electrolyzer: Elevation



Electrolyzer: Plan



Electrolyzer Enclosure Features

- Internally insulated carbon steel
- Body flange to facilitate replacing internals
- All nozzles except sweep gas exit in the top head
- All internals are hung from the top head to accommodate thermal expansion
- Atmosphere is exit sweep gas to avoid wetting insulation
- Manifolding appears adequate

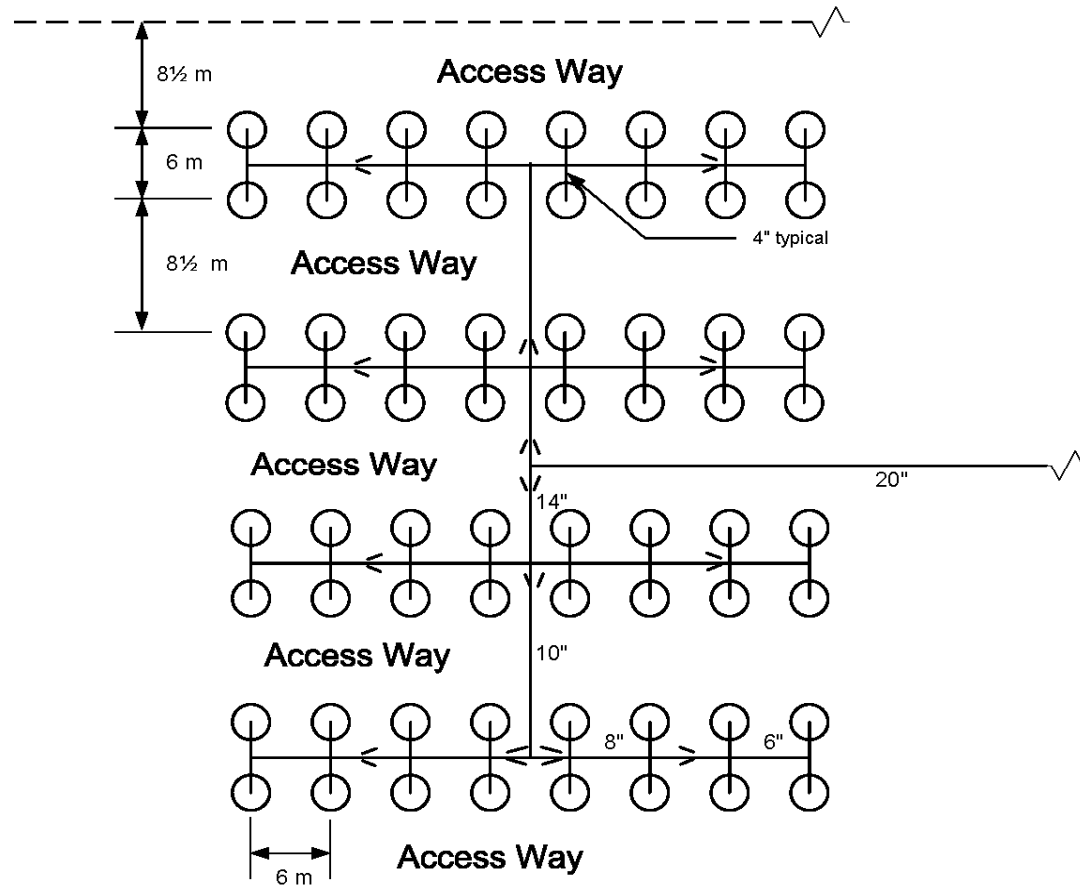
HTSE Technical Issues

- Electrolysis Cell Poisoning
 - Rapid degradation; cause unknown
 - Suspect chromium or other alloying material picked up from stainless piping
 - Cell tolerance to contaminants needs to be established
 - ***Cause unknown; probability of success uncertain***
- Electrolysis Cell Flow Distribution
 - Flow must be distributed evenly between 76 modules; 304 stacks; 760,000 cells
 - Uneven distribution causes inefficient operation and other problems
 - Flow distribution in cells will depend upon manufacturing and assembly variations
 - Tolerance and variability of distribution must be established
 - ***Possibly solved by higher flow rates and pressure drops; probability of success fair to good***

HTSE Technical Issues (continued)

- Reliable seals
 - Oxygen/ Hydrogen in electrolyzers
 - Cables into electrolyzer enclosures
 - Gaskets
 - Tension bars at high temperature
 - **Conditions are very demanding; probability of success fair to poor**
- Seals and electrical connections in very high temperature oxidizing atmosphere
 - **Conditions are very demanding; probability of success fair to poor**
- Thermal expansion of piping, equipment, tension bars, etc.
 - Must be addressed with a combination of materials science and engineering
 - **Probability of success poor**
- Area Specific Resistance (ASR):
 - Needs to be confirmed for the cell technology being considered
 - **Measurement assured; resulting economics uncertain**

Partial Electrolyzer Layout



Technology Readiness Levels (TRLs)

- U** Uncertain at this phase in design and development.
- 1** Basic principles observed and reported in white papers, industry literature, lab reports, etc.
- 2** Technology concept and application formulated.
- 3** Proof-of concept: Analytical and experimental critical function and/or characteristic proven in laboratory..
- 4** Technology or Component is tested at bench scale to demonstrate technical feasibility and functionality.
- 5** SSC demonstrated at experimental scale in relevant environment.
- 6** SSCs have been demonstrated at a pilot scale in a relevant environment.
- 7** SSCs integrated engineering scale demonstration in a relevant environment.
- 8** Integrated prototype of the SSC is demonstrated in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance.
- 9** The project is in final configuration tested and demonstrated in operational environment.
- 10** Commercial-scale demonstration is achieved.

TRLs of Critical SSCs

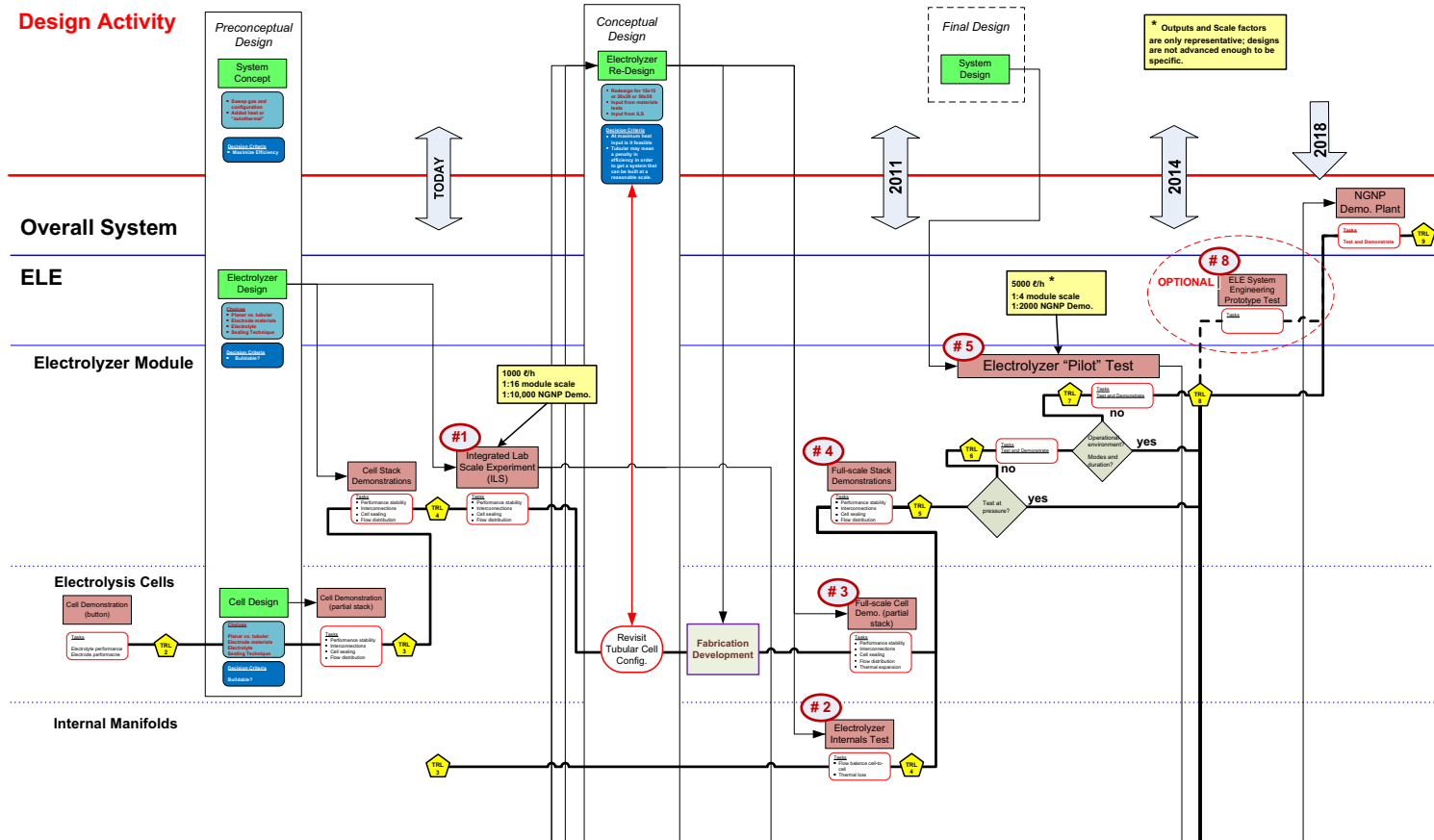
High Temperature Steam Electrolysis

Overall HTSE HPS	2
ELE System (Electrolysis System)	2
Electrolyzer Module	3
SOE Cells	4
Internal Manifolds	3
Sweep Gas Coupling Heat Exchanger	5
Process Coupling Heat Exchanger	5
Piping, Manifolds, Insulation	2
HRS System (Heat Recovery System)	5
Heat Exchangers	5
Recirculator	8
FUS System (Feed & Utility System)	U
Feed Purification System	U
Sweep Gas Turbine	7
PPU System (Product Purification Unit)	8

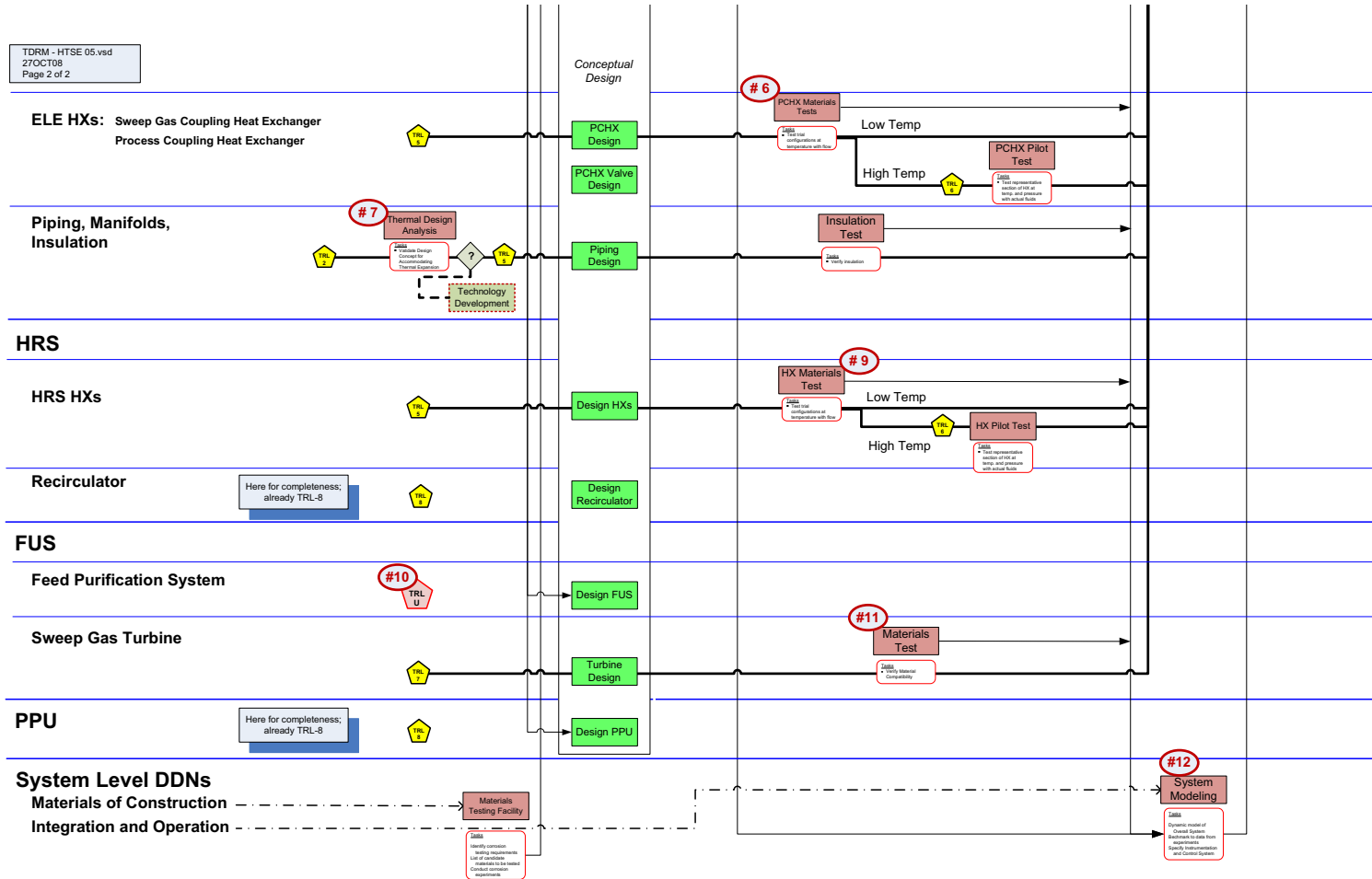
HTSE Roadmap: Part 1

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Hydrogen Production System (HPS) Technology Development Road Map (TDRM) Process Technology #4: High Temperature Steam Electrolysis (HTSE)



HTSE Roadmap: Part 2



Design Data Needs for Feed Purification and Instrumentation and Controls

- HPS-FUS-01 Identify Critical Impurities and Determine Critical Component Tolerance
- HPS-FUS-02 Develop Feed Water Purification Methods
- HPS-FUS-03 Develop Process Fluid Purification Methods
- HPS-PCN-04 Develop and Test High Temperature Helium Control Valves

Design Data Needs for Electrolysis (including PCHX)

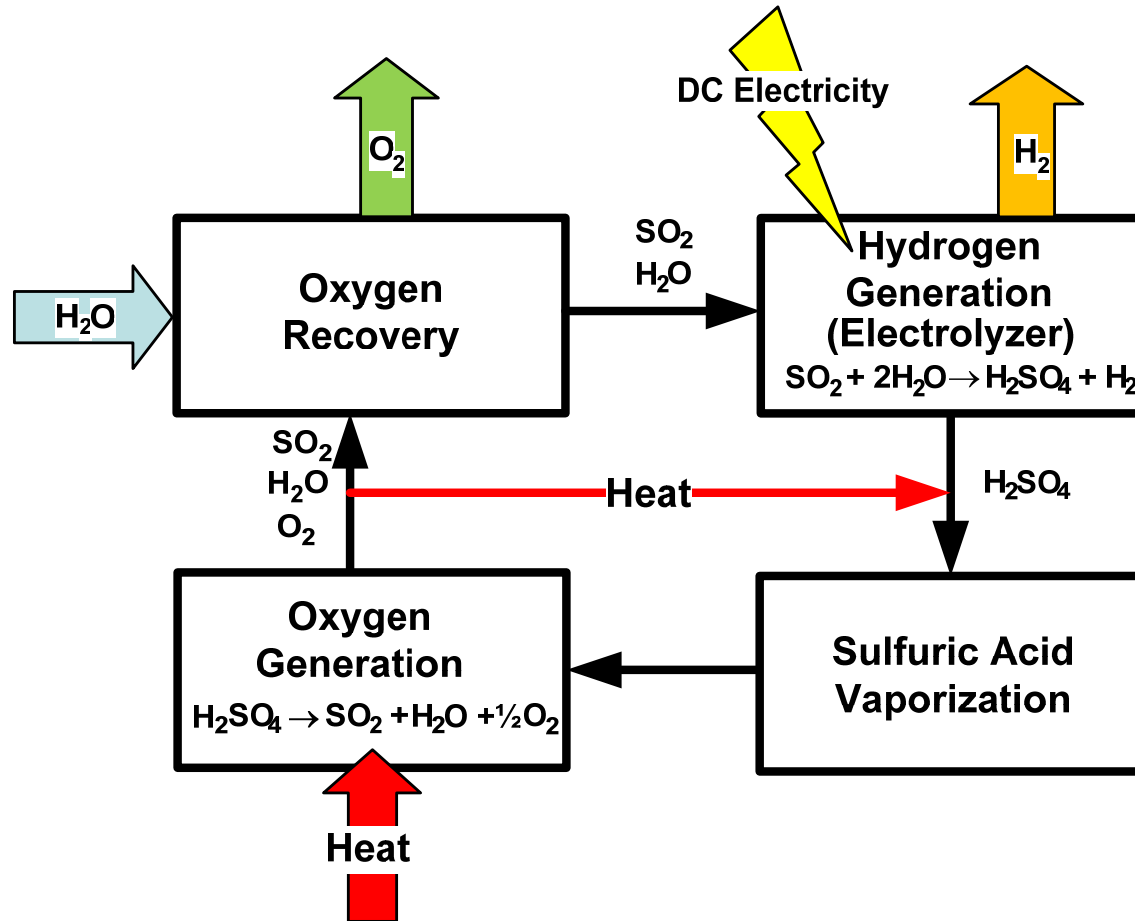
- HPS-ELE-01 Develop a Cell with a commercially acceptable activity and life
- HPS-ELE-02 Optimize Catalyst Loading in the Electrodes
- HPS-ELE-03 Develop a Cell Configuration and Materials
- HPS-ELE-04 Build and Test a Prototype Cell
- HPS-ELE-05 Build and Test a Pilot-scale Cell
- HPS-ELE-06 Build and Test a Stack of Cells in a Pilot Plant
- HPS-ELE-07 Test Alloy 230 and Alloy 617 in High Temperature Helium and Air/Oxygen and Steam/Hydrogen Mixtures
- HPS-ELE-08 Test a Pilot-Scale PCHX
- HPS-ELE-09 Provide Data Supporting a Design Code Case
- HPS-ELE-10 Develop Gasket Materials and Design
- HPS-ELE-11 Develop Seal Materials and Design
- HPS-ELE-12 Develop Welding Materials
- HPS-ELE-13 Develop Piping Materials and Design Methods

HTSE Design Tasks

- HPS-FUS-DT-01 Design a feed water purification system including equipment sizing and economics
- HPS-FUS-DT-02 Design a process fluid purification system including equipment sizing and economics
- HPS-ELE-DT-03 Design a cell stack suitable for operation at high temperature in a high pressure, oxygen-rich environment
- HPS-ELE-DT-04 Design an economical stack enclosure that minimizes heat loss, sealing and stack handling and maximizes safety
- HPS-ELE-DT-05 Design a conceptual plant layout and piping arrangement that accommodates expected thermal expansion
- HPS-ELE-DT-06 Design and rate conceptual PCHXs

6.2 HyS

Hybrid Sulfur Cycle



The diagram illustrates a complex industrial process for producing hydrogen and oxygen. The process begins with a **Water Feed** (green arrow) entering stream 1, which goes to the **Electrolyzer**. The **Electrolyzer** also receives stream 3 from the **Anolyte Prep Tank** and stream 11 from the **Vacuum Stripper**. The **Electrolyzer** produces **Hydrogen** (green arrow, stream 2) and a gas stream (stream 17) that goes to the **Anolyte Prep Tank**. The **Anolyte Prep Tank** also receives stream 10 from the **Decomposer** and stream 15 from the **SO₂ Absorber**. The **Anolyte Prep Tank** produces **Oxygen** (green arrow, stream 16) and a gas stream (stream 7) that goes to the **SO₂ Absorber**. The **SO₂ Absorber** also receives stream 14 from the **Vacuum Stripper** and stream 12 from the **Recycle Flash**. The **SO₂ Absorber** produces a gas stream (stream 13) that goes to the **Recycle Flash**. The **Recycle Flash** also receives stream 5 from the **Feed Flash** and stream 6 from the **Vacuum Stripper**. The **Recycle Flash** produces a gas stream (stream 4) that goes to the **Feed Flash** and stream 14 to the **SO₂ Absorber**. The **Feed Flash** also receives stream 11 from the **Vacuum Stripper** and stream 1 from the **Water Feed**. The **Vacuum Stripper** also receives stream 8 from the **Decomposer** and stream 11 from the **Electrolyzer**. The **Vacuum Stripper** produces a gas stream (stream 6) that goes to the **Recycle Flash** and stream 11 to the **Electrolyzer**. The **Decomposer** also receives stream 8 from the **Electrolyzer** and stream 11 from the **Electrolyzer**. The **Decomposer** produces a gas stream (stream 9) that goes to the **Anolyte Prep Tank** and stream 10 to the **SO₂ Absorber**.

HyS Flowsheet

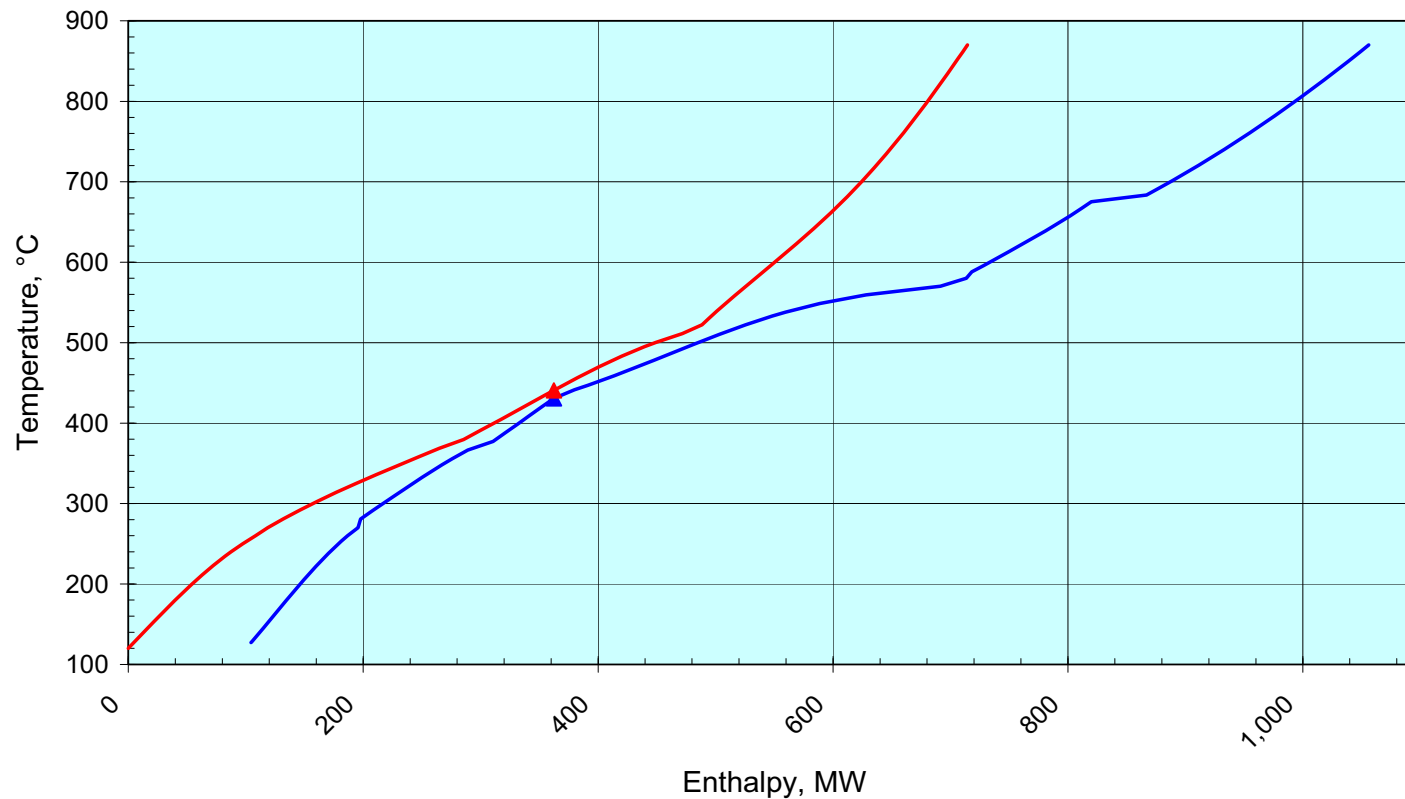
- No separations or reactions appear unreasonable
 - Thermodynamic and VLE data is needed to confirm the validity of separations
- Some flows, especially around the vacuum tower are very high.
- Four (4) trains of process equipment per reactor [eight (8) trains per 2-reactor plant] are needed to fall within reasonable equipment and piping sizes
- Materials of construction for sulfuric acid, oxygen and sulfur dioxide in the same stream require further investigation
- Reasonable pressure drops have been incorporated
- As in HTSE, sensitivity of key components to impurities have not been established
 - Blowdown or a slipstream to be processed will probably be required
- Recovery of sulfur species from waste streams will probably be required
 - Costed as blowdown, neutralization and disposal

Sulfuric Acid Decomposition Reactor Heating and Cooling Curves

Bayonet Reactor Heating and Cooling Curves

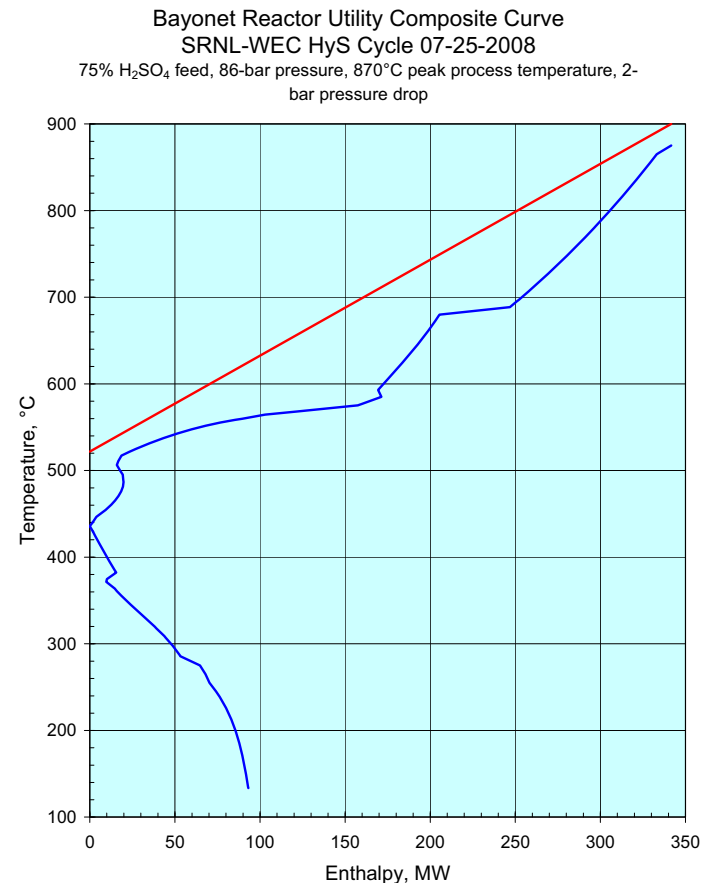
SRNL-WECHyS Cycle 07-25-2008

75% H_2SO_4 feed, 86-bar pressure, 870°C peak process temperature, 2-bar pressure drop



Sulfuric Acid Decomposition Reactor Composite Utility Curves

- Heat required from He and cooling requirement is set by the pinch point
- Pinch point calculated assuming chemical and thermal equilibrium
- Departure from equilibrium can change the heating and cooling requirements
- Sensitivity to heat transfer resistance and reaction kinetics must be investigated, modeled and confirmed by testing



HyS Life Cycle Costs: Capital and Reliability

- Capital cost (*provisional*):
 - Total Installed Cost: \$1.2 billion (not including 2 HTGRs)
 - Decomposers: \$156 million (equipment only)
 - Cells: \$150 million (stacks only)
 - Power supply: \$ 39 million
- Reliability:
 - High temperature equipment is either SiC or internally insulated
 - Lower temperature equipment will be as reliable as any similar chemical plant:
30 year life
 - Cell stacks will require frequent maintenance and replacement: corrosive environment

HyS Life Cycle Costs: Operating Costs

- Raw Material
 - Availability not an issue
- Maintenance
 - Seals
 - Water treatment facilities
- Inspection
 - Piping and equipment lining faults
- Waste disposal
 - Water treatment wastes
 - Sulfur dioxide and blowdown neutralization
- Staff requirements:
 - Maintenance staff requirements:
 - » 3 maintenance personnel per shift (mechanical, electrical, controls) plus
 - » 5 day shift only
 - Operating staff requirements:
 - Water treatment: 1 operator per shift
 - Decomposition: 4 operators per shift
 - Electrolysis: 3 operator per shift
 - Management: 1 Plant manager; 1 Assistant; 1 Engineer and Administrative staff

HyS Life Cycle Costs: Utilities, Catalyst and Chemicals

- Electrical usage
 - Electrolyzers: 236 MW_e
 - Other users: Pending
 - Generated on site: 148 MW_e
 - Imported electricity: 88 MW_e
- Thermal usage
 - Hot helium: 712 MW_{th}
- Other utilities Pending
 - Water treatment chemicals
 - Cooling Water:
 - Replacement sulfuric acid:
 - Caustic for treating waste and blowdown:

HyS Preliminary Hazard and Operability Review

- Loss of containment of a highly corrosive acid. High pressure can result in a jet or spray leak.
- Loss of containment of a toxic gas
- Loss of containment of a flammable gas at high pressure and temperature resulting in a fire or explosion
- The enhanced flammability of materials in oxygen resulting in an equipment fire
- Loss of containment of high pressure He or cross contamination between primary and secondary He streams due to acid corrosion of He heat exchange equipment

Sulfuric Acid Decomposition Technical Issues

- Economic catalyst and basic data and analysis
 - Catalyst with economic life
 - Thermodynamic and VLE data
 - Thermo-hydraulic analysis with reaction kinetics
 - ***Probability of success fair***
- Flow distribution between bayonet tubes
 - Good distribution is essential to efficient operation
 - High tube pressure drop will allow good distribution
 - New decomposer design may be required
 - ***Path forward unclear; probability of success fair***
- Distribution of temperature across the reactor elements
 - Good distribution is essential to efficient operation
 - Longitudinal flow along tubes will provide good temperature distribution
 - ***Probability of success good, but possibly uneconomic***

Sulfuric Acid Decomposition Technical Issues (Continued)

- Transition between SiC decomposer tubes and metallic vessel
 - Reliable seals
 - Forgiving design
 - ***Transition technology is being developed in other fields; thermal shielding may be possible. Probability of success fair to good***

HyS Electrolysis Technical Issues

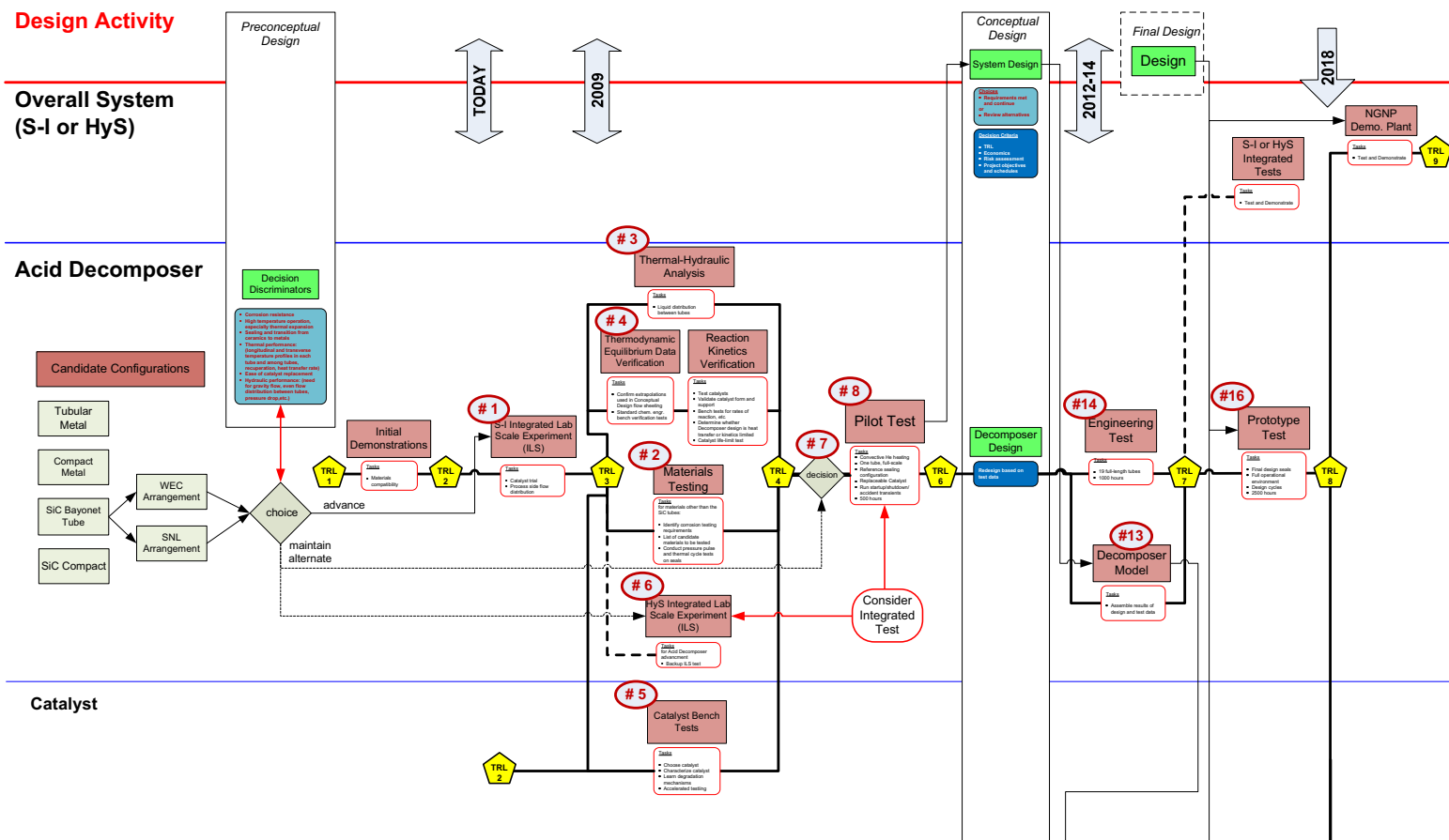
- Electrolysis Cell Operation
 - Membrane permeability to sulfur species
 - Cell tolerance to contaminants needs to be established
 - ***Causes known; probability of success fair to good***
- Electrolysis Materials of Construction
 - Economic materials depend upon coating integrity

TRLs of Critical SSCs Sulfuric Acid Decomposition

Acid Decomposition Section	2
Acid Decomposer (decomposition reactor) [H₂SO₄ → ½O₂ + SO₂ + H₂O]	2
Catalyst	2
Decomposer product handling equipment	6
Acid concentration vacuum column	6
Feed acid handling and concentrating equipment	6
Steam ejectors and vacuum pump	6

Sulfuric Acid Decomposition: Part 1

Hydrogen Production System (HPS) Technology Development Road Map (TDRM) Process Technology #1: Sulfuric Acid Decomposition



Sulfuric Acid Decomposition Roadmap: Part 2

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Balance of System

Reactor Product And Recycle Flash

#9

VLE Data Verification

Tasks
• Get VLE (Vapor Liquid Equilibrium) data for design

TRL 6

TRL 8

Design

Vacuum Stripper

#10

Stripper Tower Design Data

Tasks
• Experimentally verify under design process
• Determine Height Equivalent to one Theoretical Plate (HETP) and/or mass transfer factor

TRL 6

TRL 8

Design

Decomposer Product Handling

#11

Materials Test

Tasks
• Verify Material Compatibility

TRL 6

TRL 8

Design

Feed Acid Handling

#12

Materials Test

Tasks
• Verify Material Compatibility

TRL 6

TRL 8

Design

System Level DDNs

Integration and Operation

#15

System Modeling

Tasks
• Dynamic model of Overall System
• Benchmark to data from experiments
• Verify Performance and Control System

TRLs of Critical SSCs Sulfur Dioxide Electrolysis

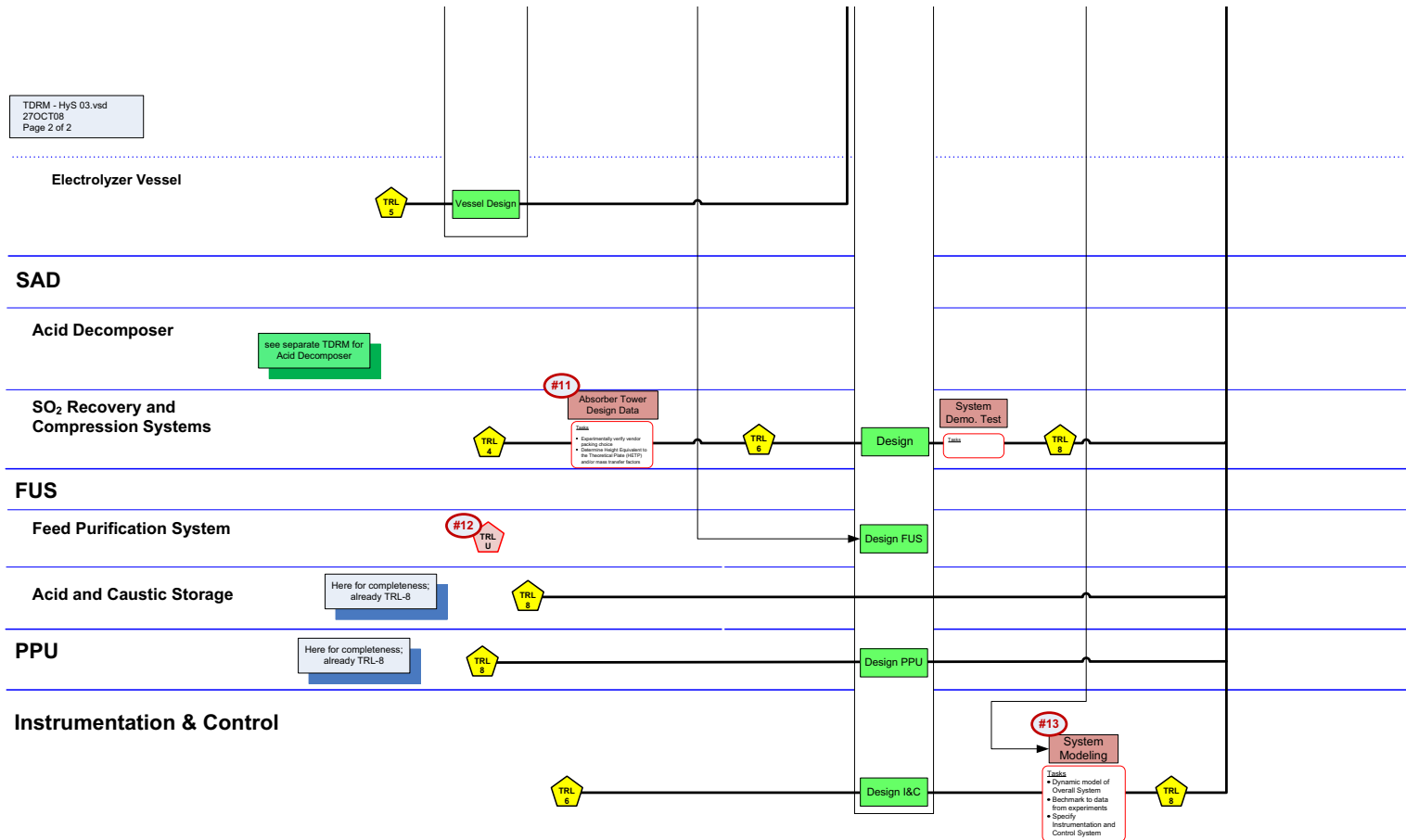
Electrolyzer System (ELE)	2
SO₂ Electrolysis Cells	3
Electrolyzer Internals	2
Electrolyzer Vessels	5
SO₂ portions of the Acid Decomposition System (SAD)	4
SO₂ Recovery System	4
SO₂ Compression System	4
Feed and Utility System (FUS)	U
Water Treatment System	U
Product Purification System (PPU)	8
Instrumentation and Control (I&C) System	6

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Design Activity



Sulfur Dioxide Electrolysis Roadmap: Part 2



Design Data Needs for Sulfuric Acid Decomposition

- HPS-SAD-01 Confirm Thermodynamic Data for the Sulfuric Acid Decomposition Process
- HPS-SAD-02 Develop a Commercial Sulfuric Acid Decomposition Catalyst
- HPS-SAD-03 Gather Decomposition Reaction Kinetics Data
- HPS-SAD-04 Test Silicon Carbide and other Ceramic Material in Decomposition Service
- HPS-SAD-05 Test Alloy 230 and Alloy 617 in a High Temperature Sulfuric Acid, Sulfur Dioxide, and Oxygen Atmosphere.
- HPS-SAD-06 Develop a Method to Bond Alloy 230 or Alloy 617 or Similar Materials to Silicon Carbide and other Ceramics.
- HPS-SAD-07 Develop Materials to Seal the Joints between Ceramic Decomposer Elements and the Metallic Tube Sheet or Vessel.
- HPS-SAD-08 Test a Pilot-Scale Decomposer.
- HPS-SAD-09 Provide Data Supporting a Design Code Case
- HPS-SAD-10 Develop Gasket Materials and Design
- HPS-SAD-11 Develop Seal Materials and Design
- HPS-SAD-12 Develop Welding Materials
- HPS-SAD-13 Develop Cladding and Coating Materials
- HPS-SAD-14 Develop Piping Materials and Design Methods
- HPS-SAD-15 Measure the Height Equivalent to a Theoretical Plate (HETP) for the Concentrator (Vacuum Tower)
- HPS-SAD-16 Measure the Height Equivalent to a Theoretical Plate (HETP) for the SO₂ Absorber

Design Data Needs for Feed and Utility Supply, Electrolyzers, Product Purification, and Instrumentation and Control

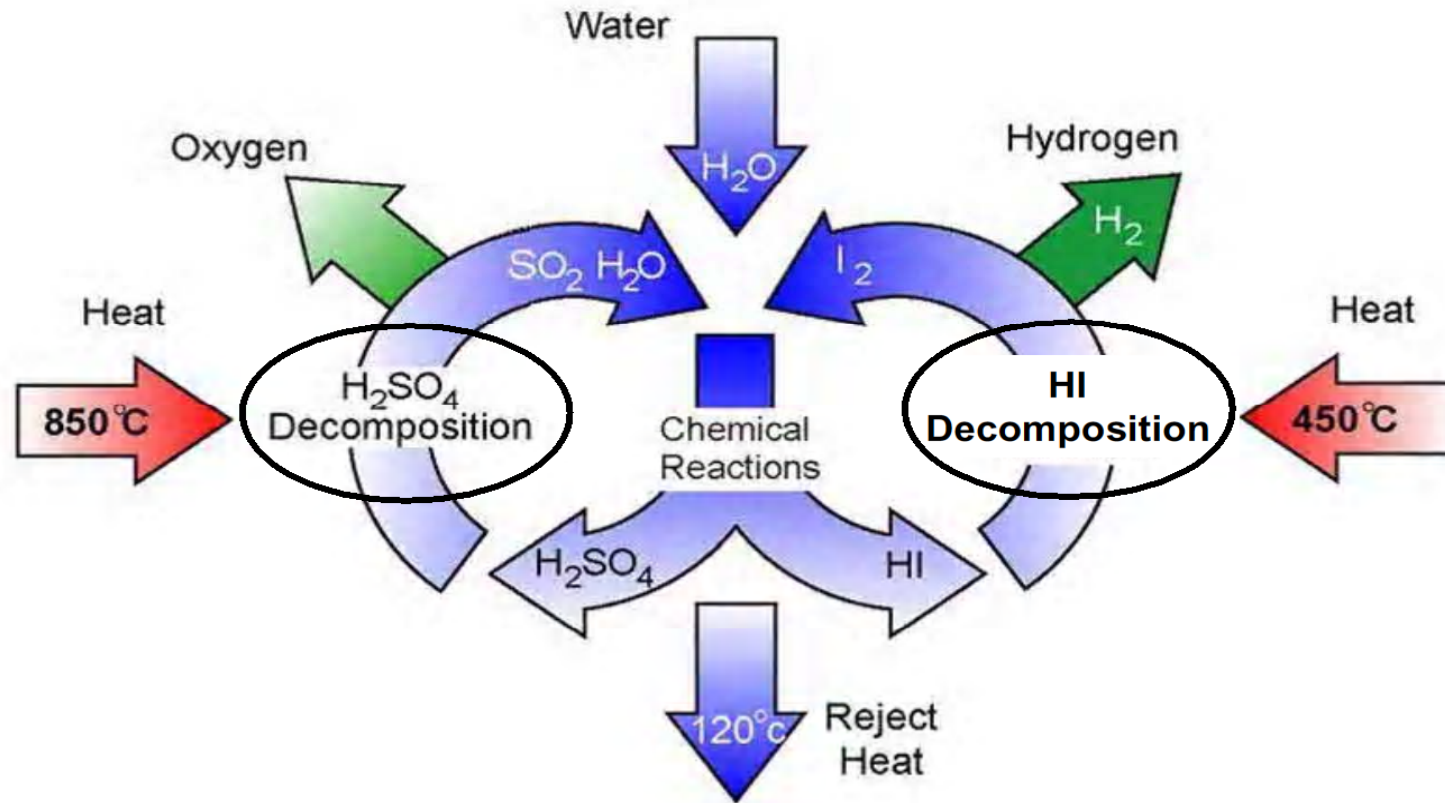
- HPS-FUS-01 Identify Critical Impurities and Determine Critical Component Tolerance
- HPS-FUS-02 Develop Feed Water Purification Methods
- HPS-FUS-03 Develop Process Fluid Purification Methods
- HPS-ELE-01 Develop a Cell Membrane
- HPS-ELE-02 Optimize Catalyst Loading in the Electrodes
- HPS-ELE-03 Develop a Cell Configuration and Materials
- HPS-ELE-04 Build and Test a Prototype Cell
- HPS-ELE-05 Build and Test a Pilot-scale Cell
- HPS-ELE-06 Build and Test a Stack of Cells in a Pilot Plant
- HPS-PPU-01 Identify Product Impurities
- HPS-PPU-02 Test Product Purification Methods
- HPS-PCN-01 Test Sensors in the Pilot Plant
- HPS-PCN-02 Develop Valves for High-Temperature Acid and/or Helium Service
- HPS-PCN-03 Test Valves in the Pilot Plant

HyS Design Tasks

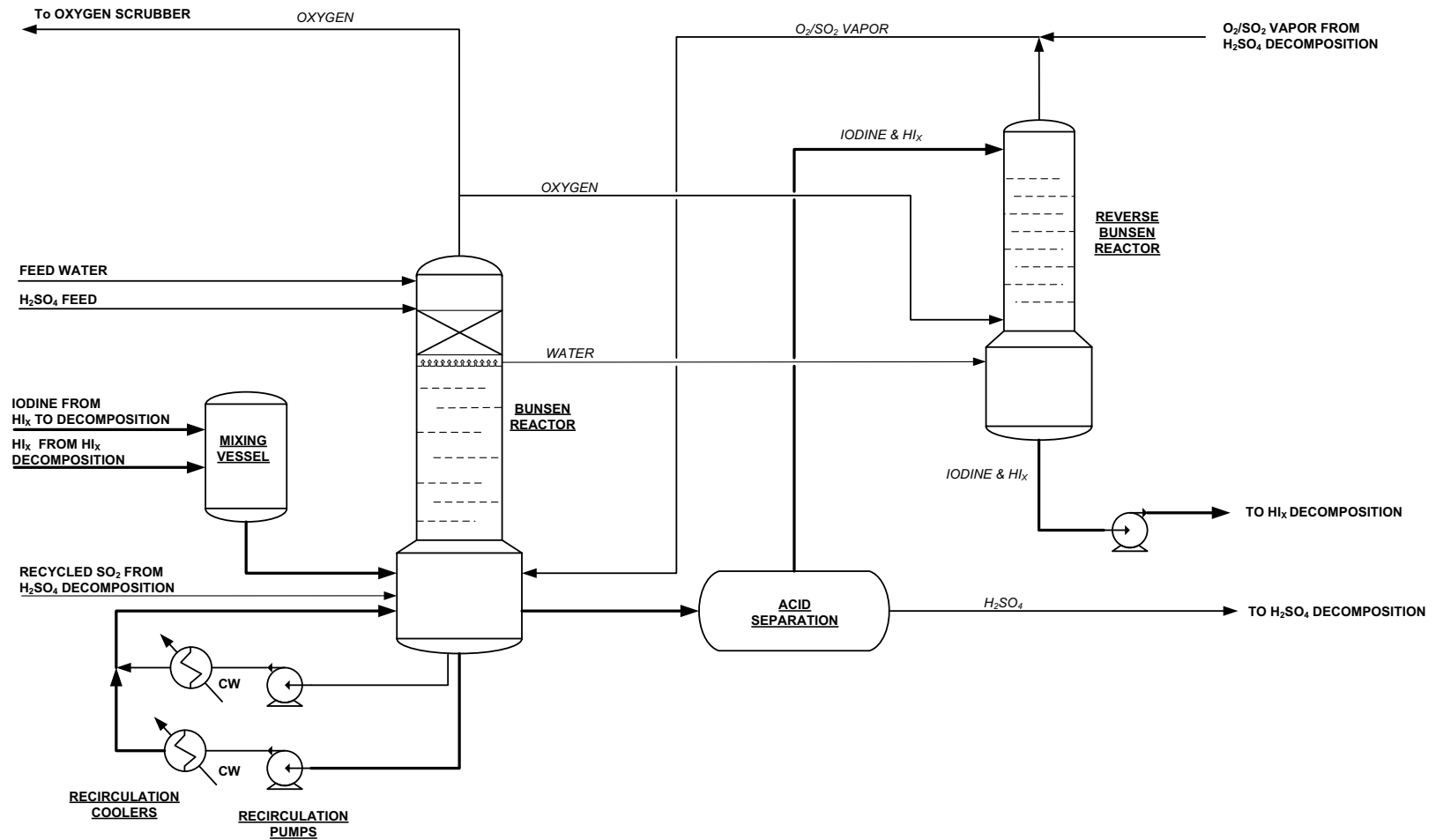
- HPS-HYS-DT-01 Analyze Data and Improve Process Simulation
- HPS-SAD-DT-02 Develop additional alternatives for the decomposition reactor
- HPS-SAD-DT-03 Complete thermal and hydraulic analyses of the alternatives using equilibrium data only
- HPS-SAD-DT-04 Complete a conceptual mechanical design of each of the alternative concepts
- HPS-SAD-DT-05 Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from bench scale testing
- HPS-SAD-DT-06 Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from engineering or pilot scale testing
- HPS-SAD-DT-07 Develop a preliminary piping spec and materials selections for equipment
- HPS-SAD-DT-08 Size conceptual equipment and track economics as technology develops
- HPS-FUS-DT-09 Design a feed water purification system including equipment sizing and economics
- HPS-FUS-DT-10 Design a process fluid purification system including equipment sizing and economics
- HPS-ELE-DT-11 Design an electrolysis system based on the electrolyzer design and track economics
- HPS-PCN-DT-12 Identify appropriate valve materials and sensing devices for the aggressive environments of the process technology
- HPS-HYS-DT-13 Develop P&IDs and operating outline including normal and abnormal transients
- HPS-HYS-DT-14 Perform appropriate hazard and operability reviews at designated stages in process development

6.3 SI

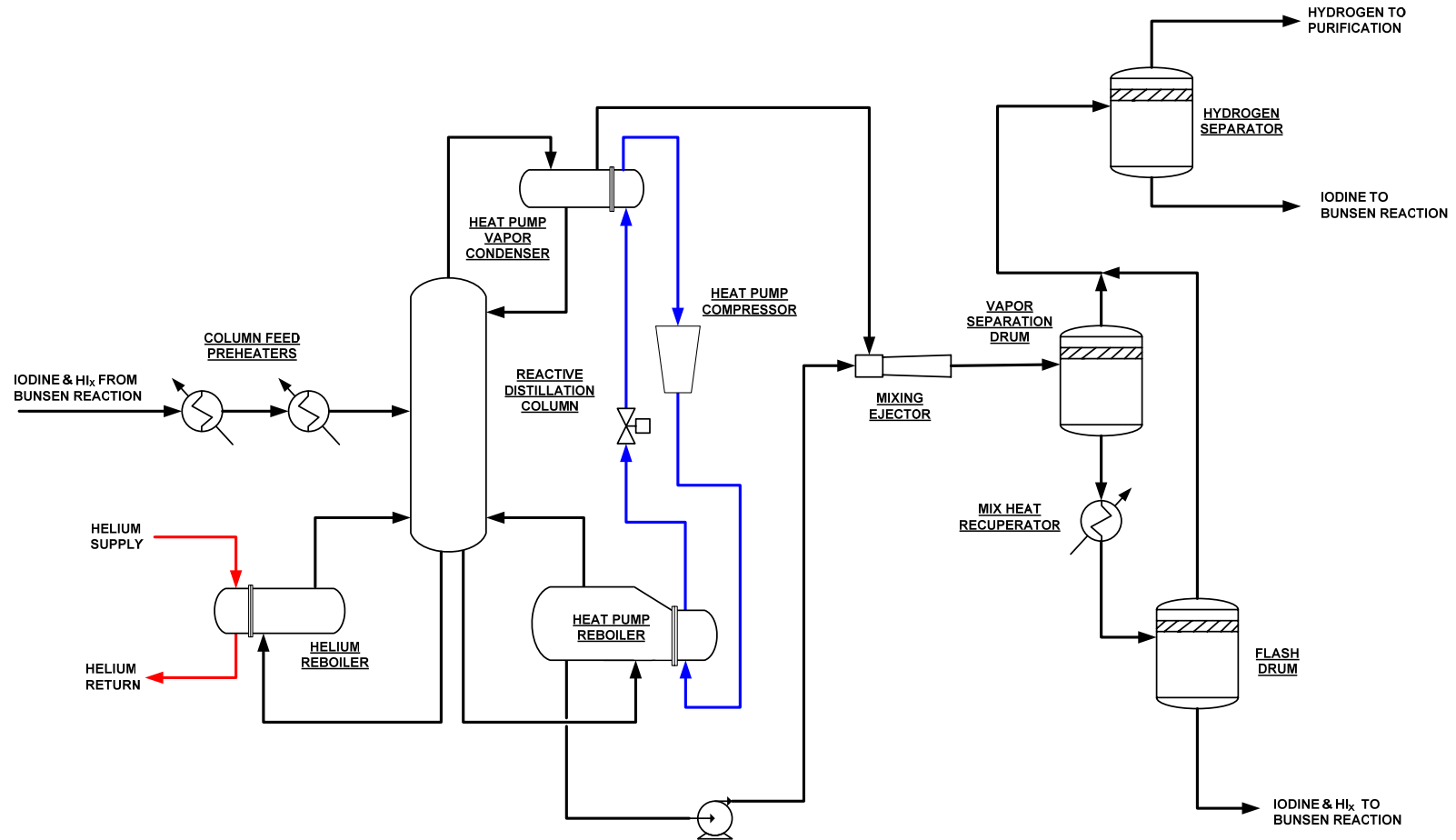
Sulfur-Iodine Cycle



Bunsen Reaction Flow Diagram



HI Decomposition Flow Sheet



SI Flowsheets

- **No separations or reactions appear unreasonable**
 - Thermodynamic and VLE data is needed to confirm the validity of reactions and separations
 - Work at University of Virginia should be incorporated
- **Iodine flows, are extremely high**
- **Materials of construction for oxygen, sulfur dioxide, iodine and hydroiodic acid require further investigation**
- **Reasonable pressure drops have been incorporated**
- **Sensitivity of key components to impurities have not been established**
 - Blowdown or a slipstream to be processed will probably be required
 - Effect of impurities on liquid/ liquid separation
- **Several efforts to recover heat in simulations were judged impractical, probably uneconomic and were removed**

SI Life Cycle Costs: Capital and Reliability

- Capital cost (*Incomplete*):
 - Total Installed Cost:
 - Decomposers: \$156 million (equipment only)
 - Initial charge of chemicals:
- Reliability:
 - High temperature equipment is either SiC or internally insulated
 - Lower temperature equipment will be somewhat less reliable than similar chemical plants because of aggressive environment: 30 year life, high maintenance
- Raw Material
 - Availability of iodine may be an issue
- Maintenance
 - Seals and gaskets
 - Water treatment facilities
 - Helium valves

SI Life Cycle Costs: Operating Costs

- Inspection
 - Piping seal leaks
 - Internal insulation faults
- Waste disposal
 - Water treatment wastes
 - Iodine contamination
- Staff requirements:
 - Maintenance staff requirements:
 - » 3 maintenance personnel per shift plus
 - » 5 day shift only
 - Operating staff requirements:
 - Water treatment: 1 operator per shift
 - Decomposition: 4 operators per shift
 - Bunsen and HI : 3 operators per shift
 - Management: 1 Plant manager; 1 Assistant; 1 Engineer and Administrative staff

SI Life Cycle Costs: Utilities, Catalyst and Chemicals

Pending

SI Preliminary Hazard and Operability Review

Pending

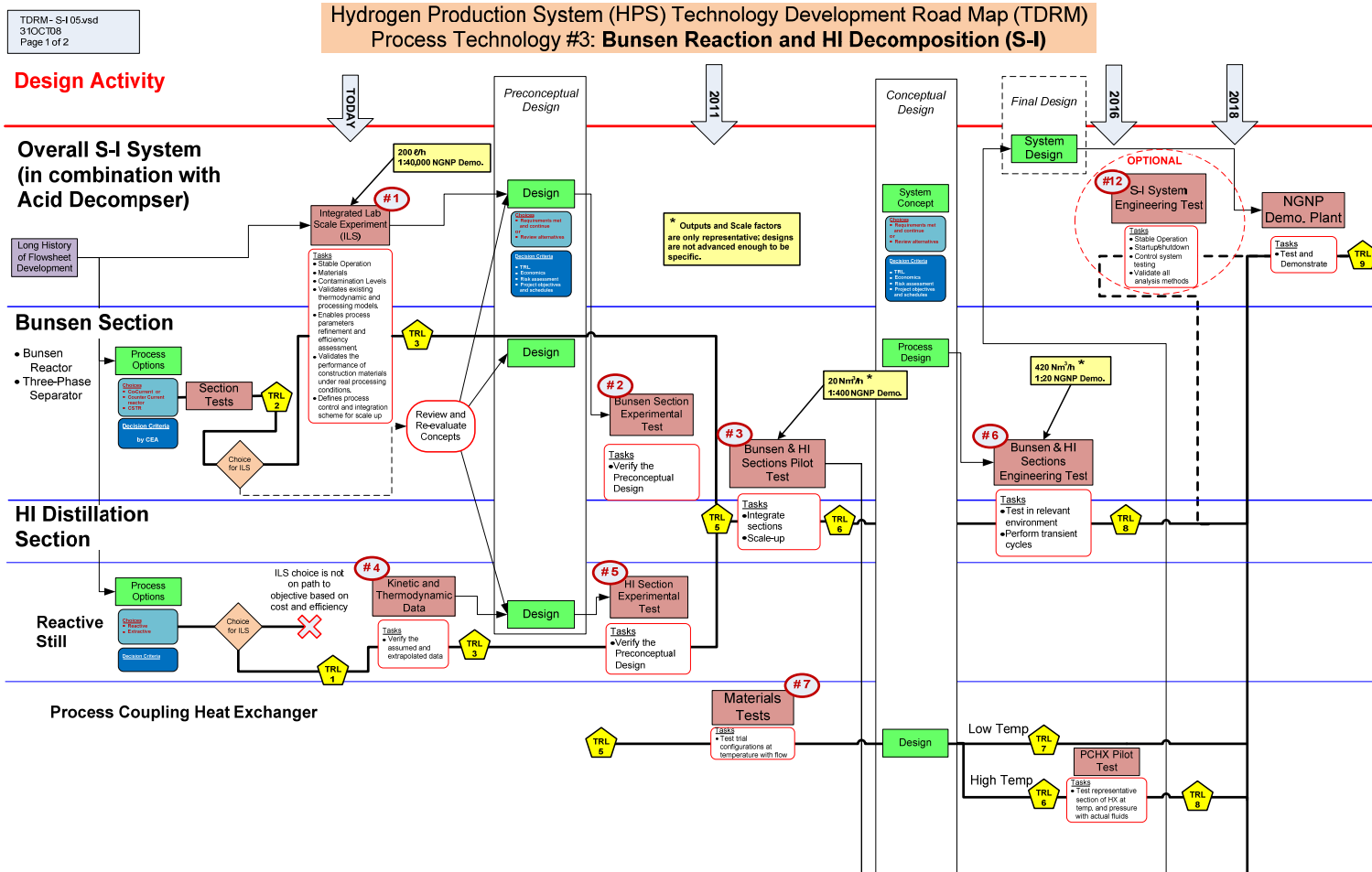
Bunsen and HI Decomposition Technical Issues

- High Iodine Circulation Rate
 - Very large flows and equipment size
 - ***Thermodynamic necessity***
- Effect of Contaminants
 - On reactions and catalysts
 - On liquid/liquid separations
 - ***Severity of problem unknown***
- Materials of Construction, Reliable Seals and Gaskets
 - ***Conditions are very demanding; probability of economic success fair to poor***
- Energy Integration
 - Proposed solutions are practically unworkable
 - ***Probability of economic success fair to poor***

TRLs of Critical SSCs Bunsen Reaction and HI Decomposition

Bunsen Reaction System	2
Bunsen Reactor	2
Three-Phase Separator	2
HI Decomposition Systems	1
Reactive Still	1
Recuperators	5
Process Coupling Heat Exchanger	5
Balance of S-I Plant	U
Reactor Products Handling	6
Feed Purification	U
Product Purification	U
Instrumentation and Controls	6

Bunsen and HI Decomposition Roadmap: Part 1

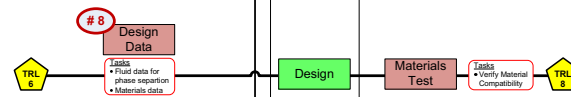


Bunsen and HI Decomposition Roadmap: Part 2

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Balance of System

Reactor Products
Handling Equipment



Feed Purification System



Design FUS

Product Purification



Design PPU

Instrumentation & Control



Design I&C



Design Data Needs for the Bunsen Reaction and Product Purification Section

- **HPS-BUN-01** Confirm Thermodynamic Data for the Bunsen Reaction Process including Phase Equilibria
- **HPS-BUN-02** Gather Kinetic and Mass Transfer Data for the Bunsen Reaction in the proposed reactor configuration
- **HPS-BUN-03** Develop Gasket Materials and Design for Bunsen Reaction Environment
- **HPS-BUN-04** Develop Seal Materials and Design for Bunsen Reaction Environment
- **HPS-BUN-05** Develop Welding Materials for Bunsen Reaction Environment
- **HPS-BUN-06** Develop Cladding and Coating Materials for Bunsen Reaction Environment
- **HPS-BUN-07** Develop Piping Materials and Design Methods for Bunsen Reaction Environment
- **HPS-PPU-01** Identify Product Impurities
- **HPS-PPU-02** Test Product Purification Methods

Design Data Needs for Hydroiodic Acid Decomposition

- **HPS-HID-01** **Demonstrate Hydroiodic Acid Reactive Distillation Decomposition in Principle**
- **HPS-HID-02** **Confirm Thermodynamic Data for the Hydroiodic Acid Decomposition Process including Phase Equilibria**
- **HPS-HID-03** **Develop commercial HI Decomposition Catalyst**
- **HPS-HID-04** **Gather Kinetic and Mass Transfer Data for the Hydroiodic Acid Decomposition in the proposed reactor configuration based on the commercial catalyst**
- **HPS-HID-05** **Develop Gasket Materials and Design for Hydroiodic Acid Decomposition Environment**
- **HPS-HID -06** **Develop Seal Materials and Design for Hydroiodic Acid Decomposition Environment**
- **HPS-HID -07** **Develop Welding Materials for Hydroiodic Acid Decomposition Environment**
- **HPS-HID -08** **Develop Cladding and Coating Materials for Hydroiodic Acid Decomposition Environment**
- **HPS-HID-09** **Develop Piping Materials and Design Methods for Hydroiodic Acid Decomposition Environment**

S I Design Tasks

- HPS-SI-DT-01 Analyze Data and Improve Process Simulation
- HPS-SAD-DT-02 Develop additional alternatives for the decomposition reactor
- HPS-SAD-DT-03 Complete thermal and hydraulic analyses of the alternatives using equilibrium data only
- HPS-SAD-DT-04 Complete a conceptual mechanical design of each of the alternative concepts
- HPS-SAD-DT-05 Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from bench scale testing
- HPS-SAD-DT-06 Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from engineering or pilot scale testing
- HPS-SAD-DT-07 Develop a preliminary piping spec and materials selections for SAD equipment
- HPS-SI-DT-08 Track equipment size and cost as development progresses
- HPS-FUS-DT-09 Design a feed water purification system including equipment sizing and economics
- HPS-FUS-DT-10 Design a process fluid purification system including equipment sizing and economics
- HPS-PCN-DT-12 Identify appropriate valve materials and sensing devices for the aggressive environments of the process technology

S I Design Tasks (continued)

- HPS-SI-DT-13 Develop P&IDs and operating outline including normal and abnormal transients
- HPS-SI-DT-14 Perform appropriate hazard and operability reviews at designated stages in process development
- HPS-BUN-DT-15 Design Alternative Bunsen Reactors
- HPS-BUN-DT-16 Complete thermal and hydraulic analyses of the alternatives using equilibrium data only
- HPS-BUN-DT-17 Complete a conceptual mechanical design of each of the alternative concepts
- HPS-BUN-DT-18 Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from bench scale testing
- HPS-BUN-DT-19 Complete a thermal, hydraulic, and reaction analysis of each alternative incorporating kinetic and heat transfer data from engineering or pilot scale testing
- HPS-BUN-DT-20 Develop a preliminary piping spec and materials selections for BUN equipment

7. Comparisons between Technologies

Economic Analysis Ground Rules - 1

- Use H2A modeling tool
- All HPS alternatives assumed to be commercially mature and evaluated for a consistent 2030 to 2070 service timeframe
- Generic HTR heat sources (NHSSs) at 550MWt core power, modeled for all cases as a fixed operating cost of TBD \$/MWt-h, based on TBD, factored for reactor outlet temperature
- Number of reactor modules determined by reference HPS output (142 million SCFD Hydrogen) with appropriate sharing factors for multiple modules
- Capacity factor of overall plant is 8200 hours per year

Economic Analysis Ground Rules - 2

- 100% equity financing with an after income tax internal rate of return (IRR) of 10% (equivalent to D/E = 75/25 with 20% IRR and 10% debt rate). Sensitivities to cover range of financing options
- Capital cost contingency adjustment is made to the total initial capital cost such that the resulting cost represents a mean or expected value. This cost is the baseline value from which hydrogen price sensitivity can be calculated. Periodic replacement capital includes the same contingency

Economic Analysis Ground Rules - 3

- Periodic capital replacements, e.g. the intermediate heat exchangers, are added to the capital cash flow and depreciated over the useful lives. In addition, an allowance for an annual capital replacement of 0.5%/year is included
- Facility lives of 30 years of operation. Any shorter life limiting components are replaced at designated intervals.
- Accelerated depreciation facility lives of 20 years and the MACRS schedule are applied for the energy source plants, as well as the hydrogen production plants.
- An effective income tax rate of 38.9 % is applied based on a federal tax rate of 35% and a state tax rate of 6%.
- Property tax and business insurance each 1% per year of the total initial overnight capital cost.

Economic Analysis Ground Rules - 4

- Reference year dollars are 2nd Quarter 2008
- General inflation is zero. In H2A analyses one can apply a general inflation rate, but in the model the results are deflated back to reference year dollars so inflation is nominally irrelevant.
- A nominal three year construction period is applied with 25%, 40% and 35% of the costs incurred respectively
- A Gulf Coast site is assumed with an average burdened operating labor rate of \$50 /hour, plus a 20% G&A adder, applied consistently for the plant staffs, which are estimated separately for the different options along with the respective maintenance cost estimates

Economic Analysis Ground Rules - 5

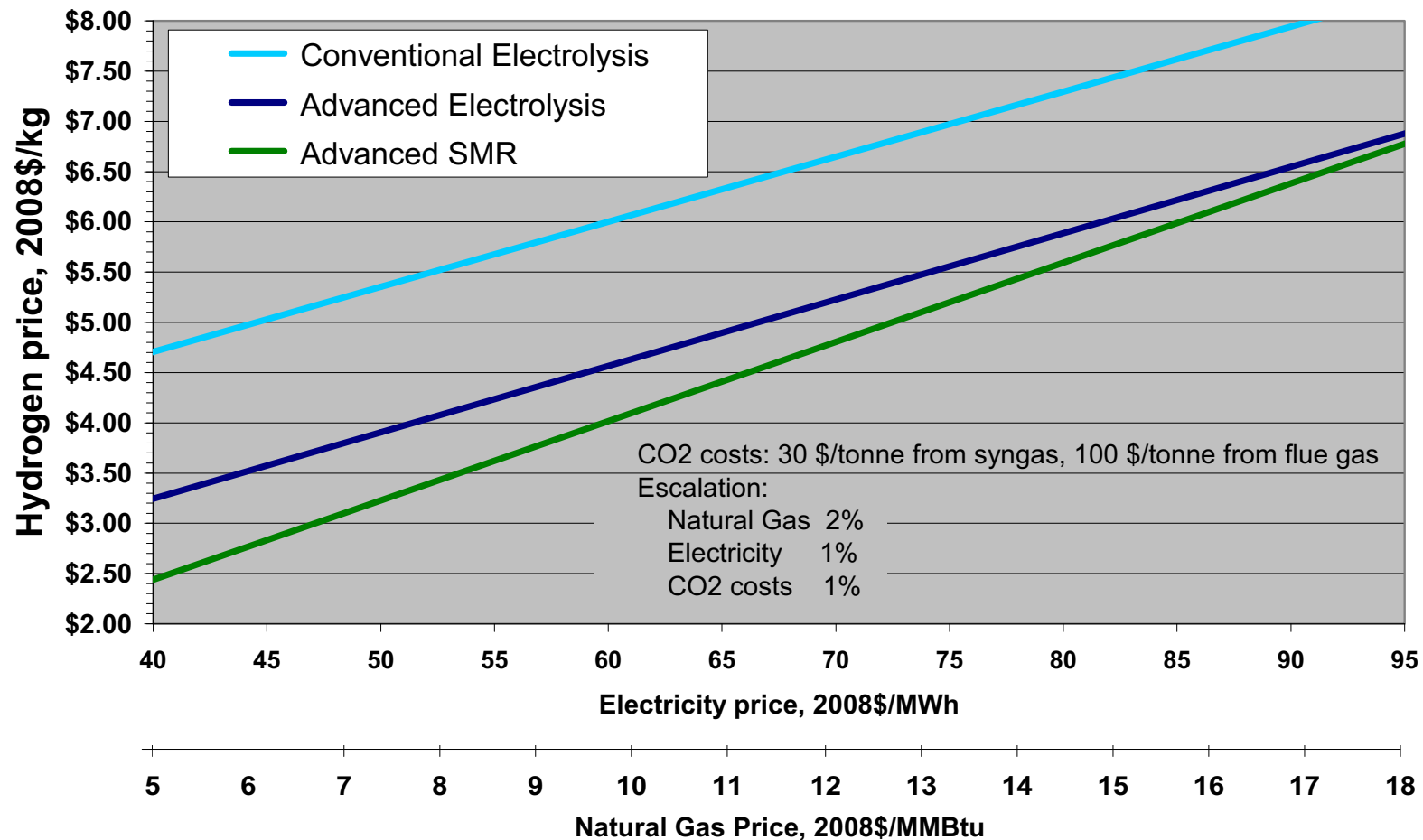
- Plant startup is considered to occur over one year. In that period, revenues are assumed to be 50% of subsequent full-year revenues and variable costs are assumed to be 50% likewise. Fixed annual costs are taken at 100% in the startup year
- The hydrogen delivery pressure at all production plant gates is consistently 50 bar (710 psig). If a lower pressure is supplied by the process, compression costs are added.
- Deficit or surplus electric power priced at 75 \$/MWh import and 60\$/MWh export.

Economic Analysis Ground Rules - 6

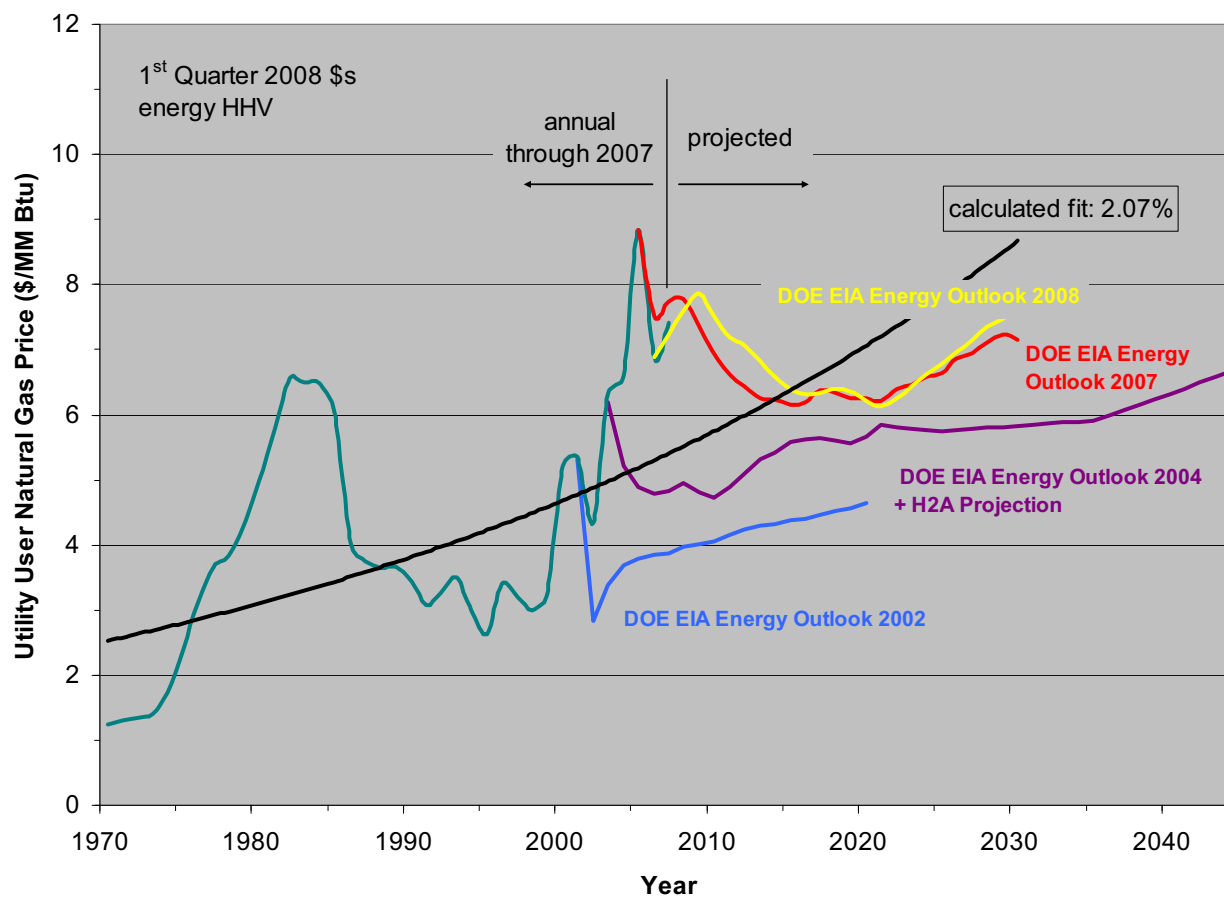
- No central hydrogen storage is included at the production plants other than buffer storage, as required for efficient operations.
- A constant site size of 400 acres has been applied for all options at an assumed unit cost of 5000 \$/acre.
- Oxygen byproduct credit is included in the analysis. The reference credit is to be applied at 40 \$/MT, which is about today's industrial oxygen price.

Baselines for Cost Comparison

Hydrogen Price from SMR and Conventional Electrolysis



Natural Gas Price Trend



Comparison Matrix

		HTSE	HyS	SI
Commercial Potential				
Capital Cost	\$			
Cost of Production	\$/kg			
Hazards & Operability	Good/Fair/Poor			
Technology Readiness				
Roadblocks and Risk	Number Good/Fair/Poor			
Schedule	Years			
Budget	\$			

8. Conclusions

Technical Issues

- HTSE
 - Electrolysis Cell Poisoning
 - Cell tolerance to contaminants needs to be established
 - Electrolysis Cell Flow Distribution
 - Reliable seals and electrical connections in oxidizing atmosphere
 - Thermal expansion of piping, equipment, tension bars, etc.
 - Area specific resistance (ASR)
- Sulfuric Acid Decomposition
 - Economic catalyst and basic data and analysis
 - Flow distribution between bayonet tubes
 - Distribution of temperature across the reactor elements
 - Transition between SiC decomposer tubes and metallic vessel

Technical Issues

- HyS Electrolysis
 - Membrane permeability to sulfur species
 - Cell tolerance to contaminants needs to be established
 - Electrolysis Materials of Construction
- Bunsen and HI Decomposition
 - High Iodine Circulation Rate
 - Effect of Contaminants
 - Materials of Construction, Reliable Seals and Gaskets
 - Energy Integration

Technical Issues

Conclusions: Process Simulation

- Simulations produced up to this study have been directed at maximizing thermal efficiency and have neglected certain practicalities and made unrealistic thermodynamic assumptions
- Practical heat integration must be simpler for commercial plants. Effort should not be expended to raise thermal efficiency by attempting to recover low quality heat
- Realistic pressure drops and temperature approaches are essential to practical process schemes

Conclusions: Major R&D Efforts

- More effort needed in gathering basic thermodynamic, equilibrium and physical property data for relevant process streams in the thermo-chemical processes
- Major gaps that will be on the critical path
 - Materials of construction
 - Seals and gaskets
 - Effect of impurities
 - Helium control valves

Conclusions: Barriers to Commercialization

- All these plants are much larger and more expensive (capital cost) in comparison with SMR plants of the same capacity; breakeven natural gas price for some lifecycle costs > 15\$/MMBtu (tentative)
- Thermo-chemical plants will require multiple trains for each reactor raising capital costs
- Sulfur Iodine requires circulation of very large amounts of iodine for even modest hydrogen production. This will be a serious barrier to commercialization
- HTSE ill-suited to centralized use of high temperature process heat; better suited to distributed generation of hydrogen, possibly using integrated recuperator, inert sweep gas, process heat source other than nuclear
- HyS cell testing shows sulfur formation between electrolyte membrane and cathode electrode. Solution needed to assure stable operation

9. Deliverable Schedule

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Study Deliverables

- Process flow sheets
- Sized equipment lists
- Capital cost estimates
- Operating cost estimates
- Economic model
- Life-cycle cost of hydrogen
- Sensitivity analyses
- Preliminary hazards analysis and operability review
- Technology readiness level scores (TRLs)
- Design readiness level scores (DRLs)
- Design data needs (DDNs)
- Technology development plan (technology maturation plan)
 - Scope
 - Schedule
 - Budget

THANK YOU!

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Backup

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Technology Readiness Levels (TRLs)

Rating Level		Rating Level	
U	Uncertain at this phase in design and development.	6	SSCs have been demonstrated at a pilot scale in a relevant environment.
1	Basic principles observed and reported in white papers, industry literature, lab reports, etc. Scientific research without well-defined application.	7	SSCs integrated engineering scale demonstration in a relevant environment.
2	Technology concept and application formulated. Issues related to performance identified. Issues related to technology concept have been identified. Paper studies indicate potentially viable system operation	8	Integrated prototype of the SSC is demonstrated in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. Analyses, if used support extension of demonstration to all design conditions. Analysis methods verified and validated. Technology issues resolved pending qualification (for nuclear application, if required). Demonstrated readiness for hot startup.
3	Proof-of concept: Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory scale to identify/screen potential viability in anticipated service.	9	The project is in final configuration tested and demonstrated in operational environment.
4	Technology or Component is tested at bench scale to demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties.	10	Commercial-scale demonstration is achieved. Technological risks minimized by multiple units built and running through several years of service cycles – Multiple Units
5	SSC demonstrated at experimental scale in relevant environment. Components have been defined, acceptable technologies identified and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection.		

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