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Preconceptual Engineering Services For The Next Generation Nuclear Plant (NGNP) With Hydrogen Production

NGNP Reactor Power Level Study

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ACRONYMS AND ABBREVIATIONS

COL	Construction and Operating License
CFR	Code of Federal Regulation
DBA	Design Basis Accident
DC	Design Certification
DOE	(United States) Department of Energy
EAB	Exclusion Area Boundary
EPC	Engineering, Procurement and Construction
EPZ	Emergency Planning Zone
GA	General Atomics
GT-MHR	Gas Turbine – Modular Helium Reactor
H2-MHR	Hydrogen Production - Modular Helium Reactor
HTE	High Temperature Electrolysis
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
MHR	Modular Helium Reactor
MHTGR	Modular High Temperature Gas-cooled Reactor
NGNP	Next Generation Nuclear Plant
NP-MHTGR	New Production – Modular High Temperature Gas Reactor
NRC	Nuclear Regulatory Commission
O&M	Operation and Maintenance
PCS	Power Conversion System
PPMP	(NGNP) Preliminary Project Management Plan
QA	Quality Assurance
S-I	Sulfur-iodine
SOEC	Solid Oxide Electrolyzer Cell
SRM	System Requirements Manual
TBD	To be determined
TRISO	TRi-ISOtropic coated fuel particle design with three materials in coating system (low-density PyC, high-density PyC, and SiC)
VHTR	Very High Temperature Reactor

1 SUMMARY

Evaluations have been performed to make recommendations for:

- The reactor power level of a passively safe prototype Generation IV Very High Temperature Reactor (VHTR) for the Next Generation Nuclear Plant (NGNP).
- The reactor power level for a commercial VHTR plant following NGNP performance demonstration
- The minimum size of a hydrogen production facility for the NGNP to demonstrate hydrogen production using high temperature nuclear heat energy.

General Atomics (GA) developed criteria for evaluation of the NGNP reactor power level from the NGNP mission requirements as defined in the Energy Policy Act of 2005 and the INL NGNP Preliminary Project Management Plan, and from NGNP mission recommendations provided by GA's utility advisors. The key evaluation criteria were determined to be:

1. Demonstration of reactor power capacity (product of power level and capacity factor).
2. Provide basis for the commercial VHTR plant engineering, procurement and construction (EPC) cost.
3. Provide basis for the commercial VHTR plant EPC schedule.
4. Support NGNP deployment in 2016 – 2018 time frame.
5. Provide basis for Design Certification of the commercial VHTR plant by the Nuclear Regulatory Commission.
6. Provide basis for operation and maintenance costs of the commercial VHTR plant.
7. Provide basis for fuel costs for the commercial VHTR plant.

In determining the optimum reactor power level for the NGNP, GA focused on consideration of passively safe modular helium reactor (MHR) concepts developed by GA that have high potential for satisfying Generation IV goals. The available concepts with well-documented design information have reactor power levels of 350 MWt, 450 MWt, 550 MWt and 600 MWt, which cover the range of reasonable power levels for the NGNP. This approach provided a framework for the quantitative evaluation presented herein, and the design definition available for these MHR variations provided a basis for grading the candidates against the evaluation criteria.

Using the above-described approach, the 550 and 600 MWt reactor designs were evaluated to be most suitable for NGNP. (The 550 MWt design is the same as the 600 MWt design but is intended to operate at lower power to provide more conservative thermal-hydraulic performance characteristics.) These MHR designs were judged to best satisfy the evaluation criteria related to the need for the NGNP to be designed such that construction, licensing, and operation of the

NGNP would eliminate much of the uncertainty associated with utility/user costs to build, license, and operate a commercial VHTR. The elimination of such uncertainty was judged to be essential to demonstrate to potential utility/users that a VHTR would enjoy a significant cost advantage with respect to alternate means of electricity and/or process heat generation (without which there would be no incentive for a utility/user to build a VHTR). Much of this cost uncertainty is due to design, licensing, and construction uncertainties associated with high risk areas such as the reactor vessel, the PCS, the IHX, and the fuel; consequently, GA considers it essential that these risk area uncertainties be resolved by the NGNP.

Another important reason for selection of 600 MWt as the recommended power level for the NGNP is that the advanced stage of design development of the 600 MWt GT-MHR results in the shortest time and lowest cost for completion of the conceptual design activities necessary to focus R&D activities for NGNP. A conceptual design for a 600 MWt NGNP reactor could be completed in about one year. On the other hand, it would take a minimum of ~2 years to complete a conceptual design for an NGNP based on either the 350 or the 450 MWt reactor design (and longer for any other reactor size). A reasonably complete conceptual design is necessary to define the required design data needs and the necessary R&D. Completion of the conceptual design in ~1 year would provide the best chance for completing the R&D in sufficient time to enable completion of NGNP construction by ~2017.

The conclusion is the 550/600 MWt reactor power level should be selected for the NGNP. The power level is indicated as 550/600 MWt because of the anticipation that the NGNP program would benefit from initial operations at the more conservative 550 MWt power level with a subsequent up-rating to 600 MWt.

For the commercial VHTR plant, the reactor power level should be as high as possible for economy-of-scale reasons. For passive safety, the NGNP reactor requires the use of a metallic reactor vessel. The design of the 550/600 MWt metallic reactor vessel is at, or close to, the physically largest practical size that can be constructed based on current manufacturing capabilities. It therefore follows that the commercial reactor power level should be the same as the power level selected for the NGNP. Selecting the commercial VHTR reactor power as 600 MWt with a reference commercial plant containing four reactor modules is projected to result in a commercial VHTR plant having a significant economic advantage relative to alternatives for electricity and/or process heat generation.

Evaluations were made of two processes for demonstration of hydrogen production using heat energy from the NGNP (1) hydrogen production by means of the Sulfur-Iodine (S-I) thermochemical water splitting process and (2) hydrogen production by means of high temperature electrolysis (HTE). The recommended minimum demonstration plant size, in terms of heat energy used, for hydrogen production by each of these processes is:

Process	Heat Energy, MWt
S-I	60
HTE	4

2 INTRODUCTION

The Energy Policy Act of 2005 (H.R. 6) establishes a project identified as the Next Generation Nuclear Plant (NGNP) for the U.S. Department of Energy (DOE) to perform research, development, design, construction, and operation of a demonstration plant that (1) includes a nuclear reactor based on the research and development activities supported by the Generation IV Nuclear Energy Systems initiative, and (2) shall be used to generate electricity, to produce hydrogen, or to both generate electricity and produce hydrogen. The DOE selected the helium-cooled Very High Temperature Reactor (VHTR) as the Generation IV reactor concept to be used for the NGNP because it is the only near-term Generation IV concept that has the capability to provide process heat at high-enough temperatures for highly-efficient production of hydrogen. The DOE has also selected the Idaho National Laboratory (INL) to lead the development of the NGNP.

As part of the NGNP design development effort, INL has contracted General Atomics to perform NGNP pre-conceptual design studies, including selected trade studies to support selection of key design parameters and characteristics. This report documents an NGNP trade study performed to evaluate and recommend (1) the thermal power level for the NGNP reactor system, (2) the optimum power level for a commercial VHTR, and (3) the size of the NGNP demonstration hydrogen production plant.

The objectives identified for the trade study through interactions with INL, and the key assumptions and constraints applied for performing the trade study, are summarized in Section 2. The bases used to establish criteria for selection of the NGNP thermal power level are provided in Section 3. The design requirements that are necessary to satisfy the criteria defined in Section 3 are developed in Section 4. In Section 5, the design requirements developed in Section 4 are used to derive the power levels for the NGNP and the commercial VHTR. Section 6 covers the evaluations and recommendations for the size of the NGNP demonstration hydrogen production plant.

3 TRADE STUDY OBJECTIVES AND KEY ASSUMPTIONS

3.1 Trade Study Objectives

3.1.1 Reactor Thermal Power Level

The key NGNP functional requirements provided in Reference 1 relevant to selection of reactor thermal power for electricity production are:

- *Develop and demonstrate a commercial scale prototype VHTR*
- *Develop and demonstrate high-efficiency power conversion for electric power production at commercial scale*

The objectives established for the reactor thermal power trade study are to evaluate and recommend the following:

- Thermal power level for a commercial reactor system
- Thermal power level for the NGNP reactor system

3.1.2 NGNP Demonstration Hydrogen Production Plant Size

The key NGNP functional requirement provided in Reference 1 relevant to selection of the NGNP demonstration hydrogen production plant size is:

- *Develop and demonstrate hydrogen production in a co-generation mode with the equivalent of up to 50 MWt of the reactor's thermal energy used for hydrogen production*

The General Atomics work plan, Reference 2, for the NGNP pre-conceptual design specifies that the study will focus on defining the minimum size demonstration hydrogen production plant that effectively demonstrates the technology for scale-up to a commercial size plant. Based on these requirements, the trade study objectives established for the NGNP demonstration hydrogen production plant size are to evaluate and recommend the following:

- Minimum size of the NGNP demonstration hydrogen production plant

3.2 Key Trade Study Assumptions

Key assumptions made for performing the trade study to evaluate and recommend the VHTR commercial plant and NGNP reactor thermal power level and the size of the NGNP demonstration hydrogen production plant are as follows:

1. The NGNP reactor power level study will be based on existing design information developed by General Atomics for passively safe modular helium reactors.
2. The NGNP reactor power level study will be based on the reactor having a prismatic core. This assumption does not flow directly from assumption 1 because GA has performed design studies of both pebble-bed and prismatic core modular helium reactors. GA does, however, have much more extensive design information on prismatic core modular helium reactors than pebble-bed reactors. Also, in a companion trade study on reactor type, Reference 3, the conclusion is reached that a prismatic core is more suitable for meeting U.S. user/utility needs than a pebble bed core.
3. The NGNP reactor design should meet U.S. Utility/User requirements as given in Reference 5.
4. The NGNP reactor design should meet stated Gen-IV goals.
5. The NGNP reactor design should be sufficient to obtain Design Certification (DC) of the reactor for follow-on commercial plants without requiring significant further R&D.
6. The NGNP reactor design should be capable of utilizing different fuel cycles.
7. For the NGNP demonstration hydrogen production plant, both the Sulfur – Iodine (S-I) and the High Temperature Electrolysis (HTE) hydrogen production processes will be considered.

4 COMMERCIAL AND NGNP REACTOR POWER LEVEL CRITERIA

Top level requirements for the NGNP are provided in References 1 and 4. General Atomics has used these top level NGNP requirements in combination with requirements obtained from utility/user organizations to establish the NGNP plant and system level requirements contained in the NGNP System Requirements Manual (SRM), Reference 5. Requirements from the SRM governing reactor power level are as follows for the VHTR commercial plant and the NGNP respectively:

Commercial Plant Power Level

The key requirements from the SRM governing the reactor power level for the commercial VHTR are:

- The VHTR commercial plant reactor power level shall be consistent with passive safety.
- The VHTR commercial plant must have an economic advantage relative to the alternatives for electricity generation.

NGNP Power Level

The key requirements from the SRM governing the reactor power level for the NGNP are:

- The NGNP reactor power level shall be consistent with passive safety.
- The reactor must be prototypical of the commercial plant.
- The reactor must be deployable by ~2017.

To have an economic advantage relative to alternatives, a commercial VHTR electric generation plant must have a lower busbar generation cost than alternatives. Busbar generation cost is an integration of all the costs for power generation. For electricity generation, the busbar generation cost is evaluated as the total annual plant generation cost divided by the total annual kw_eh generated, $/$kw_eh$, where the components of the annual generation plant costs are:

- return of and on the capital investment,
- operation and maintenance (O&M) expenses,
- fuel consumption costs, and
- an allowance for decommissioning[1].

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[1] The annual decommissioning cost is usually determined as the funding that must be set aside each year in a sinking fund such that at the end of plant life there will be the total funding needed for decommissioning.

Every single element of the cost to generate power falls into one of these four cost categories.

Since electricity generation cost is given by \$/kw$_e$h, to make generation cost low, the annual cost (\$) needs to be made low and the electricity generation high [product of plant capacity (kw$_e$) times the production time (calendar time, h, times capacity factor, C_f)]. This simple relationship coupled with proven economy of scale laws leads to the conclusion that plant capacity, kw$_{e,}$ needs to be as high as possible along with a high plant capacity factor, $C_{f.}$ A further consideration for low generation cost is that the plant capacity, kw$_{e,}$ is equal to the plant thermal efficiency, ϵ_t, times the reactor thermal capacity, kw$_t$, which means that both the thermal capacity and thermal efficiency should be made as high as possible.

While these economic parameters have been developed based on consideration of electricity generation, the results apply equally as well to a reactor for production of process heat. The key reactor parameter can be seen in the above to be kw$_t$, and for low process heat cost, \$/kw$_t$ should be as low as low as possible, the same as for electricity generation.

Based on the foregoing economic considerations, the key reactor plant characteristics for the commercial plant that need to be taken into account for derivation of reactor power level criteria are as follows:

1. Power capacity (reactor power and capacity factor)
2. Capital cost
3. O&M cost
4. Fuel cost

Each of these characteristics is used to derive reactor plant power level criteria in the following subsections.

4.1 Power Capacity Criteria

Generation capacity criteria required to satisfy the top level economic criterion are:

- High reactor thermal power
- High power conversion efficiency
- High plant capacity factor

For the reactor portion of a commercial nuclear power plant, the key criteria are high thermal power and high capacity factor. For the energy conversion portion of a VHTR commercial electric generation plant, capacity factor and thermal efficiency are important criteria for consideration of direct vs indirect power cycles as well as type of power cycle (Brayton, Rankine, or combined)

Generation capacity economic considerations lead to the following two correlative criteria for reactor power:

- The reactor power and capacity factor for the commercial VHTR plant should be as high as possible consistent with passive safety.
- The NGNP reactor power should be as high as necessary to demonstrate the commercial reactor will achieve its power capacity (power level and capacity factor) with high confidence.

4.2 Capital Cost Criteria

For a nuclear plant, the largest component of the generation cost is plant capital cost. Because nuclear power plants are intrinsically capital cost intensive, there needs to be detailed bases for the plant capital costs, and the capital costs need to be known with high certainty. For a VHTR commercial power plant, the uncertainties in the plant capital cost must be sufficiently low that the economic advantage criterion can be satisfied with high confidence.

There are several important plant capital cost considerations. The most important ones for derivation of the commercial plant power level criteria are (1) plant construction cost, (2) plant construction schedule and (3) plant safety licensing. Plant licensing requires due consideration because it can significantly impact the construction schedule. Each of these cost elements are addressed separately in the following subsections.

4.2.1 Plant Construction Cost

Plant construction cost includes the cost and cost uncertainties for all of the equipment, materials, labor, and construction services required for construction of the plant including the plant engineering and procurement services preceding actual plant construction activities. The total plant construction cost is sometimes referred to as engineering, procurement and construction (EPC) cost. The NGNP construction objectives should include establishing bases for the commercial plant EPC costs and their uncertainties. The commercial plant reactor power and NGNP reactor power levels must be sufficiently similar to enable determination of the commercial plant EPC costs with sufficient certainty that the economic advantage criterion can be satisfied with high confidence. These considerations result in the following two correlative plant power level criteria:

- The commercial VHTR plant power should be a power for which the plant EPC cost can be established with sufficient certainty that the economic advantage criterion can be satisfied with high confidence.

- The NGNP reactor power should be sufficient to serve as a basis for establishing the commercial plant EPC cost with sufficient certainty to satisfy the economic advantage criterion with high confidence.

4.2.2 Plant Construction Schedule

Not only does there need to be detailed bases for the commercial plant EPC cost, there must also be reasonable certainty that the plant construction will proceed on schedule because schedule uncertainties represent financial risk.

Another schedule related issue is that for there to be industry interest in pursuing the NGNP as a commercial demonstration project, there must be potential for first commercial deployment of the technology in the 2020 time frame. For first commercial deployment in the 2020 time frame, the NGNP must be completed in the 2016 – 2018 time frame.

Once a decision has been made to proceed with construction of a commercial nuclear power plant, the EPC activities must proceed on a schedule consistent with the one used in making the construction decision because of the plant's capital intensiveness. If there are any significant delays, the plant capital cost is likely to increase and adversely impact the plant's economics. So, one criterion for minimizing capital cost uncertainty is a highly certain plant EPC schedule. This criterion applies to the balance of plant as well as to the reactor. Construction of a sufficiently representative NGNP in the 2016 – 2018 time frame would provide information to characterize the commercial plant EPC schedule certainty for commercial deployment in the 2020 time frame. These considerations lead to the following correlative plant power level criteria:

- The commercial plant reactor power should be selected on the basis of having a highly certain construction schedule.

- The NGNP reactor power should be selected such that construction of the plant will provide the information necessary for establishing a highly certain commercial plant construction schedule.

- The NGNP reactor power should be selected on the basis of supporting deployment of the NGNP in the 2016 -2018 time frame.

4.2.3 Plant Safety Licensing

Plant safety licensing risk is an important element of schedule risk. In the past, delays in obtaining the necessary licenses for operation of nuclear power plants have led to considerable increases in plant capital costs, primarily due to interest payments on invested capital. Legislation has been passed to manage licensing risk by providing regulations for a one-step licensing procedure. The regulations, codified in 10 CFR 52, provide for obtaining a combined construction and operation license (COL). The issuance of a COL provides reasonable assurance before plant construction begins that the plant can proceed into operation once construction has been completed. During the course of construction, inspections, tests, analyses, and acceptance criteria (ITAAC), as defined in the COL must be satisfied. If satisfied, there would be no regulatory delays in beginning plant operation.

A key criterion for assuring successful implementation of the one-step licensing process for a commercial plant is acquiring an NRC Design Certification (DC) for the plant design prior to making application for a COL. The NGNP should be designed and operated to serve as a basis for obtaining a DC for a VHTR commercial plant design. This does not imply that the NGNP has to be licensed using the 10 CFR 52 process. It could be licensed using either the 10 CFR 50 or the 10 CFR 52 process. The key criterion identified here is that the NGNP be designed, licensed, constructed and operated, such that it can be used as a basis to obtain a Design Certification for the commercial plant. These considerations result in the following two correlative plant power level criteria:

- The commercial reactor plant power should be a power level for which a DC can be obtained.

- The NGNP reactor power should be sufficient to serve as a basis for obtaining a commercial plant DC.

4.3 Operation and Maintenance (O&M) Cost Criteria

Operation and Maintenance (O&M) costs are the costs for the plant operating staff, technical support services, maintenance materials, plant supplies, spare parts, fees and taxes, insurance and plant general and administrative expenses. As in the case of the plant capital costs elements, objectives of the NGNP should include establishing bases for the commercial plant O&M costs and the O&M cost uncertainties. The commercial plant reactor power and NGNP reactor power levels must be sufficiently similar to enable determination of the commercial plant O&M costs with sufficient certainty that when coupled with the other cost components, the economic advantage criterion can be satisfied with high confidence. These considerations result in the following two correlative plant power level criteria:

- The commercial reactor plant power should be a power for which the plant O&M cost and cost uncertainties, coupled with the other cost components, satisfy the economic advantage criterion with high confidence.

- The NGNP reactor power should be sufficient to serve as a basis for establishing the commercial plant O&M costs and cost uncertainties that satisfy the economic advantage criterion with high confidence.

4.4 Fuel Costs

The fuel costs are the costs for the reactor nuclear fuel. As in the case for the other cost components, objectives of the NGNP reactor should include establishing bases for the commercial plant fuel costs and the fuel cost uncertainties. The commercial reactor plant power and NGNP reactor power levels must be sufficiently similar to enable determination of the commercial reactor plant fuel costs with sufficient certainty that, when coupled with the other cost components, the economic advantage criterion can be satisfied with high confidence. These considerations result in the following two correlative plant power level criteria:

- The commercial reactor plant power should be a power for which the plant fuel cost can be established with sufficient certainty that when coupled with the other cost components, the economic advantage criterion can be satisfied with high confidence.

- The NGNP reactor power should be sufficient to serve as bases for establishing the commercial plant fuel cost with sufficient certainty to satisfy the economic advantage criterion with high confidence.

4.5 Summary of Plant Reactor Power Criteria

4.5.1 Commercial Plant

A top level criterion for the commercial VHTR plant power is that it should have an economic advantage relative to alternatives for electricity generation. A set of criteria for the commercial reactor plant power level has been derived based on this top level economic criterion. A summary of the criteria, as derived in the foregoing sections, for the commercial reactor plant power is as follows:

1. The commercial reactor power capacity (reactor power and capacity factor) should be as high as possible.

2. The commercial reactor plant power should be a power for which the costs for the plant engineering, procurement and construction (EPC) can be established with sufficient certainty that the economic advantage criterion can be satisfied with high confidence.

3. The commercial reactor plant power should be selected on the basis of having a highly certain EPC schedule.

4. The commercial reactor plant power should be a power level for which a DC can be obtained.

5. The commercial reactor plant power should be a power for which the plant O&M cost and cost uncertainties, when coupled with the other cost components, satisfy the economic advantage criterion with high confidence.

6. The commercial reactor plant power should be a power for which the plant fuel cost can be established with sufficient certainty that when coupled with the other cost components the economic advantage criterion can be satisfied with high confidence.

4.5.2 NGNP Reactor

A summary of the NGNP reactor power criteria that are corollaries to the criteria for the commercial reactor plant power criteria are as follows:

1. The NGNP reactor power should be as high as necessary to demonstrate the commercial reactor will achieve its power capacity (power level and capacity factor) with high confidence.

2. The NGNP reactor power should be sufficient to serve as a basis for establishing the commercial plant engineering, procurement and construction (EPC) cost with sufficient certainty to satisfy the economic advantage criterion with high confidence.

3. The NGNP reactor power should be selected such that construction of the plant will provide the information necessary for establishing a highly certain commercial plant EPC schedule.

4. The NGNP reactor power should be selected on the basis of supporting cost effective deployment of the NGNP in the 2016 -2018 time frame.

5. The NGNP reactor power should be selected to serve as a basis for obtaining a commercial plant DC.

6. The NGNP reactor power should be sufficient to serve as a basis for establishing the commercial plant O&M costs and cost uncertainties that satisfy the economic advantage criterion with high confidence.

7. The NGNP reactor power should be sufficient to serve as a basis for establishing the commercial plant fuel cost with sufficient certainty to satisfy the economic advantage criterion with high confidence.

5 DESIGN REQUIREMENTS TO SATISFY REACTOR POWER LEVEL CRITERIA

In this section, design requirements are developed to satisfy the criteria established in Section 3 for use in deriving the power levels for the commercial reactor and the NGNP reactor.

5.1 Commercial Reactor Power

Criterion #1, Commercial Reactor Plant Power:

The commercial reactor power (kw_t) needs to be as high as possible consistent with passive safety for economy of scale reasons, and the capacity factor needs to be as high as possible to maximize the power generated (kwh). The following design requirements are considered to be necessary to make the commercial reactor power and capacity factor as high as possible consistent with passive safety:

- Low power density (kw_t/cc) to enable the fuel to adequately contain fission products during loss of forced cooling events.
- Physically as large as possible to maximize the core power within the constraint of the low power density criterion.
- Use of a metallic reactor vessel for containing the reactor core to enable rejection of reactor core decay heat during lost of forced cooling events by means of passive radiation heat transfer.
- Use of a metallic reactor vessel as large as possible.
- A reactor power level for which a high capacity factor can be established with high certainty based on NGNP performance information.

Commercial Reactor Plant Power Criteria #2, #3, #4, #5, & #6.

The following design requirements are considered necessary to satisfy commercial reactor power plant criteria #2, #3, #4, #5, & #6.

- Criteria #2 & #3, Construction Cost and Schedule: The commercial plant reactor power shall be a power for which the commercial plant construction cost and schedule can be established with high certainty based on information from the NGNP reactor.

- Criterion #4, Commercial Plant DC: The commercial plant reactor power shall be a power for which a DC can be obtained based on information from the NGNP reactor.

- Criterion #5, Commercial Plant O&M Cost: The commercial plant reactor power shall be a power for which plant O&M cost and schedule can be established with high certainty based on information from the NGNP reactor.

- Criterion #6, Commercial Plant Fuel Cost: The commercial plant reactor power shall be a power for which plant fuel cost can be established with high certainty based on the NGNP fuel and fuel supply information.

5.2 NGNP Reactor Power

<u>NGNP Reactor Power Capacity, Criterion #1</u>.

This criterion addresses two NGNP reactor attributes, power level and capacity factor. The following design requirements are considered necessary for the NGNP reactor to adequately demonstrate the commercial reactor:

- The reactor thermal power level must be sufficient to enable scaling of the reactor construction and O&M costs to the commercial reactor power level.

- The reactor core must use a fuel element design the same as that intended for the commercial plant and the fuel element arrangement needs to be either the same as, or representative of, that intended for the commercial plant.

- The balance of the reactor system components must be representative of those intended to be used in the commercial plant, including having the same mechanical design features for supporting the core, spacing the fuel elements, and controlling the coolant flow distribution.

- The reactor core must be operated under nuclear, thermal-hydraulic, and mechanical conditions representative of conditions projected for the commercial plant.

- For demonstration of capacity factor, the reactor must include auxiliary systems representative of those intended to be used for the commercial plant [e.g., power level control systems, helium control and neutron control systems, core refueling system(s), reactor decay heat removal system(s) and any other required system(s)].

NGNP Reactor EPC Cost, Criterion #2.

To satisfy this criterion, the NGNP design must satisfy the following requirements, in addition to those identified above for satisfying criterion #1:

- The reactor must use a reactor vessel that has design features, design conditions and fabrication requirements representative of those intended for the commercial reactor vessel.
- The reactor vessel must use a support system that is representative of the system intended to be used for the commercial reactor vessel.
- The reactor vessel must use a system for management of the reactor vessel temperatures during all design basis conditions representative of that intended to be used for the commercial reactor vessel.
- Shipping and handling of the reactor vessel from fabrication facility through installation in the plant must be representative of that intended to be used for the commercial reactor vessel.
- The physical size characteristics and design features of the reactor must require the use of construction processes representative of those intended to be used for construction of the commercial reactor plant.

NGNP Reactor EPC Schedule, Criterion #3.

To provide the information necessary to establish a highly certain commercial plant EPC schedule, the NGNP reactor design must satisfy the following requirements, in addition to the requirements specified above for Criteria #1 & #2:

- Construction of the NGNP reactor should be based, to the maximum practical extent, on the use of construction practices representative of those that would be used for construction of the commercial reactor plant.
- Construction of the NGNP reactor should require the performance of inspections, tests, analyses, and acceptance criteria representative of the ITAAC expected to be required during construction of the commercial reactor plant.

Support NGNP Deployment in 2016 – 2018 Time Frame, Criterion #4.

To support deployment of the NGNP in the 2016 -2018 time frame, the NGNP reactor design must satisfy the following power level requirements:

- The design of the required systems and components must be based on the use of either existing technology, or technology that can be developed within the next few years (≤~5years).
- A reference design, at a conceptual level of detail, is required within ~1 year to support identification, specification, execution and completion of any technology development activities within the ~5 year period available for the performance of these activities.
- Based on presently projected NGNP budget constraints, the completion of conceptual design within ~1 year must be accomplished as economically as is practical. To satisfy this requirement, the conceptual design must be based to maximum practical extent on existing design information.
- The required systems and components must be manufactured in existing facilities or in facilities that can be designed, constructed and qualified in sufficient time to meet the requirements of the NGNP construction schedule (i.e., facilities that are either currently qualified or facilities that can be qualified within the next ~5 years). Note that since the design can not be finalized in less than ~5 years, it is unlikely the requirements for any new manufacturing facilities could be established in sufficient time to enable the design, construction and qualification of new facilities.

Provide Basis for DC, Criterion #5.

To provide the basis to obtain design certification for the commercial reactor plant, the NGNP reactor plant must have the same safety performance characteristics as the commercial reactor. To have the same safety performance characteristics, the NGNP reactor design must satisfy the following power level requirements:

- Have the same reactor system design characteristics as specified for Criterion #1 above including the following key safety characteristics:
  - Fuel design that is representative of that intended for the commercial plant.

  - Core configuration representative of that intended for the commercial plant (e.g., if the commercial plant has an annular core, the NGNP reactor needs to have an annular core)
  - Safety related decay heat removal system(s) for transfer of the decay heat from the reactor core to the ultimate heat sink representative of those intended for the commercial plant.

- Satisfy the following top-level radionuclide control regulatory requirements (as specified in the SRM, Reference 5):
  - During normal operation, off-site radiation doses to the public shall be < limits specified in Appendix I of 10 CFR 50 and 40 CFR 190.
  - Occupational radiation exposures shall be ≤10% of the limits specified in 10 CFR 20.
  - During DBAs, off-site doses at the site EAB shall be less than those specified in the Manual of Protective Action Guides and Protective Actions for Nuclear Incidents (EPA-520/1-75-001) for sheltering and evacuation
- Reactor plant systems and components that provide accident event probabilities and sequences representative of those projected for the commercial plant.
- Reactor operating characteristics that result in accident conditions (temperatures, pressures, and other nuclear, thermal-hydraulic and mechanical phenomena) in the fuel, core and reactor components representative of those that would be experienced during accident events in the commercial plant.

Provide Basis for O&M Costs, Criterion #6.

To provide a basis for O&M costs and cost uncertainties, the NGNP reactor design must satisfy the following power level requirements:

- As in the case for demonstration of capacity factor (Criterion #1), the reactor plant must include all of the systems and components that require O&M representative of those intended to be used for the commercial plant.
- The NGNP reactor should be designed to demonstrate an operational duty cycle (power level variations) representative of that projected for the commercial plant.

Provide Basis for Fuel Costs, Criterion #7.

To provide a basis for fuel costs and cost uncertainties, the NGNP reactor design must satisfy the following power level requirements:

- A fuel supply capability for the NGNP reactor shall be established and operated to provide the information necessary to determine:
  - Cost to establish commercial fuel supply capability
  - Fuel fabrication costs and cost uncertainties.
- Fuel for the NGNP reactor shall be designed and utilized to satisfy the commercial plant performance requirements.

6 NGNP AND COMMERCIAL REACTOR POWER LEVEL DETERMINATION

In this section, the design requirements developed in Section 4 are used to derive power levels for the NGNP reactor and the commercial VHTR plant.

6.1 Reactor Power Level Possibilities

Common design characteristics of most all previous GA designs of passively safe high temperature helium-cooled reactors for commercial deployment are:

- Use of the hexagonal graphite prismatic fuel element block design proven in the Fort Saint Vrain reactor (360 mm across flats by 793 mm long)
- An arrangement of the prismatic fuel element blocks in an annular core array
- A core stack height of ten (10) fuel element blocks high (~8 m high core)
- A three (3) fuel element wide annular core width (~0.94 m effective core width)
- An outer graphite reflector about the same width as the core
- A core power density of 6 w/cc to 7 w/cc

Reactor designs using a combination of the fuel element design with the core power density, core width and reflector width parameters have been developed that have acceptable maximum fuel temperatures during loss of forced cooling.

GA has developed conceptual designs of the following plants:

1. 4 x 350 MWt Modular High Temperature Gas-cooled Reactor (MHTGR) plant, Reference 6, for electricity generation based on thermal energy conversion using the steam (Rankine) cycle.

   In addition to a conceptual design for the MHTGR, a Preliminary Safety Information Document (PSID) was developed and submitted to the NRC, and was reviewed by the NRC over a 3 year period. This effort is the foundation on which most all of the gas reactor passive safety development is based.

A variant of the 4 x 350 MWt MHTGR design, identified as the NP-MHR, which was to become a new weapons material production reactor was developed to near completion of preliminary design, Reference 7, but was discontinued when the Cold War ended.

2. 4 x 450 MWt MHTGR plant for electricity generation based on thermal energy conversion using the steam (Rankine) cycle, Reference 8.

This plant was developed to improve economic performance relative to the 4 x 350 MWt MHTGR plant, which was concluded to have inadequate economics relative to alternatives. The level of design development is equivalent to that of the 4 x 350 MWt MHTG plant because the designs are essentially identical.

3. 4 x 600 MWt Gas Turbine –Modular Helium Reactor (GT-MHR) plant, Reference 9, for electricity generation based on thermal power conversion using the Brayton cycle. This plant design evolved from the 4 x 450 MWt steam cycle MHTGR → 4 x 450 MWt GT-MHR → 4 x 550 MWt GT-MHR → 4 x 600 MWt GT-MHR.

A conceptual design for the 4 x 600 MWt GT-MHR plant is available. A variant of this plant design has been completed through preliminary design for disposition of weapons grade plutonium in Russia.

In the evolution of the reactor power level from 350 → 450 → 550 MWt, the annular active core width was maintained constant (3 rings wide) and the power density was kept essentially the same. The increased core power comes from making the core larger by moving the 3 ring wide active core out to larger rings for each of these power increments. The final evolution of 550 MWt to 600 MWt is accomplished by a slight increase in power density.

Based on the foregoing, candidate reactor power levels for the NGNP are concluded to be as follows:

A. 350 MWt

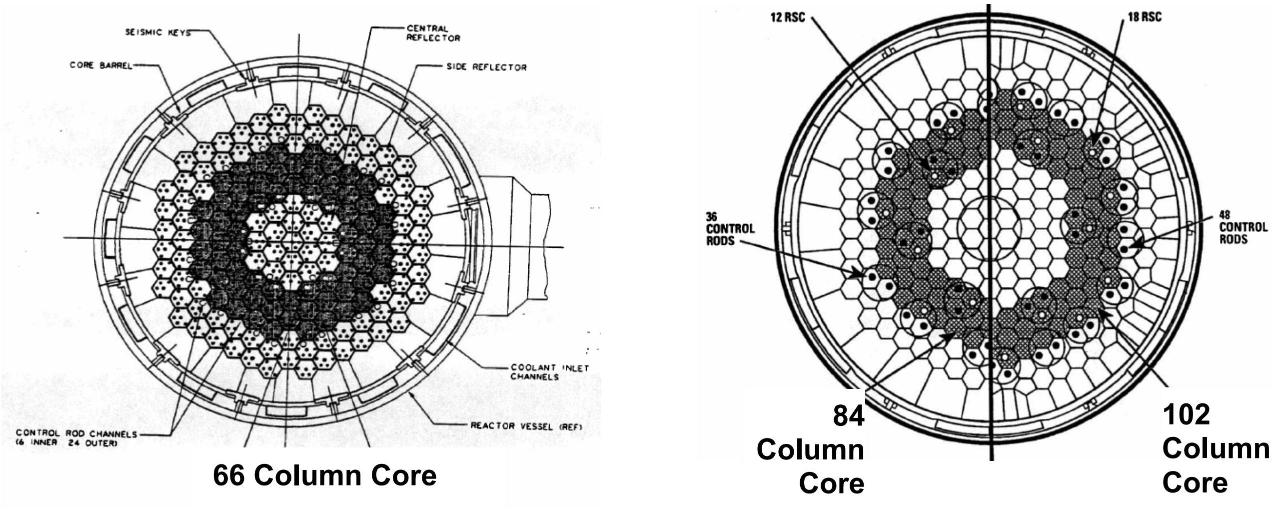
B. 450 MWt

C. 550 (or 600) MWt

A summary of design parameters for each of these design options is provided in Table 1, and a comparison of the reactor core cross sections is given in Figure 1.

Table 1 Comparison of Reactor Parameters

Reactor Parameter	**350 MWt Reactor**	**450 MWt Reactor**	**550 MWt Reactor**	**600 MWt Reactor**
Power, MWt	350	450	550	600
Fuel columns, number	66	84	102	102
Power density, w/cc	5.9	6.0	6.1	6.6
Inlet He pressure, MPa	6.38	7.07	6.48	7.07
Core inlet temperature, °C	258	288	490	490
Core outlet temperature, °C	689	704	850	850
Reactor vessel ID, m	6.55	7.22	7.22	7.22
Reactor vessel material	SA508/SA533	SA508/SA533	2¼Cr–1Mo or 9Cr–1 Mo	2¼Cr–1Mo or 9Cr–1 Mo



66 Column Core

84 Column Core

102 Column Core

Figure 1. Comparison of 66, 84 and 102 Column Prismatic Reactor Core Cross Sections

6.2 Selection of NGNP and Commercial Plant Reactor Power Level

For selection of the NGNP reactor power level, a grading has been performed for each of the candidate reactor power levels identified in Section 5.1. The following grading system was used:

Grade	Satisfaction of Criteria
4	Excellent
3	Good
2	Fair
1	Poor
0	Not acceptable

The grading of the candidate reactor power levels against the NGNP reactor power criteria is given in Table 2. In general, the grading was performed using a relative grading process. The power level candidate that satisfies each criterion the best was given the highest grade, grade 4. The other candidates were graded relative to the highest graded candidate. The rationale for the grades given to the various NGNP power level candidates for each evaluation criterion is explained following Table 2.

Table 2. Grading of Candidate NGNP Reactor Power Levels

Criterion	**350 MWt Reactor**	**450 MWt Reactor**	**550 MWt Reactor**	**600 MWt Reactor**
1. Demonstrate Power Capacity	1	2	3	4
2. Provide Basis for EPC Cost	2	4	4	4
3. Provide Basis for EPC Schedule	2	4	4	4
4. 2016 – 2018 Deployment	1	2	3	4
5. Provide Basis for DC	3	3	4	4
6. Provide Basis for O&M Cost	3	3	4	4
7. Provide Basis for Fuel Cost	3	3	4	4
Grade Average	2.1	3.0	3.7	4.0

1. Power Capacity Demonstration

Power capacity is a product of power level and capacity factor. For power level demonstration alone, the 600 MWt unit received the highest grade. The other candidates received a lower grade that declined with power level. Power factor takes into account planned and unplanned power production reductions and outages. Key drivers of capacity factor are equipment operation and maintenance requirements. The 550 and 600 MWt units involve the largest quantities of equipment items and, assuming all of the equipment was prototypic of the commercial unit, these units would provide the best performance information on capacity factor. Assuming the 350 and 450 MWt units also used prototypic equipment, these units would also provide good capacity factor performance information. However, the number of some items would be less and the size of some items would be less. The smaller quantities and sizes of equipment items would result in less representative O&M requirements and would, therefore, not provide information as good as the larger size units. In consideration of both power level and capacity factor, the grades chosen were 4 3, 2 and 1 for the 600, 550, 450 and 350 MWt units, respectively.

2. Engineering, Procurement, and Construction (EPC) Cost Demonstration

In the case of EPC cost, the 450, 550 and 600 MWt physical sizes are relatively the same and each of these candidates received the highest grade (grade 4) for demonstration of the commercial plant EPC cost. The 350 MWt size was graded lower (grade 2) because its smaller size would not provide as good a demonstration of construction cost.

3. Engineering, Procurement, and Construction (EPC) Schedule Demonstration

The same grades chosen for EPC cost demonstration were chosen for EPC schedule demonstration for the same reasons discussed above for EPC cost demonstration.

4. 2016 – 2018 Deployment

The 600 MWt size was graded highest (grade 4) because of its advanced design status for anticipated representative NGNP design conditions. A 600 MWt NGNP is judged to require the least time for design development, which enhances the potential to meet the 2016 – 2018 deployment time. A NGNP 550 MWt unit could take advantage of much of the 600 MWt design information, but it is judged to require slightly more design effort because of its different power rating; for this reason it was given a lower grade (grade 3). The 450 MWt unit would require considerable design upgrading to satisfy the NGNP design conditions, but some advantage could be taken of the 600 MWt design information to minimize the design effort. But, relative to the 550 MWt unit, it was given a lower grade (grade 2). The 350 MWt unit would require the most design effort and has the lowest potential to satisfy the 2016 – 2018 deployment time, so it received the lowest grade (grade 1).

5. Provide Basis for Commercial Plant Design Certification (DC)

All of the candidate NGNP power levels can provide a reasonable basis for obtaining design certification for a commercial plant. However, the 550 and 600 MWt units are more representative of the projected commercial size and would provide better bases than the smaller 350 and 450 MWt sizes. For this reason, the 550 and 600 MWt sizes were provided the highest grade (grade 4) and the 350 and 450 MWt sizes were provided a slightly lower grade (grade 3).

6. Provide Basis for Commercial Plant O&M Cost

The primary consideration used for grading each of the candidate power levels for demonstration of O&M cost was essentially the same as that described above for demonstration of capacity factor. The 550 and 600 MWt units involve the largest quantities of equipment items and, assuming the equipment items are prototypic of the commercial plant, these units would provide the best O&M cost information for the commercial plant. Consequently, the 550 and 600 MWt units were given the highest grade (grade 4). Assuming the 350 and 450 MWt units also use prototypic equipment, these units would also provide good O&M cost information. However, the number of some items would be less and the size of some items would be less. The smaller quantities and sizes of equipment items would result in less representative O&M

requirements and would, therefore, not provide information as good as the larger size units. The 350 and 450 MWt units were, accordingly, given a slightly lower grade (grade 3).

7. Provide Basis for Commercial Plant Fuel Cost

The main fuel cost consideration is fuel cycle cost for which there are two main cost factors that require demonstration for the commercial plant; fuel manufacturing cost and fuel cycle length. There are other fuel cycle costs (uranium ore, conversion and enrichment), but these do not require demonstration. All of the candidate NGNP reactor power levels would provide a reasonable basis for the commercial plant fuel cost. All of the plants should be relatively equivalent for demonstration of the fuel cycle length. The larger plants would provide a better basis than the smaller plants for the manufacturing costs based simply on the quantities of fuel elements involved. For this reason, the 550 and 600 MWt units were given the highest grade (grade 4) and the 350 and 450 MWt units were given a slightly lower grade (grade 3).

The 550 and 600 MWt reactor power levels score highest. These MHR designs were judged to best satisfy the evaluation criteria related to the need for the NGNP to be designed such that construction, licensing, and operation of the NGNP would eliminate much of the uncertainty associated with utility/user costs to build, license, and operate a commercial VHTR. The elimination of such uncertainty was judged to be essential to demonstrate to potential utility/users that a VHTR would enjoy a significant cost advantage with respect to alternate means of electricity and/or process heat generation (without which there would be no incentive for a utility/user to build a VHTR). Much of this cost uncertainty is due to design, licensing, and construction uncertainties associated with high risk areas such as the reactor vessel, the PCS, the IHX, and the fuel; consequently, GA considers it essential that these risk area uncertainties be resolved by the NGNP.

Another important reason for selection of 600 MWt as the recommended power level for the NGNP is that the advanced stage of design development of the 600 MWt reactor results in the shortest time and lowest cost for completion of the design activities necessary to focus R&D activities. It is estimated that a conceptual design for a 600 MWt NGNP reactor could be completed in about one year. On the other hand, it would take a minimum of about two years to complete a conceptual design of either the 350 or the 450 MWt reactors (and longer for any other reactor size). A reasonably complete conceptual design is necessary to define the required design data needs and the R&D necessary to develop the data. Completion of the conceptual design in about one year would provide the best chance for completing the R&D in sufficient time to enable completion of NGNP construction by about 2017.

The conclusion is that the 550/600 MWt reactor power level should be selected for the NGNP. The power level is indicated as 550/600 MWt because of the anticipation the NGNP program would benefit from initial operations at the slightly lower 550 MWt power level. This should be explored further during detailed design.

Selection of the 550/600 MWt reactor power level for the NGNP makes selection of the commercial reactor power level straight forward. The commercial reactor power level should be as high as possible. The design of the 550/600 MWt reactor (metallic) vessel is at or close to the physically largest practical size to construct based on current manufacturing capabilities. It therefore follows that the commercial reactor power level selection should be the same as for the NGNP. Based on the economic data given in Reference 10, selecting the commercial reactor power as 600 MWt with a reference commercial plant containing four reactor modules, and making the NGNP the same as that projected for the commercial reactor modules best satisfies the commercial reactor power level criteria given in Section 4.1.

7 HYDROGEN PRODUCTION PLANT SIZES

The study objective for evaluation and recommendation of hydrogen production plant sizes is:

- Minimum size of the NGNP demonstration hydrogen production plant

In the following, evaluations and recommendations are made for two hydrogen production processes, (1) hydrogen production by means of the Sulfur-Iodine (S-I) thermochemical water splitting process and (2) hydrogen production by means of high temperature electrolysis (HTE).

7.1 S-I Thermochemical Water Splitting Hydrogen Production

7.1.1 S-I Hydrogen Production Process Description

There is currently no large scale, cost-effective, environmentally attractive hydrogen production process available for commercialization. Hydrogen production by thermochemical water-splitting, a chemical process that accomplishes the decomposition of water into hydrogen and oxygen using only heat, could meet these goals if coupled to a High-Temperature Gas-Cooled Reactor (HTGR).

One thermochemical cycle that has been studied extensively, References 11 – 14, is the Sulfur-Iodine (S-I) Cycle, invented at General Atomics (GA) in the 1970's. The S-I cycle consists of three coupled chemical reactions as shown in Figure 2. Sulfuric acid and hydrogen iodide are generated in the central low temperature reaction, the Bunsen reaction. Sulfuric acid is decomposed at high temperature and hydrogen iodide (HI) at lower temperatures in the other two reactions. There are significant chemical separations associated with each chemical reaction. Water is the primary solvent in the system and iodine is also an important solvent in the Bunsen reaction.

The overall process naturally divides itself into process sections in which there is significant recycle. Interconnection of the sections involves a minimum number of streams. For the S-I cycle, these natural sections roughly correspond to the chemical reactions. Sections 1, 2 and 3 are used to designate the portions of the process flowsheet associated with the Bunsen reaction (where the acids are formed), the sulfuric acid decomposition reaction, and the HI decomposition reaction. Figure 3 is a schematic of the S-I cycle.

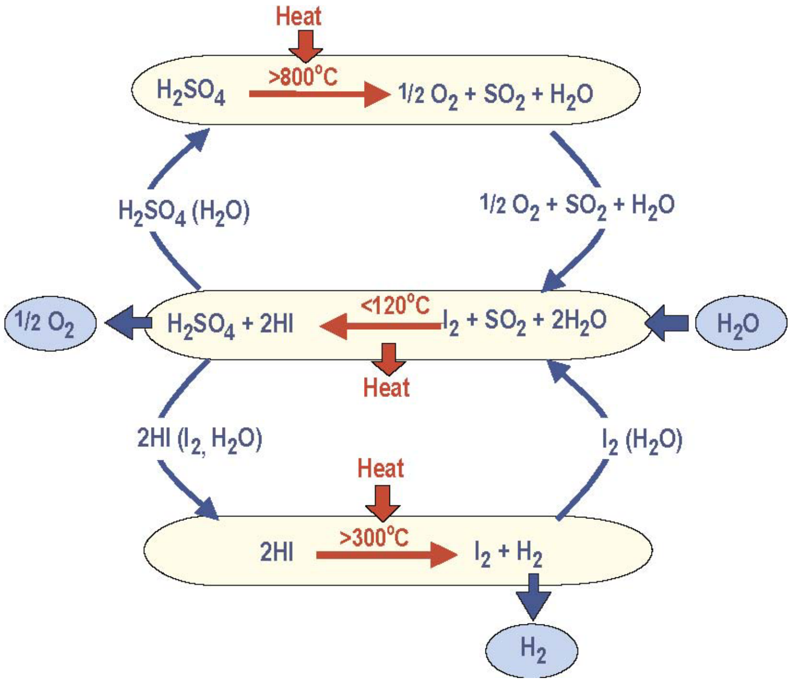


Figure 2. Coupled Chemical Reactions of the S-I Cycle.

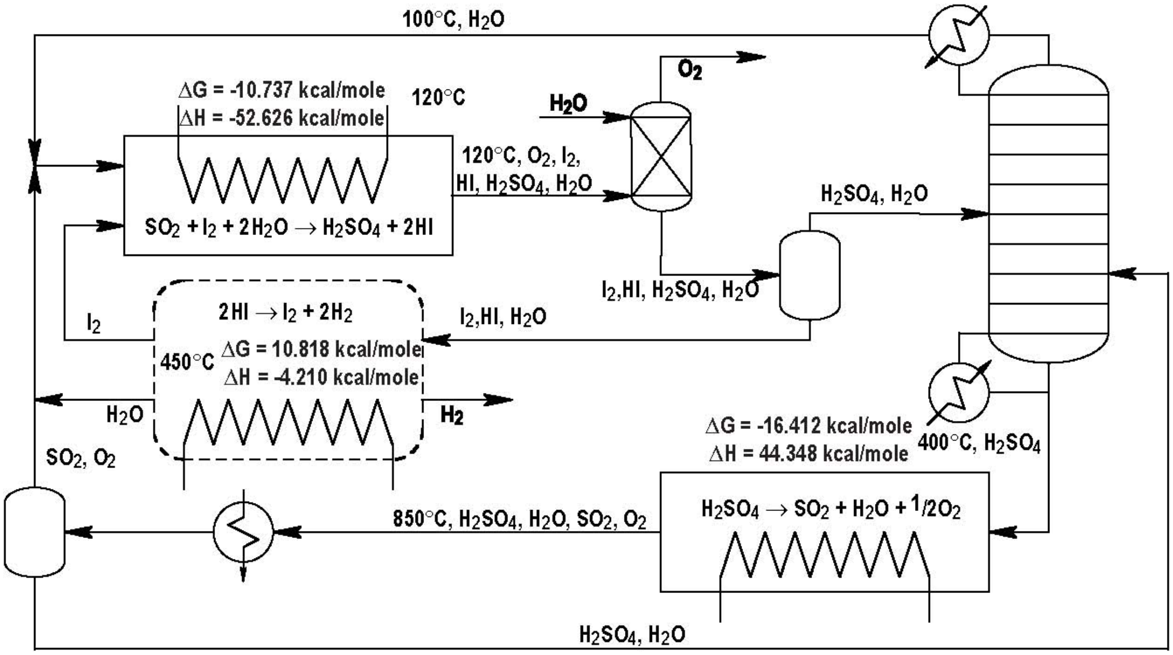


Figure 3. Sulfur-Iodine Cycle Process Flow Diagram

7.1.2 NGNP S-I Hydrogen Production Plant

A demonstration hydrogen plant is to be coupled to the NGNP. A study has been performed to determine a suggested size of an S-I demonstration hydrogen plant, based on consideration of the following evaluation criteria:

1. Potential NGNP Hydrogen Plant Users/Owners
2. Component Design Considerations and Scalability
3. Hydrogen Plant Control, Operation, and Protection
4. Hydrogen Plant Safety
5. Economics of the Demonstration and Commercial Designs

An evaluation of each of these criteria is provided in the following:

Criterion #1: Potential NGNP Hydrogen Plant Users/Owners

There does not appear to be a large market for hydrogen in the Idaho Falls area, where the nuclear hydrogen demonstration reactor is planned to be constructed. Even considering all of Idaho and the immediately surrounding states the demand for merchant hydrogen is insufficient to require the output of even a modest size demonstration plant. A more likely customer will be one of the oil refineries in northern Utah. Given a competitive price, one of the refineries is likely to purchase the total output of the plant. In one scenario, the refinery would have to shut down some of their on-site hydrogen production to accept the hydrogen product from the demonstration plant. They are unlikely to do this unless they are assured of a steady supply of hydrogen. This scenario is further hampered by the fact that refineries typically enter into long-term contracts with hydrogen suppliers. Thus, the demonstration hydrogen plant will have to be operating reliably at the time when a refinery is considering a contract renewal for it to be considered as a viable alternative candidate for supplying hydrogen.

A more likely scenario is that a refinery would take the total output of the demonstration hydrogen plant and add it to its existing capacity. So, one measure for a minimum size of the NGNP hydrogen demonstration plant is the typical minimum increment in capacity increase that a refinery would consider when boosting hydrogen use. A survey of refinery operators in Utah and surrounding states showed that an incremental increase of at least 5 million standard cubic feet of hydrogen per day could be reasonably expected to occur. This is equivalent to a hydrogen plant producing approximately 70 moles of hydrogen per second. At a thermal efficiency of 45%, the required minimum thermal power from the NGNP to the demonstration hydrogen plant would be about 40MWt.

Criterion #2: Component Design Considerations and Scalability

There is no generic limit to the degree of scale-up for a chemical plant. In practice, the acceptable scale-up for a given process step is a function of how well the process thermodynamics, physical properties and kinetics are known. The complexity of the unit operations involved and the importance of an accelerated schedule relative to the risk of the plant not operating at design capacity, and the value of the product relative to the cost of the process also play roles. As an example, scale-up factors of 5×10^4 are common in petroleum refining technology. On the other hand, factors of three to five are employed for poorly defined processes.

The thermodynamic uncertainties of the S-I thermochemical hydrogen process vary within the process. The thermodynamics of sulfuric acid are well known and, based on thermodynamic considerations, there is no reason that the sulfuric acid processing portion of the process could not be designed and constructed full scale from the present information. There remain some uncertainty in the kinetics of SO_3 decomposition and catalyst life.

There is significant uncertainty in the thermodynamics of the system $HI/I_2/H_2O$ and even greater uncertainty in the thermodynamics of the systems $HI/I_2/H_2O/H_3PO_4$ and $HI/I_2/H_2O/SO_2/H_2SO_4$. Unless a serious effort succeeds to obtain good thermodynamic data for these systems, a conservative recommendation would be that the scale-up from pilot plant to commercial plant be no more than a factor of three. The 2003 INERI study [7] suggested that 40 trains be used for the HI decomposition section of a 4200 mole/sec (2400 MWt) hydrogen plant. In this case, each train produces 105 moles of hydrogen per second. Using this as a basis, it could be suggested that the demonstration plant be no smaller than one-third the size of these trains, or 35 moles of hydrogen per second. Thus, based on conservative scaling factors, with a thermal efficiency of 45%, the required minimum thermal power from the NGNP to a single train in the demonstration hydrogen plant would be about 20MWt.

Criterion #3: Hydrogen Plant Control, Operation, and Protection

The controls and operating strategy is not fully developed for a full-scale plant. The plant control strategy must be based upon realistic plant performance objectives which can be used to determine the control objectives of the individual unit processes making up the plant. A full-scale nuclear hydrogen facility is envisioned to be composed of four 600 MWt VHTR modules powering a multi-train hydrogen plant. Even with one VHTR module, there will be several hydrogen trains. Validating the yet-to-be-developed control strategy will require demonstration of the control of multiple hydrogen trains. A suggested minimum would be three trains to validate the plant controls and operations. If desired, one train could be built first and the others could be brought on-line later. As the process is scaled up, the plant control hierarchy would be more likely to be decomposed into small groups of trains, rather than one overarching control system. Thus, for validation of plant controls and operations, with conservative scaling factors and a thermal efficiency of 45%, the required minimum thermal power from the NGNP to a three-train demonstration hydrogen plant would be about 60MWt.

Criterion #4: Hydrogen Plant Safety

There are several aspects to safety that could have a bearing on the scale of the demonstration plant. Within the chemical plant, the concern is with personnel safety and material safety, both on-site and off-site. Off-site considerations include the effect on operation of the nuclear plant. There are four broad classes of safety issues: chemical safety, high-pressure safety, hydrogen safety and electrical safety. From a scaling standpoint, none of the safety considerations should have a major affect on the size of the demonstration hydrogen plant, though they may affect siting/location considerations. There are in-plant physical and organizational considerations as the plant size increases, but with good engineering practice these should not greatly influence the size of the demonstration hydrogen plant.

Criterion #5: Economics of the Demonstration and Commercial Designs

A recent study, Reference 15, calculated that cost of hydrogen production from an nth-of-a-kind, full-scale hydrogen plant based on the S-I cycle would be $1.95/kg. It is unlikely that the hydrogen produced from the NGNP demonstration plant will be cost competitive with hydrogen from steam reformation of methane at the time the plant is built. The larger the scale of hydrogen production, the more economical the hydrogen production cost, but the more capital at risk and the greater the difficulty in locating near-by customers. The chemical engineering costing techniques used to estimate the S-I plant cost assume that the starting point is a valid flow sheet from which the plant is to be designed and engineered. From that standpoint, the costs are as valid for a first-of-a-kind as for an nth-of-a-kind. The difference is one of uncertainty and is quantified by a difference in the contingency. The desirability of continuous hydrogen production from a refinery consumer gives further weight to the arguments for building the hydrogen plant with multiple parallel trains as suggested above.

7.1.3 NGNP S-I Hydrogen Production Plant Conclusions

Several factors allow for a quantitative estimate of the minimum size for the NGNP demonstration hydrogen plant. Potential customers, such as oil refineries, would require minimum thermal input from the NGNP in the range of 40MWt to make economic sense. From a process equipment scalability standpoint, a 20MWt plant would suffice. However, to validate the operation and controls systems, operation of a minimum of three trains is recommended.

The combination of the controls validation requirement with the minimum power per train from scaling factors leads to a total thermal power input of 60MWt. This size plant would satisfy all criteria analyzed. A refinery customer would easily be able to accept a reliable hydrogen output from a 60MW hydrogen demonstration plant. Therefore, a conservative recommendation of the minimum size of the S-I NGNP hydrogen demonstration plant is 60 MWt, with an output of 7.5 million standard cubic feet of hydrogen per day.

7.2 HTE Hydrogen Production

7.2.1 Process Description

A basic flow diagram for the HTE process is shown in Figure 4. The Solid Oxide Electrolyte Cell (SOEC) is the key component of the HTE process. Design conditions for a SOEC connected to a VHTR module are provided in Table 3. Figure 5 shows the general configuration of a SOEC module. It consists of an internally insulated pressure vessel housing electrolysis cells. Scale up of the SOEC hydrogen production process can be accomplished by having more pressure vessel modules or by using larger modules having larger pressure vessels containing more electrolysis cells. Figure 6 shows vessel weights for SOEC pressure vessel modules having hydrogen production capacities of 150Nm^3/hr (@0.6A/cm^2), 600Nm^3/hr (@0.6A/cm^2), and 1200Nm^3/hr (@0.6A/cm^2).

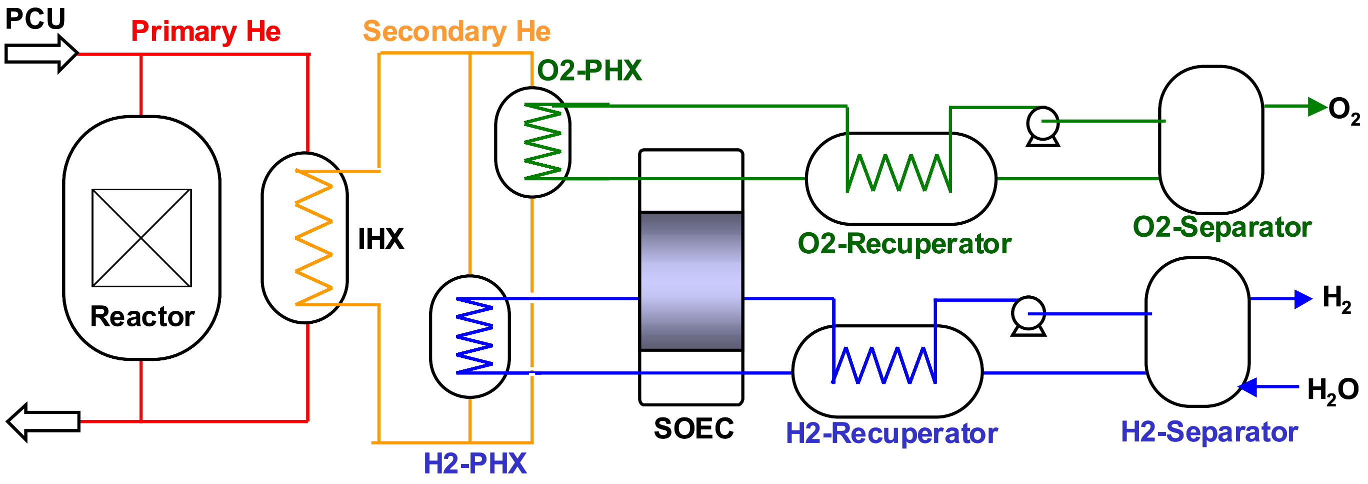


Figure 4. HTE Process Flow Diagram

Table 3 Design Conditions for SOEC Connected to a Modular Reactor

Design Parameter	Value
Inner temperature, °C	900
Vessel temperature, °C	200
Vessel pressure, MPa	5
ΔP between anode and cathode, MPa	0
Anode fluid	N_2 & O_2
Cathode fluid	H_2O & H_2
Electrolysis cell shape	Cylindrical
Current density, A/cm^2	0.6

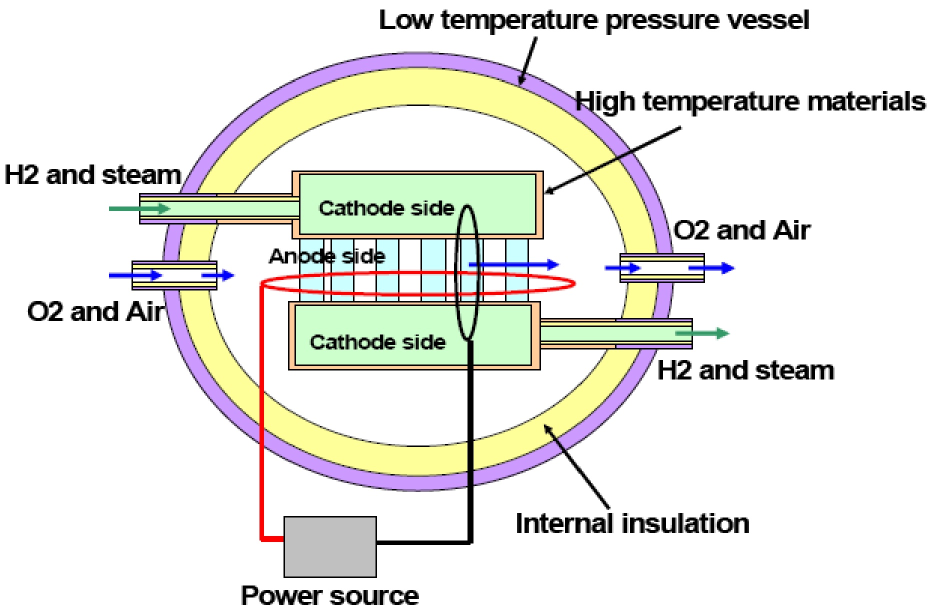


Figure 5. High Pressure SOEC Module Configuration

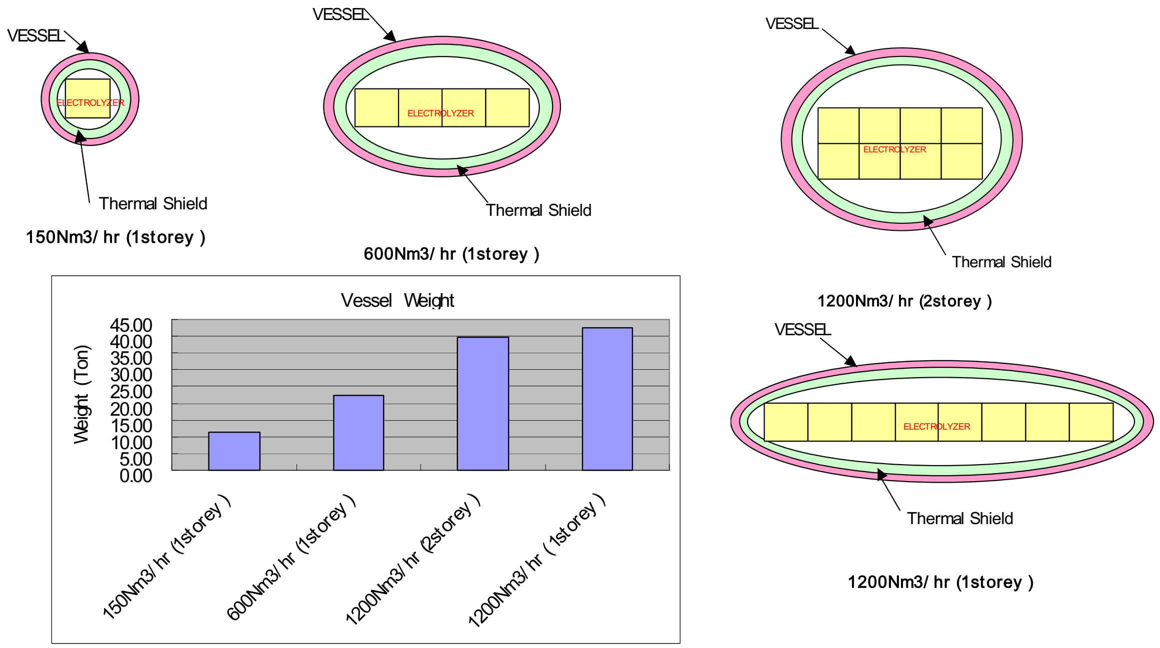


Figure 6. SOEC Module Scale Up Possibilities

7.2.2 NGNP Demonstration HTE Hydrogen Production Plant

As in the case of the S-I process, a demonstration HTE hydrogen plant is to be coupled to the NGNP. A study has been performed to determine a suggested size of an HTE demonstration hydrogen plant based on consideration of the following evaluation criteria:

1. Potential NGNP Hydrogen Plant Users/Owners
2. Component Design Considerations and Scalability
3. Hydrogen Plant Control, Operation, and Protection
4. Hydrogen Plant Safety
5. Economics of the Demonstration and Commercial Designs

An evaluation of each of these criteria is provided below.

Criterion #1: Potential NGNP HTE Hydrogen Plant Users/Owners

Because user/owners are interested in minimizing risk, they would be more interested in replicating SOEC modules for a commercial hydrogen production plant than scaling up a SOEC module. If both the NGNP demonstration and commercial plant SOEC modules were of the same size (e.g., 600 Nm^3/hr (@0.6A/cm^2) the risks to the user/owner would be minimized. In addition, there would be better reliability, as well as operations and maintenance data, available to the user/owner if the commercial hydrogen production plant was to use the same SOEC module size as demonstrated in the NGNP plant. The most common SOEC module size is estimated to have the capacity 600 Nm^3/hr (@0.6A/cm^2). From considerations of NGNP hydrogen plant control, operations and protection, a minimum 10 SOEC modules are recommended (i.e., a minimum NGNP HTE hydrogen production plant capacity of 6000 Nm^3/hr (@0.6A/cm^2). This capacity corresponds to 0.167 kg/sec which requires about 4 MWt of heat energy to be transferred from the reactor system through an intermediate heat exchanger to the HTE hydrogen production system.

6000 Nm^3/hr (@0.6A/cm^2) is the minimum NGNP HTE hydrogen production plant size for demonstration of the process for commercialization purposes. The criterion used for section 6.1.2 for the minimum S-I hydrogen production plant size is a plant capacity usable in the vicinity of the NGNP which is indicated to be about 5 million standard cubic feet per day. This plant capacity equates to about 6000 Nm^3/hr.

Criterion #2: HTE Component Design Considerations and Scalability

The main components of the SOEC HTE system are the electrolysis cells and the pressure vessels. The number of electrolysis cell increases with increasing scale of hydrogen production.

The vessel weight, as shown in Figure 6 saturates around a SOEC size of 600Nm^3/hr (@ 0.6A/cm^2). The merit of larger scale SOEC vessel modules is small.

Criterion #3: HTE Hydrogen Plant Control, Operation, and Protection

Commercial HTE based plants coupled to 600MWt VHTRs likely have multiple SOECs modules for reliability reasons so operations require the control of several SOECs. In case of failures SOEC modules, spare SOEC modules could be provided to replace the failed modules to maintain hydrogen production at an adequate level. The recommendation for the NGNP demonstration HTE-based plant to have at least 10 SOEC modules is to maintain hydrogen production within 10% of full capacity in the event of an inoperable module, either planned or unplanned, to demonstrate control and operation characteristics.

Criterion #4: HTE Hydrogen Plant Safety

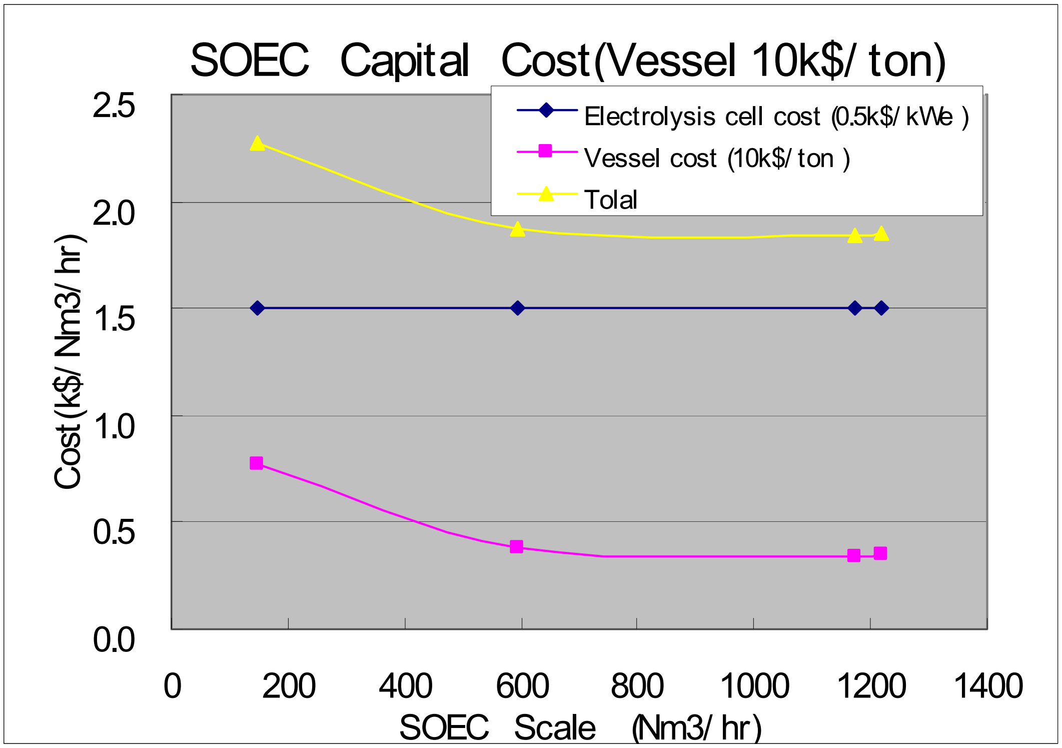
Plant operations for safe handling, storage, transfer, distribution, and utilization of the HTE hydrogen would require the least effort to develop and apply if the hydrogen quantities involved were similar to other plants dealing with hydrogen such as a fuel cell vehicle (FCV) hydrogen station. The 600Nm^3/hr (@0.6A/cm^2) SOEC HTE module corresponds to the most common hydrogen production units used for FCV. Accordingly, the HTE hydrogen production plant is not expected pose difficult safety issues.

Criterion #5: Economics of the HTE Demonstration and Commercial Designs

The cost of hydrogen using the HTE SOEC production process was estimated by using the unit capital cost of 0.5$/kWe for the electrolysis cell and lower and upper unit capital costs of 10k$/ton and 100$/ton, respectively, for the pressure vessel. Figure 7 shows the resulting capital cost component hydrogen production in terms of $/Nm^3/hr as a function of the SOEC scale (Nm^3/hr). These results indicate that the hydrogen production capital cost for SOEC modules larger than 600Nm^3/hr (@0.6A/cm$^{2)}$ remains almost the same as for the 600Nm^3/hr (@0.6A/cm^2) unit. The HTE-based plant is most economic when it is composed of 600Nm^3/hr (@0.6A/cm^2) SOEC HTE modules and would realize benefits from cost reductions resulting from mass production.

7.2.3 HTE Hydrogen Plant Conclusions

The primary conclusions from the evaluations performed to determine a suggested size of a HTE demonstration hydrogen plant are as follows:



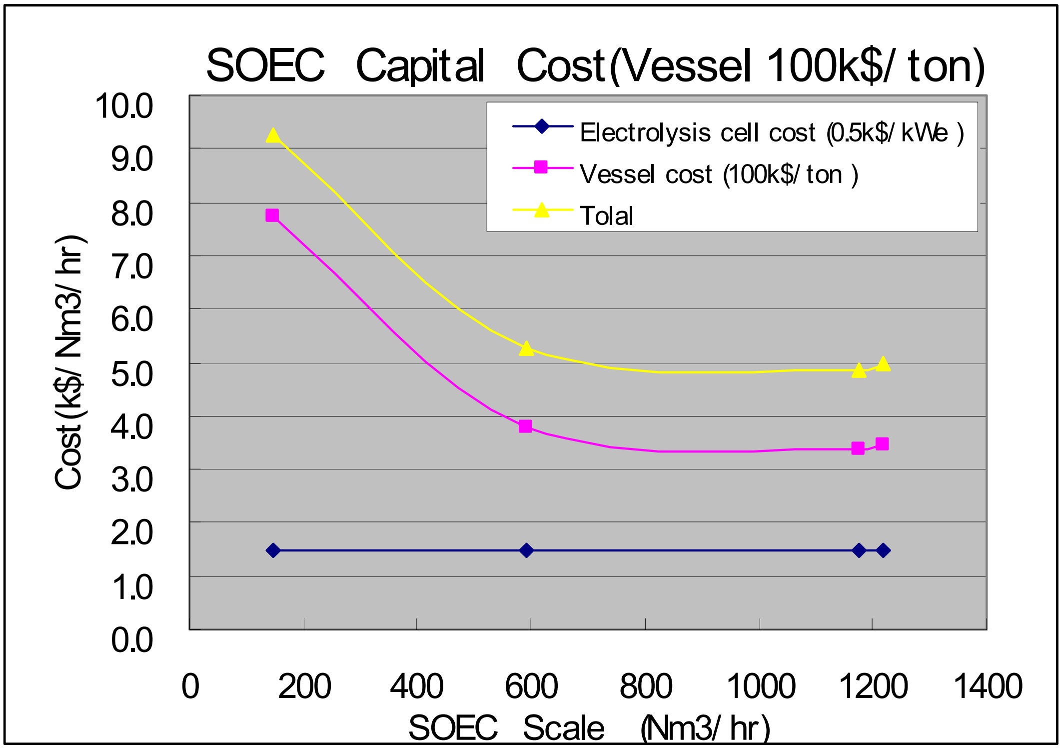


Figure 7. Estimated HTE SOEC Capital Costs

- From considerations of scalability and economics, a HTE SOEC module size of 600 Nm^3/hr (@0.6A/cm^2) would be best for both the NGNP demonstration and follow-on commercial VHTR HTE hydrogen production plant
- From considerations of the hydrogen plant control, operation and protection, 10 or more HTE SOEC modules are required to confirm operational capability of the commercial scale plant. A 10 modules demonstration plant would required about 4 MWt of heat energy and would produce 6000 Nm^3/hr (@0.6A/cm^2). This is equal to about 5 million standard cubic feet per day.
- The above conclusions for the HTE SOEC module size and number of modules are completely compatible with results from considerations of both user/owner requirements and hydrogen plant safety.

Note that a variation of the electrolysis cell operating current density varies the SOEC module size because the number of HTE cells is proportional to operating current density. The effect of alternative electrolysis cell operating current densities should be evaluated in more in detail during detail design.

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