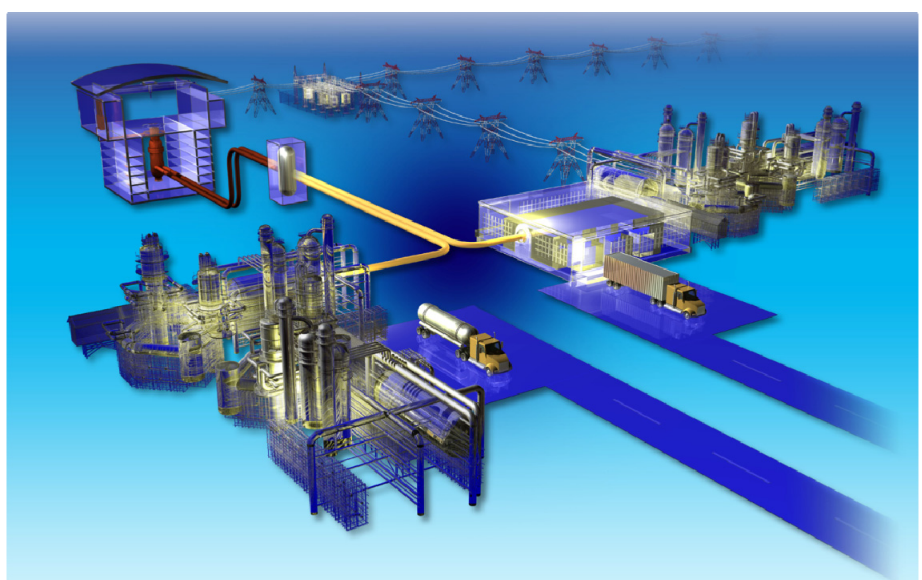
Document ID: TEV-961
Revision ID: 0
Effective Date: 09/15/2010

Technical Evaluation Study

Project No. 23843

Sensitivity of Hydrogen Production via Steam Methane Reforming to High Temperature Gas-Cooled Reactor Outlet Temperature Process Analysis



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SENSITIVITY OF HYDROGEN PRODUCTION VIA STEAM METHANE REFORMING TO HIGH TEMPERATURE GAS-COOLED REACTOR OUTLET TEMPERATURE PROCESS ANALYSIS	Identifier: TEV-961 Revision: 0 Effective Date: ~~08/31/2010~~ 09/15/2010	Page: 1 of 22

NGNP Project	Technical Evaluation Study (TEV)		eCR Number:	583106

~~Manual: TKA 11-509~~
TKA 9-2-10

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REVISION LOG

Rev.	Date	Affected Pages	Revision Description
0	09/15/10	All	Newly issued document.

EXECUTIVE SUMMARY

This technical evaluation (TEV) has been prepared as part of a study for the Next Generation Nuclear Plant (NGNP) Project to evaluate integration of High Temperature Gas-cooled Reactor (HTGR) technology with conventional chemical processes. This TEV addresses the impact of increasing HTGR reactor outlet temperature (ROT) on hydrogen production via steam methane reforming (SMR) of natural gas.

The production of hydrogen via SMR has previously been addressed in detail in TEV-953 (INL 2010a). In that report, detailed process models for both conventional SMR hydrogen production and HTGR-integrated SMR hydrogen production with an ROT of 750°C (1,382°F) were developed. This report is done as a follow-up to TEV-953, and evaluates the impact of increasing the ROT to 925°C (1,697°F).

For this evaluation, six cases were considered, all of which include carbon capture (CC):

Case 1 – Conventional non-HTGR-integrated SMR

Case 2 – HTGR-integrated SMR with an ROT of 725°C (supplying 700°C heat)

Case 3 – HTGR-integrated SMR with an ROT of 775°C (supplying 750°C heat)

Case 4 – HTGR-integrated SMR with an ROT of 825°C (supplying 800°C heat)

Case 5 – HTGR-integrated SMR with an ROT of 875°C (supplying 850°C heat)

Case 6 – HTGR-integrated SMR with an ROT of 925°C (supplying 900°C heat).

The optimal steam reforming temperature selected for this analysis was 871°C (1,600°F). In Case 6, the HTGR is capable of providing heat to the process at 900°C (1,652°F), thereby supplying the entire heat duty required for reforming. Although follow-on HTGRs are planned to have an ROT as high as 950°C (1,742°F), there is little or no benefit to the SMR process of pushing the ROT higher than required to supply heat to the reformer. Hence, ROTs above 925°C (1,697°F) were not investigated in this study.

A simplified diagram showing the major inputs and outputs from the process is shown in Figure ES-1 (Case 5 results shown). Primary inputs to the process are natural gas, heat in the form of hot helium from the HTGR, electricity from the HTGR, and water. Primary outputs from the process are hydrogen, 4.2 MPa (600 psig) steam, concentrated CO_2 (suitable for sequestration or use in enhanced oil recovery), and combustion exhaust that also contains CO_2.

In Case 1, reforming heat is provided to a single reformer by combusting a combination of natural gas and fuel gas. In Cases 2–5, two reforming stages are used. In the first stage, heat is provided from hot helium supplied by the HTGR. In the second stage, combustion of fuel gas is used to raise the reforming temperature to the target temperature of 871°C (1,600°F). In Case 6, all reforming heat is provided from hot helium supplied by the HTGR to a single reformer. In all cases, heat recuperation is utilized to raise steam for use within the plant. Steam generated in excess of that required for use within the plant is exported as a saleable byproduct.

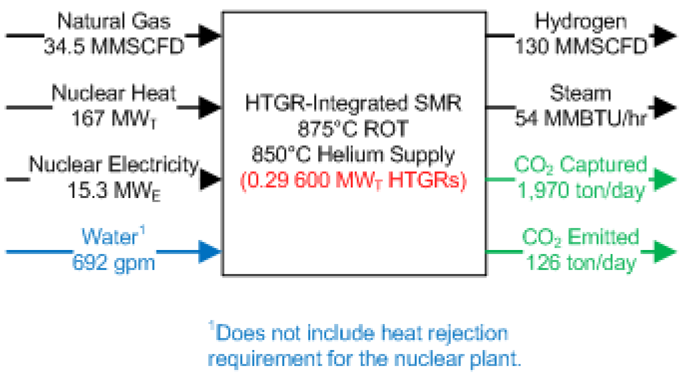


Figure ES-1. SMR SMR H_2 production material balance results for Case 5.

Significant results from this evaluation are:

- Increasing the HTGR ROT significantly reduces natural gas consumption, as shown in Figure ES-2. By integrating nuclear heat at the lowest temperature considered, 725°C (1,337°F) ROT, natural gas consumption can be reduced by 11.6% compared to the conventional process. If the ROT is increased to 925°C (1,697°F), a reduction of 30.9% can be realized compared to the conventional process.

- As the ROT is increased, the ratio of hydrogen product to natural gas feed increases significantly. Also, by shifting the required reforming duty from fuelgas combustion to nuclear heat, less combustion exhaust gas is generated. Because steam is raised to recover heat from the combustion exhaust gas, a decrease in fuelgas combustion leads to a corresponding decrease in the amount of steam generated and exported from the plant. These results are shown in Figure ES-3.

- CO_2 emissions are also reduced as the ROT is increased. For an ROT of 725°C (1,337°F), CO_2 emissions are reduced by 39% compared to the conventional SMR case. For an ROT of 925°C (1,697°F), CO_2 emissions are reduced by an additional 73% from the 725°C (1,337°F) ROT case, representing a total CO_2 emissions reduction of 83% compared to the conventional SMR case. CO_2 disposition for each case is shown graphically in Figure ES-4.

- As the ROT increases, the difference between the helium return temperature and the optimal helium inlet temperature to the HTGR decreases. At an ROT of

725°C (1,337°F), the difference is 71°C (128°F), while an ROT of 925°C (1,697°F) produces a difference of only 3°C (5°F). Hence, the higher ROT is more compatible with a "heat-only" HTGR configuration. At lower ROTs, inserting a power cycle is the most likely scenario to utilize the excess heat returned from the reformer.

- Of all the HTGR-integrated cases considered, only the 925°C (1,697°F) ROT case completely eliminates the need for two reforming stages—nuclear heat alone is adequate in this case to provide the desired reforming temperature. This greatly simplifies the design of the reformer.

Based on the results of this study, an economic analysis is recommended to further quantify the benefits offered by increasing the ROT from 725°C (1,337°F) to 925°C (1,697°F).

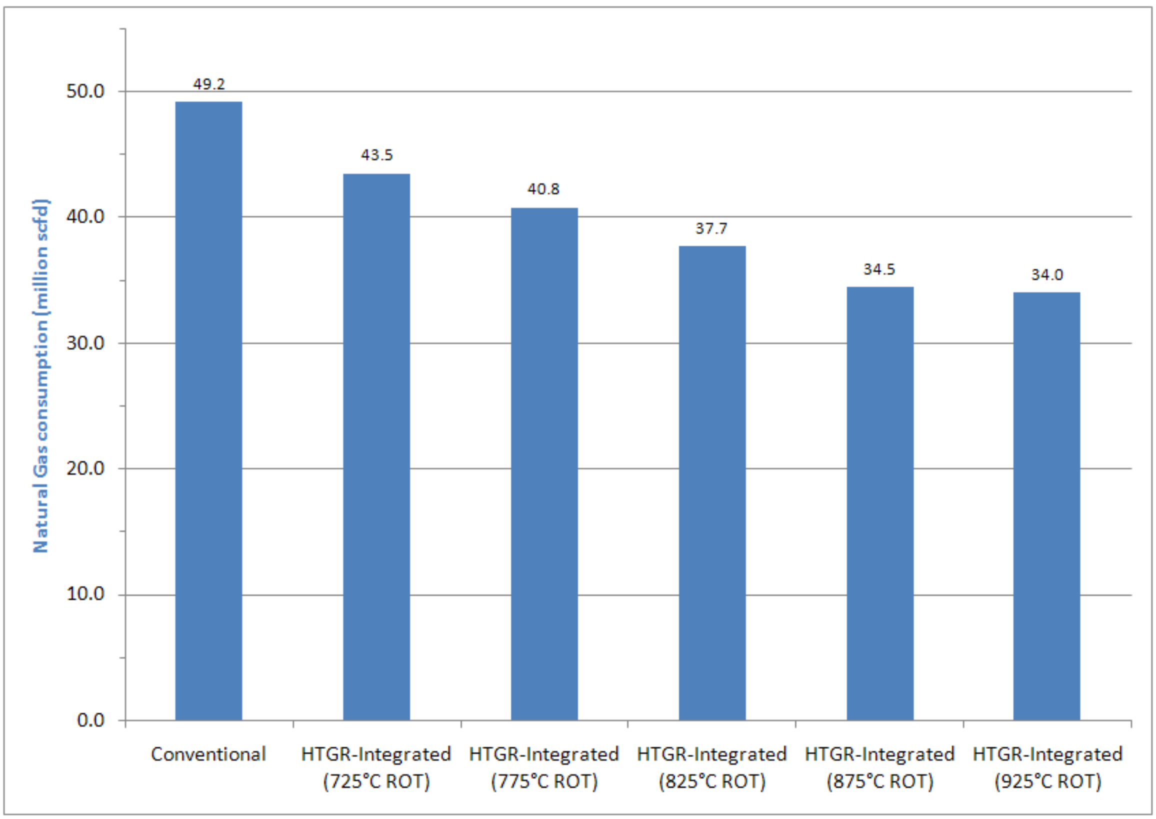


Figure ES-2. Natural gas consumption as a function of ROT.

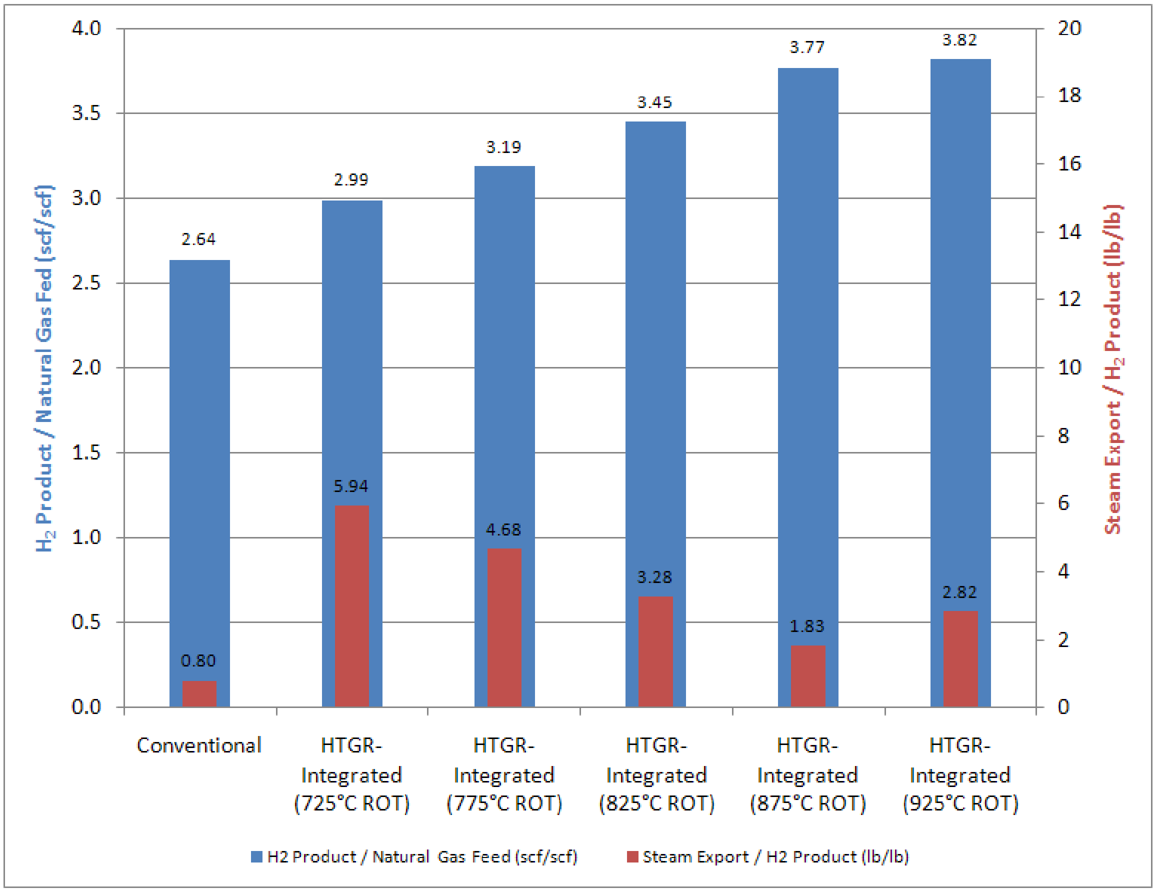
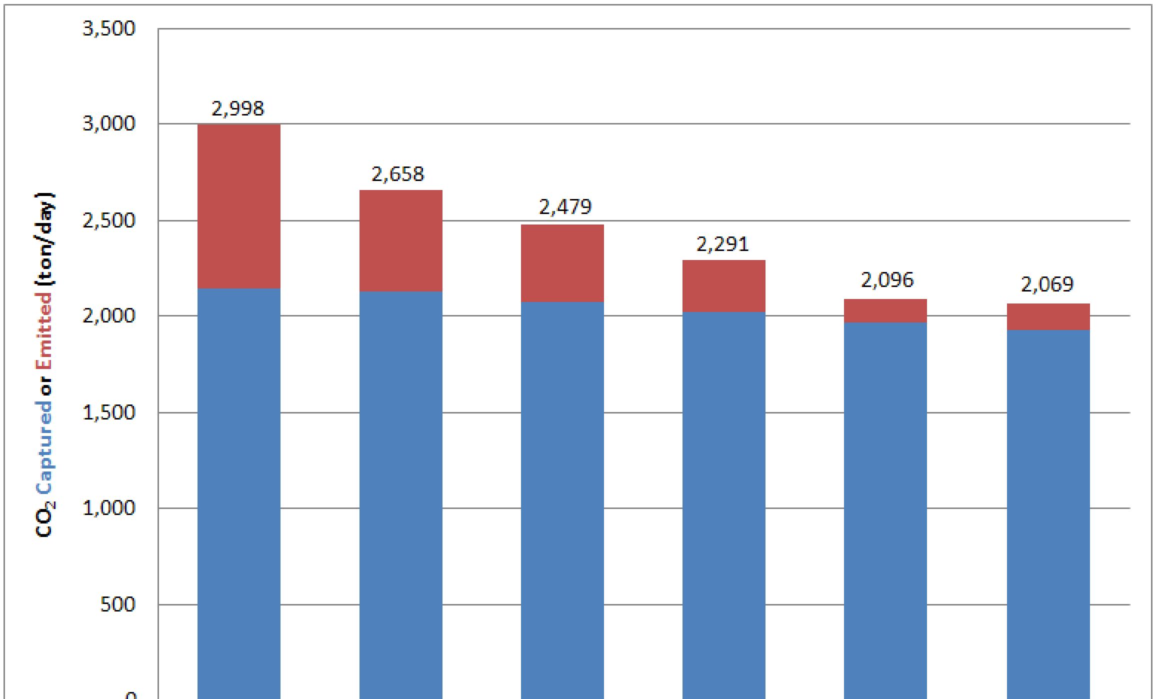


Figure ES-3. SMR H_2 product and steam export yields as a function of ROT.



	Conventional	HTGR-Integrated (725°C ROT)	HTGR-Integrated (775°C ROT)	HTGR-Integrated (825°C ROT)	HTGR-Integrated (875°C ROT)	HTGR-Integrated (925°C ROT)
Emitted	855	525	403	267	126	142
Captured	2,143	2,133	2,076	2,024	1,970	1,927

Figure ES-4. SMR CO_2 disposition as a function of ROT.

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ACRONYMS AND NOMENCLATURE

CC	carbon capture
DOE	Department of Energy
HHV	higher heating value
HTGR	High Temperature Gas-cooled Reactor
INL	Idaho National Laboratory
MMBTU	1,000,000 British thermal units
MMSCF	1,000,000 standard cubic feet
NGNP	Next Generation Nuclear Plant
ROT	reactor outlet temperature
SMR	steam methane reformer
TEV	technical evaluation

1. INTRODUCTION

This technical evaluation (TEV) has been prepared as part of a study for the Next Generation Nuclear Plant (NGNP) Project to evaluate integration of High Temperature Gas-cooled Reactor (HTGR) technology with conventional chemical processes. The NGNP Project is being conducted under U.S. Department of Energy (DOE) direction to meet a national strategic need identified in the *2005 Energy Policy Act* to promote reliance on safe, clean, economical nuclear energy and to establish a greenhouse-gas-free technology for the production of hydrogen. NGNP represents an integration of high-temperature reactor technology with advanced hydrogen, electricity, and process heat production capabilities, thereby meeting the mission need identified by DOE. The strategic goal of the NGNP Project is to broaden the environmental and economic benefits of nuclear energy in the U.S. economy by demonstrating its applicability to market sectors not being served by light water reactors.

The HTGR produces steam, high-temperature helium that can be used for process heat, and/or electricity. Previous studies conducted by Idaho National Laboratory (INL) over the past year have assumed an HTGR outlet temperature of 750°C (1,382°F); this reflects the initial HTGR design and assumes a more conservative outlet temperature. Additionally, a 50°C (90°F) temperature approach was assumed between the primary and secondary helium loops when helium was the delivered working fluid. As a result, the maximum helium stream temperature available for heat exchange in those studies was 700°C (1,292°F).[a]

Although initial HTGR implementations will likely target an HTGR outlet temperature of 750°C (1,382°F), temperatures of up to 950°C (1,742°F) are anticipated for later designs. Unlike previous INL studies performed during the last year, this study removes the 750°C (1,382°F) maximum HTGR outlet temperature assumption. Instead, the impact of increasing the HTGR reactor outlet temperature (ROT) is assessed. For this study, a 25°C (45°F) temperature approach is assumed between the primary and secondary helium loops, as opposed to the 50°C (90°F) assumption used in previous studies. This study investigates the impact of varying ROTs from 725°C (1,337°F) to 925°C (1,697°F). Hence, using the 25°C (45°F) temperature approach assumption between the primary and secondary loops, high-temperature helium can be delivered at temperatures between 700°C (1,292°F) and 900°C (1,652°F). HTGR product conditions assumed for this analysis are shown in Table 1.

a. See TEV-666, TEV-667, TEV-671, TEV-672, TEV-674, TEV-693, TEV-704, TEV-953, and INL/EXT-09-16942.

Table 1. Projected outputs of NGNP.

HTGR Product	Product Description
Steam	540°C (1,004°F) and 17 MPa
High-Temperature Helium	Delivered at 700°C (1,292°F) and 9.1 MPa
Electricity	Generated by Rankine cycle with 40% thermal efficiency

The production of hydrogen via steam methane reforming (SMR) of natural gas has previously been addressed in detail in TEV-953 (INL 2010a). In that report, detailed process models for both conventional SMR hydrogen production and HTGR-integrated SMR hydrogen production were developed. The models documented in TEV-953 are used as the basis for the temperature sensitivity analysis conducted in this report. This TEV assumes familiarity with TEV-953; hence, detailed descriptions of the process models documented in TEV-953 are not presented here.

The process simulations used for this analysis have been developed in Aspen Plus, a state-of-the-art, steady-state chemical process simulator (Aspen 2006). This study makes extensive use of these models; this TEV assumes familiarity with Aspen Plus. A detailed explanation of the software capabilities, thermodynamic packages, unit operation models, and solver routines is beyond the scope of this study.

This TEV first presents the general process configuration on which the sensitivity analysis is based. Next, conditions for the specific cases modeled are presented. Issues discovered during modeling that required slight modification to the process flowsheet are then presented, followed by a brief discussion of the study limitations. Finally, results of the temperature sensitivity analysis are presented and discussed.

2. SENSITIVITY ANALYSIS DESCRIPTION

2.1 Baseline Process Configuration

The process configuration selected as the basis for the temperature sensitivity study includes carbon capture (CC) and is taken from TEV-953. A simplified block flow diagram of the process is presented in Figure 1; a detailed process description can be found in TEV-953, "HTGR-Integrated Hydrogen Production via Steam Methane Reforming (SMR) Process Analysis." Carbon capture was included in this study for the following reasons:

1. Removal of CO_2 produces a smaller volume of fuelgas. It is more reasonable to recycle a smaller volume to the reformer, as it will not dramatically increase the size of the reformer and gas cleanup equipment.

2. Fuelgas in excess of what is required to fire the second stage reformer can be recycled to the reformer tubes to increase syngas production and ultimately maximize hydrogen production.

3. Removal of CO_2 limits CO_2 concentration in the reformer which improves hydrogen yield by suppressing the reverse water gas shift reaction. This reduces the load on the downstream water gas shift reactors.

4. The feasibility of recycling fuel gas to the reformer tubes is questionable unless CC is implemented. If fuel gas cannot be recycled, it must be used for a purpose other than to increase hydrogen production. The most likely use would be to generate additional steam for export from the plant. However, the nuclear reactor is itself an excellent heat source—generation of additional export heat in the form of steam from the reformer is therefore undesirable.

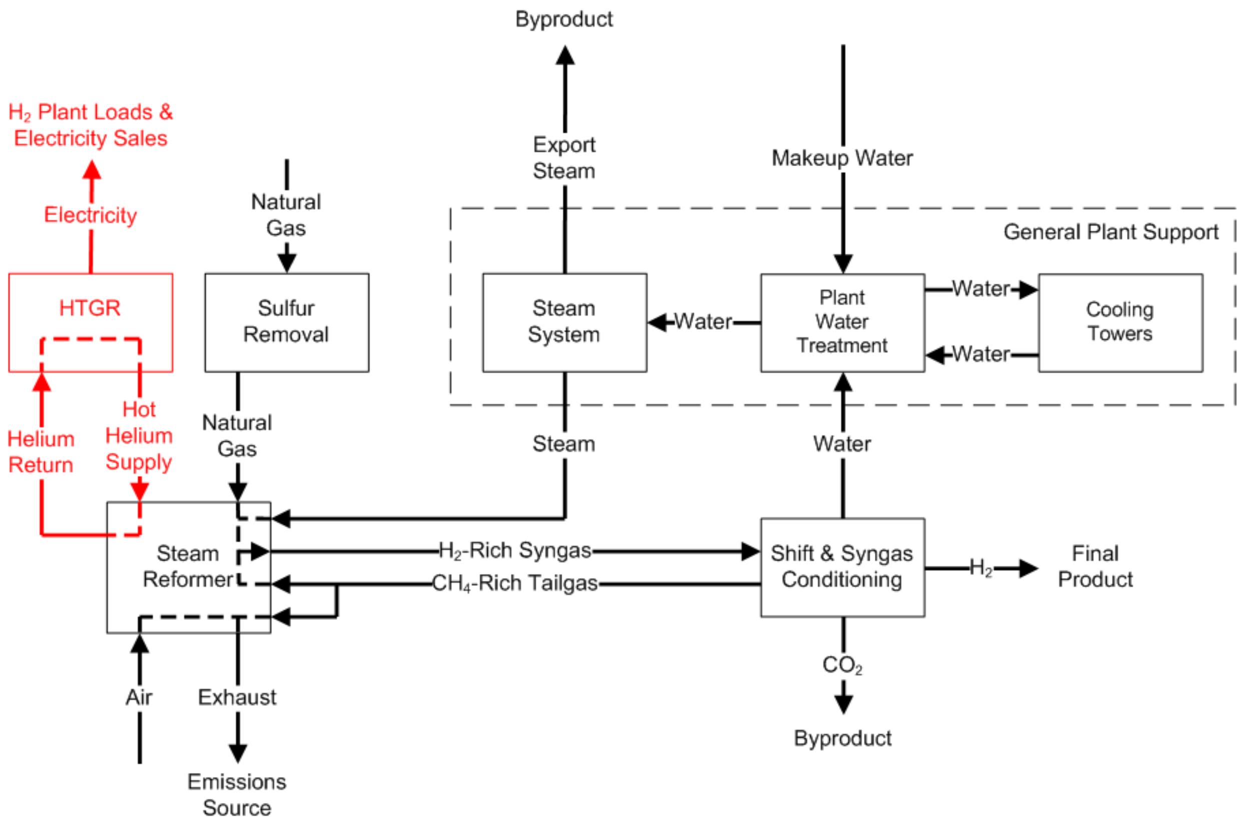


Figure 1. SMR process used in the sensitivity analysis.

As described in TEV-953, two reforming stages are utilized: the first stage uses helium from the HTGR as the heat transfer medium, and the second stage combusts fuelgas to supply additional higher-temperature heat to complete the reforming process. Increasing the ROT of the HTGR allows more of the reforming to be accomplished in the first stage. When helium can be supplied to the process at a temperature above 871°C (1,600°F) [corresponding to an ROT of 896°C (1,645°F) for the assumed 25°C (45°F) temperature approach between the primary and secondary loops], the potential exists to supply all reforming heat from the HTGR, thus completely eliminating the fuelgas-fired reformer stage.

2.2 Cases Considered

Two cases from TEV-953 are included in this study for comparison purposes: (1) the conventional non-HTGR-integrated SMR case with CC, and (2) the HTGR-integrated SMR case with an ROT of 725°C (1,337°F) and CC.[b] Four additional cases are evaluated as part of this study, each increasing the HTGR ROT by 50°C (90°F) until a maximum ROT of 925°C (1,697°F) is achieved. Hence, a total of six cases are compared and evaluated in this study, all of which include CC:

Case 1 – Conventional non-HTGR-integrated SMR

Case 2 – HTGR-integrated SMR with an ROT of 725°C (supplying 700°C heat)

Case 3 – HTGR-integrated SMR with an ROT of 775°C (supplying 750°C heat)

Case 4 – HTGR-integrated SMR with an ROT of 825°C (supplying 800°C heat)

Case 5 – HTGR-integrated SMR with an ROT of 875°C (supplying 850°C heat)

Case 6 – HTGR-integrated SMR with an ROT of 925°C (supplying 900°C heat).

The optimal steam reforming temperature selected for this analysis was 871°C (1,600°F). In Case 6, the HTGR is capable of providing heat to the process at 900°C (1,652°F), thereby supplying the entire heat duty required for reforming. Although follow-on HTGRs are planned to have an ROT as high as 950°C (1,742°F), there is little or no benefit to the SMR process of pushing the ROT higher than required to supply heat to the reformer. Hence, ROTs above 925°C (1,697°F) were not investigated in this study.

2.3 Gas Recycle Considerations

The natural gas feedstock considered in this study contains 1.2 mol% nitrogen. Because the Selexol solvent used for CO_2 removal is not selective for nitrogen removal, and because the pressure swing absorption process is extremely efficient

b. A process description and flowsheet for the conventional non-HTGR-integrated case can be found in TEV-953. Note that for Case 2, a ROT of 725°C (1,337°F) corresponds to the 750°C (1,382°F) ROT case from TEV-953 due to changing the assumption for temperature approach between the primary and secondary helium loops from 50°C (90°F) to 25°C (45°F).

at separating only hydrogen, the nitrogen present in the feedstock is partitioned almost exclusively to the fuelgas stream. As the ROT is increased, the fraction of fuelgas recycled to the reformer tubes also increases. In Case 6 where it is possible to recycle all of the fuelgas to the reformer tubes, there is no outlet in the system for nitrogen; hence, nitrogen will build up to unacceptable levels in the process. There are several options to alleviate this problem, the two most obvious being: (1) purge a small fraction of fuelgas solely for the purpose of controlling nitrogen buildup; and (2) include a small separation unit to remove nitrogen from the fuelgas. For this analysis, it was decided to add a small cryogenic separation unit to remove nitrogen from the fuelgas in Case 6. This option was selected over the purge option because it has the potential to maximize hydrogen production for a given natural gas feed rate. Hence, for Case 6 the flowsheet shown in Figure 1 was modified to eliminate the second reforming stage and to add a small cryogenic separation unit on the fuelgas stream. Details of the modified flowsheet for Case 6 can be found in Appendix A.

3. PROCESS MODELING RESULTS AND OBSERVATIONS

High-level material and energy balances from the modeling are presented in Figure 2 and detailed results are tabulated in Table 2. For the complete modeling results, see Appendix A. Aspen stream results for all cases are presented in electronic Appendixes B, C, D, E, F, and G. Analysis indicates that integrating nuclear heat into the SMR flowsheet and increasing the HTGR ROT significantly reduces natural gas consumption. By integrating nuclear heat at the lowest temperature considered [700°C (1,292°F) helium supply; 725°C (1,337°F) ROT], natural gas consumption can be reduced by 11.6% compared to the conventional process. If the helium supply temperature can be increased to 900°C (1,652°F) [925°C (1,697°F) ROT], a reduction of 30.9% can be realized compared to the conventional process. Natural gas consumption results for each case are shown graphically in Figure 3.

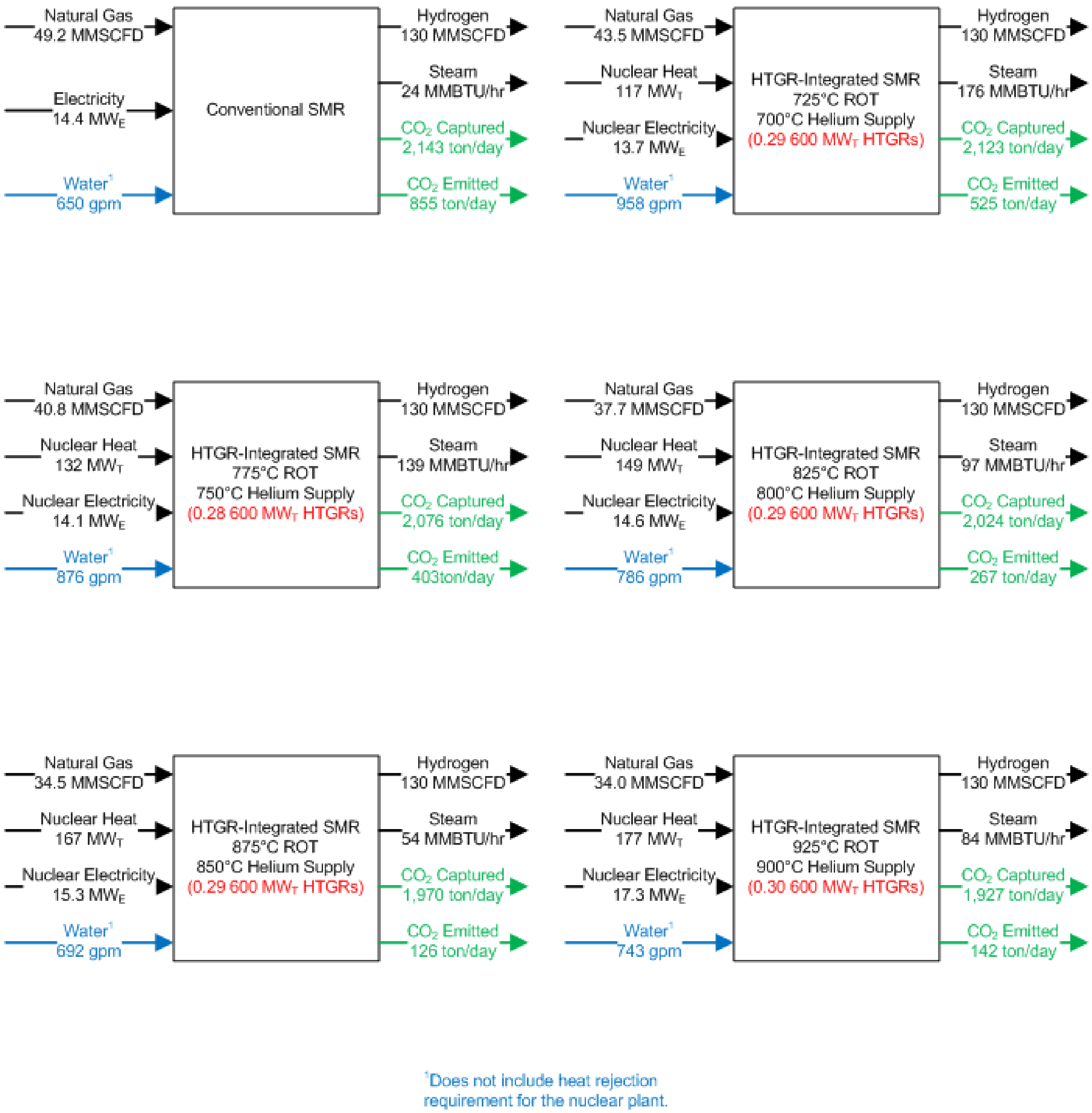


Figure 2. SMR hydrogen production temperature sensitivity modeling material balance results.

Table 2. SMR hydrogen production temperature sensitivity modeling results.

	Conventional	HTGR-Integrated (725°C ROT)	HTGR-Integrated (775°C ROT)	HTGR-Integrated (825°C ROT)	HTGR-Integrated (875°C ROT)	HTGR-Integrated (925°C ROT)
Inputs						
Natural Gas Feed Rate (MMSCFD)[1]	49.2	43.5	40.8	37.7	34.5	34.0
Outputs						
Hydrogen (MMSCFD)[1]	130	130	130	130	130	130
Steam Export (MMBtu/hr)	23.6	176.2	138.8	97.4	54.3	83.7
Performance Metrics						
H_2 Product/Natural Gas Feed (scf/scf)	2.64	2.99	3.19	3.45	3.77	3.82
Steam Export/H_2 Product (lb/lb)	0.80	5.94	4.68	3.28	1.83	2.82
Process Thermal Efficiency, HHV Basis (%)	77.8	80.1	80.7	81.5	82.2	82.5
Utility Usage						
Total Power (MW_e)	14.4	13.7	14.1	14.6	15.3	17.3
Natural Gas Reforming	3.3	2.0	2.7	3.6	4.7	1.2
Syngas Purification	2.3	2.3	2.3	2.3	2.3	2.1
Steam System	0.2	0.4	0.3	0.3	0.3	0.3
CO_2 Compression	7.1	7.0	6.9	6.7	6.5	6.4
Purge Recovery	n/a	n/a	n/a	n/a	n/a	5.7
Cooling Towers	0.1	0.1	0.1	0.1	0.1	0.1
Water Treatment	1.4	2.0	1.8	1.6	1.4	1.5
Total Water (gpm)[2]	650	958	876	786	692	743
Evaporation Rate (gpm)	341	348	350	353	355	354
CO_2 Emissions						
Captured (ton/day CO_2)	2,143	2,123	2,076	2,024	1,970	1,927
Emitted (ton/day CO_2)	855	525	403	267	126	142
Nuclear Integration Summary						
Electricity Demand (MW_e)	n/a	13.7	14.1	14.6	15.3	17.3
Process Heat Demand (MW_t)	n/a	116.9	132.2	149.1	166.6	176.8

Table 2. (continued).

	Conventional	HTGR-Integrated (725°C ROT)	HTGR-Integrated (775°C ROT)	HTGR-Integrated (825°C ROT)	HTGR-Integrated (875°C ROT)	HTGR-Integrated (925°C ROT)
Helium Flow Rate (kg/s)	n/a	83.62	79.78	79.21	79.42	78.49
Helium Supply Temperature (°C)	n/a	700	750	800	850	900
Helium Return Temperature (°C)	n/a	431	431	437	446	466
Integration Assessment						
Ideal Helium Return Temperature (°C)[3]	n/a	303	343	382	421	461
Excess Heat for Power Generation (MW_t)[4]	n/a	55.6	36.5	22.6	10.3	2.0
Power Generation Efficiency (%)[3]	n/a	38.4	38.4	38.7	39.0	39.7
Power Generation Capability (MW_e)[5]	n/a	21.4	14.0	8.7	4.0	0.8
Excess Power Generation Capability (MW_e)[6]	n/a	7.7	-0.1	-5.9	-11.3	-16.5
# 600 MW_t HTGRs Required (Heat + Power)	n/a	0.29	0.28	0.29	0.29	0.30
# 600 MW_t HTGRs Required (Heat Only)	n/a	0.19	0.22	0.25	0.28	0.29
# 600 MW_t HTGRs Required (Power Only)	n/a	0.09	0.06	0.04	0.02	0.00
Equivalent Reactor Size Required (MW_t)	n/a	172.5	168.7	171.7	176.9	178.8

1. Standard temperature of 60 degrees F.
2. Does not include heat rejection for the nuclear plant; does not include credit for export steam condensate return.
3. Interpolated from TEV-981.
4. Based on the calculated helium flowrate and the calculated and ideal helium return temperatures.
5. Based on the excess heat available and power generation efficiency.
6. A negative value indicates that a small amount of power would need to be imported from the grid, or the reactor size could be increased accordingly.

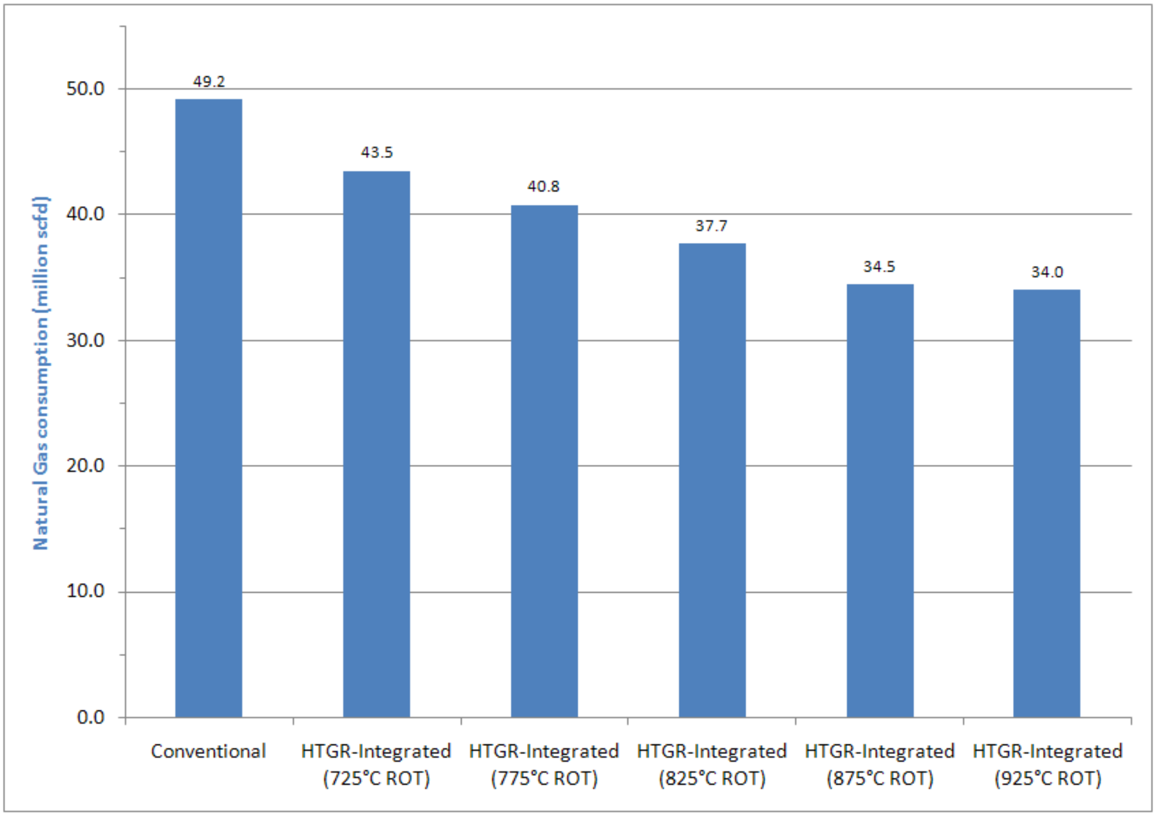


Figure 3. Natural gas consumption as a function of ROT.

As ROT is increased, the ratio of hydrogen product to natural gas feed increases significantly. Also, by shifting the required reforming duty from fuelgas combustion to nuclear heat, less combustion exhaust gas is generated. Because steam is raised to recover heat from the combustion exhaust gas, a decrease in fuelgas combustion leads to a corresponding decrease in the amount of steam generated and exported from the plant. These results are shown in Figure 4. The increase in hydrogen product yield going from an ROT of 875°C (1,607°F) to 925°C (1,697°F) is relatively small. In addition, steam export increases slightly between these cases. This result is due in part to the flowsheet modifications made for the 925°C (1,697°F) ROT case—complete removal of the fired reforming stage and inclusion of the cryogenic separation unit to remove nitrogen from the fuelgas prior to recycle to the reformer.

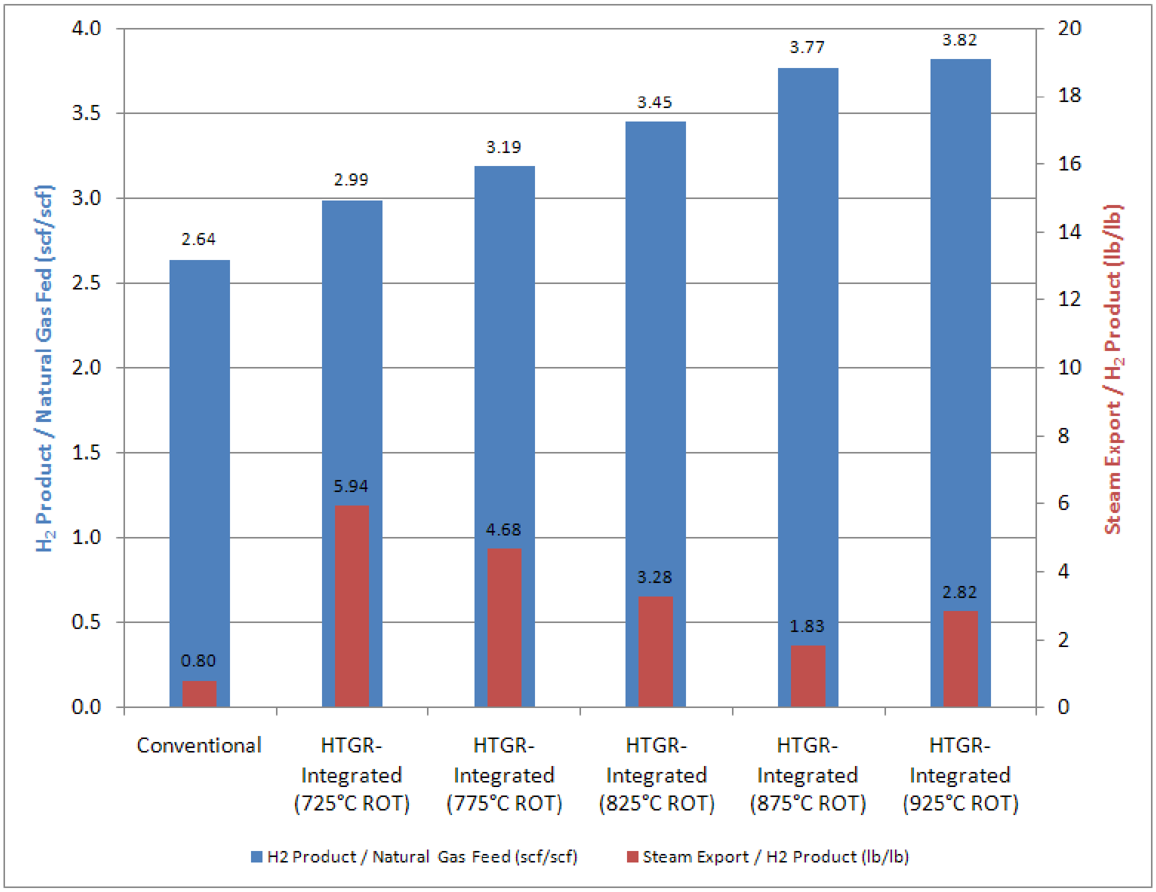


Figure 4. SMR H_2 product and steam export yields as a function of ROT.

Power consumption in the conventional SMR process is quite modest. Integrating nuclear heat with limited fuelgas recycle (i.e., ROT of 725°C) results in a small decrease in power consumption, primarily due to a reduction in the CO_2 compression power requirement. However, as ROT increases, fuelgas recycle compression requirements also increase, resulting in a small increase in power consumption.

As seen in Table 2, the trend for water consumption mirrors the trend for steam export from the plant. This is because the model does not make the assumption that condensate will be returned from exported steam; hence, an increase in export steam will result in additional water loss from the plant.

CO_2 emissions are also reduced as a result of integrating nuclear heat. As the ROT increases, a higher percentage of the fuelgas is recycled, leading to a decrease in CO_2 emissions. For an ROT of 725°C (1,337°F), CO_2 emissions are reduced by 39% compared to the conventional SMR case. For an ROT of 925°C (1,697°F), CO_2 emissions are reduced by an additional 73% from the 725°C (1,337°F) ROT case, representing a total CO_2 emissions reduction of 83% compared to the conventional SMR case. Due to the recycle of fuelgas, the amount of captured CO_2 also decreases slightly as ROT is increased. CO_2 disposition for each case is shown graphically in Figure 5.

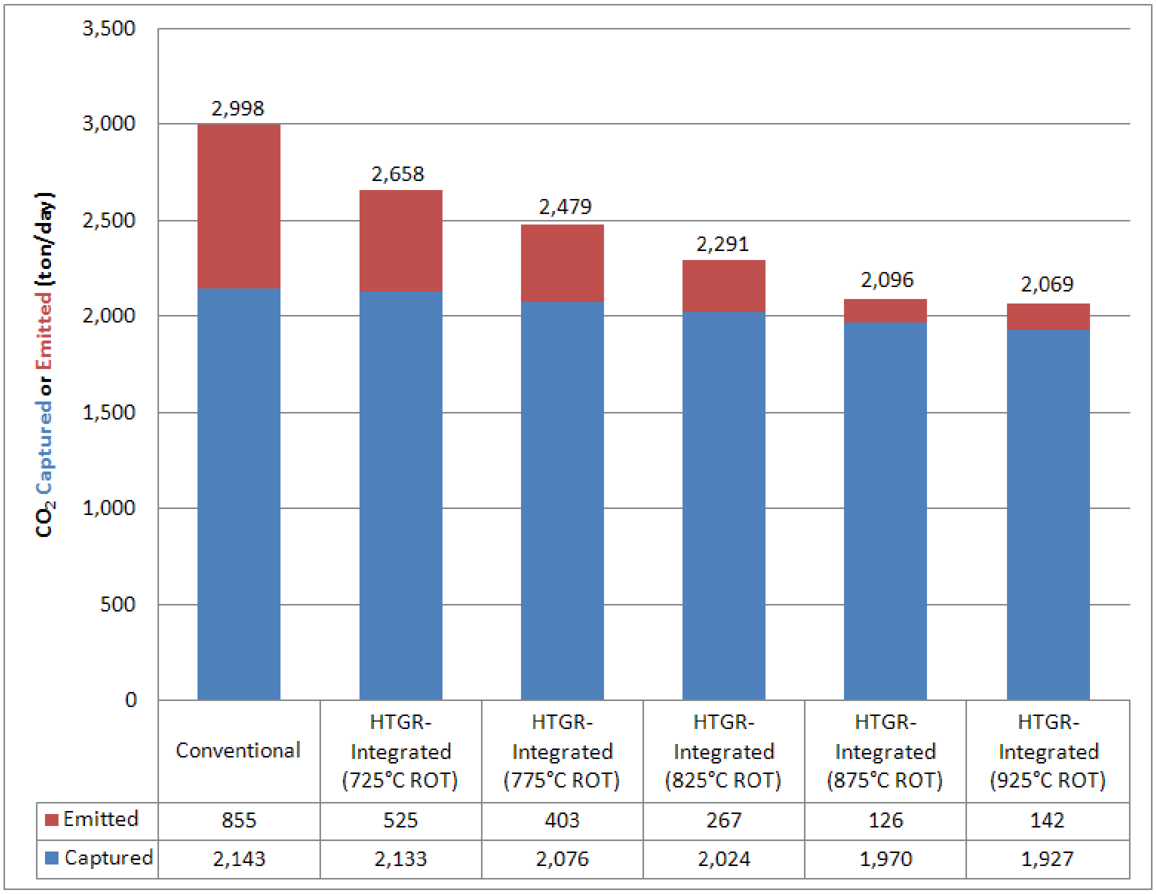


Figure 5. SMR CO_2 disposition as a function of ROT.

As the ROT increases, the difference between the helium return temperature and the optimal helium inlet temperature to the HTGR decreases. At an ROT of 725°C (1,337°F), the difference is 71°C (128°F), while an ROT of 925°C (1,697°F) produces a difference of only 3°C (5°F). Hence, the higher ROT is more compatible with a "heat-only" HTGR configuration. At lower ROTs, inserting a power cycle is the most likely scenario to utilize the excess heat returned from the reformer.

As the ROT increases from 725°C (1,337°F) to 925°C (1,697°F), the process heat demand increases from 117 MW_t to 177 MW_t. However, over this same range, the heat available for power generation decreases from 56 MW_t to 2 MW_t. Hence, the output required from the nuclear plant to support the SMR does not change appreciably as a result of increasing the ROT. In all cases, less than ⅓ of a 600 MW_t reactor would be sufficient to support a world-scale single-train hydrogen plant regardless of the ROT selected.

As the ROT increases from 725°C (1,337°F) to 925°C (1,697°F), the amount of excess heat available to generate power decreases. Above an ROT of 775°C, import of power from an external source would be required to support operation of the SMR (17 MW_e for the 925°C (1,697°F) ROT case). As an alternative, the capacity of the HTGR could be increased slightly to meet the power demand of the SMR. This is the likely scenario if the HTGR is built to support the needs of multiple industrial users.

Of all the HTGR-integrated cases considered, only the 925°C (1,697°F) ROT case completely eliminates the need for two reforming stages—nuclear heat alone is adequate in this case to provide the desired reforming temperature. This greatly simplifies the design of the reformer.

4. FUTURE WORK AND RECOMMENDATIONS

Several recommendations relating to HTGR-integrated SMR development were previously summarized in TEV-953. In addition to those recommendations, the following items are also recommended for future consideration:

- An economic analysis should be performed using the modeling results from this study as input. It is believed that such an analysis is required in order to further quantify the benefits offered by increasing the ROT from 725°C (1,337°F) to 925°C (1,697°F).

- If HTGR-integrated SMR technology is selected for further development, a more detailed model of the cryogenic separation unit should be developed for the 925°C (1,697°F) ROT case. The current model uses simplistic flash separators rather than multi-stage distillation columns, which significantly under-predicts the actual separation efficiency that could be achieved.

5. REFERENCES

Aspen Plus, Version 2006, Burlington, Massachusetts: Aspen Tech, 2006.

INL, 2010a, “HTGR-Integrated Hydrogen Production via Steam Methane Reforming (SMR) Process Analysis,” Idaho National Laboratory, TEV-953, Rev. 0.

INL, 2010b, “An Analysis of the Effect of Reactor Outlet Temperature of a High Temperature Reactor on Electric Power Generation, Hydrogen Production, and Process Heat,” Idaho National Laboratory, TEV-981, Rev. 0.

6. APPENDIXES

Appendix A, Detailed Modeling Results and Flowsheets

Appendix B, [Electronic] Case 1 – Conventional SMR Stream Results.xlsx

Appendix C, [Electronic] Case 2 – 725C ROT SMR Stream Results.xlsx

Appendix D, [Electronic] Case 3 – 775C ROT SMR Stream Results.xlsx

Appendix E, [Electronic] Case 4 – 825C ROT SMR Stream Results.xlsx

Appendix F, [Electronic] Case 5 – 875C ROT SMR Stream Results.xlsx

Appendix G, [Electronic] Case 6 – 925C ROT SMR Stream Results.xlsx

Appendix A
Detailed Modeling Results and Flowsheets

HTGR-Integrated SMR Temperature Sensitivity Case Summary

	Conventional	HTGR-Integrated (725°C ROT)	HTGR-Integrated (775°C ROT)	HTGR-Integrated (825°C ROT)	HTGR-Integrated (875°C ROT)	HTGR-Integrated (925°C ROT)
Inputs						
Natural Gas Feed Rate (MMSCFD)[1]	49.2	43.5	40.8	37.7	34.5	34.0
Outputs						
Hydrogen (MMSCFD)[1]	130	130	130	130	130	130
Steam Export (MMBtu/hr)	23.6	176.2	138.8	97.4	54.3	83.7
Performance Metrics						
H_2 Product / Natural Gas Feed (scf/scf)	2.64	2.99	3.19	3.45	3.77	3.82
Steam Export / H_2 Product (lb/lb)	0.80	5.94	4.68	3.28	1.83	2.82
Process Thermal Efficiency, HHV Basis (%)	77.8	80.1	80.7	81.5	82.2	82.5
Utility Usage						
Total Power (MW_e)	14.4	13.7	14.1	14.6	15.3	17.3
Natural Gas Reforming	3.3	2.0	2.7	3.6	4.7	1.2
Syngas Purification	2.3	2.3	2.3	2.3	2.3	2.1
Steam System	0.2	0.4	0.3	0.3	0.3	0.3
CO_2 Compression	7.1	7.0	6.9	6.7	6.5	6.4
Purge Recovery	n/a	n/a	n/a	n/a	n/a	5.7
Cooling Towers	0.1	0.1	0.1	0.1	0.1	0.1
Water Treatment	1.4	2.0	1.8	1.6	1.4	1.5
Total Water (gpm)[2]	650	958	876	786	692	743
Evaporation Rate (gpm)	341	348	350	353	355	354
CO_2 Emissions						
Captured (ton/day CO_2)	2,143	2,123	2,076	2,024	1,970	1,927
Emitted (ton/day CO_2)	855	525	403	267	126	142
Nuclear Integration Summary						
Electricity Demand (MW_e)	n/a	13.7	14.1	14.6	15.3	17.3
Process Heat Demand (MW_t)	n/a	116.9	132.2	149.1	166.6	176.8
Helium Flow Rate (kg/s)	n/a	83.62	79.78	79.21	79.42	78.49
Helium Supply Temperature (°C)	n/a	700	750	800	850	900
Helium Return Temperature (°C)	n/a	431	431	437	446	466
Integration Assessment						
Ideal Helium Return Temperature (°C)[3]	n/a	303	343	382	421	461
Excess Heat for Power Generation (MW_t)[4]	n/a	55.6	36.5	22.6	10.3	2.0
Power Generation Efficiency (%)[3]	n/a	38.4	38.4	38.7	39.0	39.7
Power Generation Capability (MW_e)[5]	n/a	21.4	14.0	8.7	4.0	0.8
Excess Power Generation Capability (MW_e)[6]	n/a	7.7	-0.1	-5.9	-11.3	-16.5
# 600 MW_T HTGRs Required (Heat + Power)	n/a	0.29	0.28	0.29	0.29	0.30
# 600 MW_T HTGRs Required (Heat Only)	n/a	0.19	0.22	0.25	0.28	0.29
# 600 MW_T HTGRs Required (Power Only)	n/a	0.09	0.06	0.04	0.02	0.00
Equivalent Reactor Size Required (MW_t)	n/a	172.5	168.7	171.7	176.9	178.8

[1] Standard temperature of 60 degrees F.

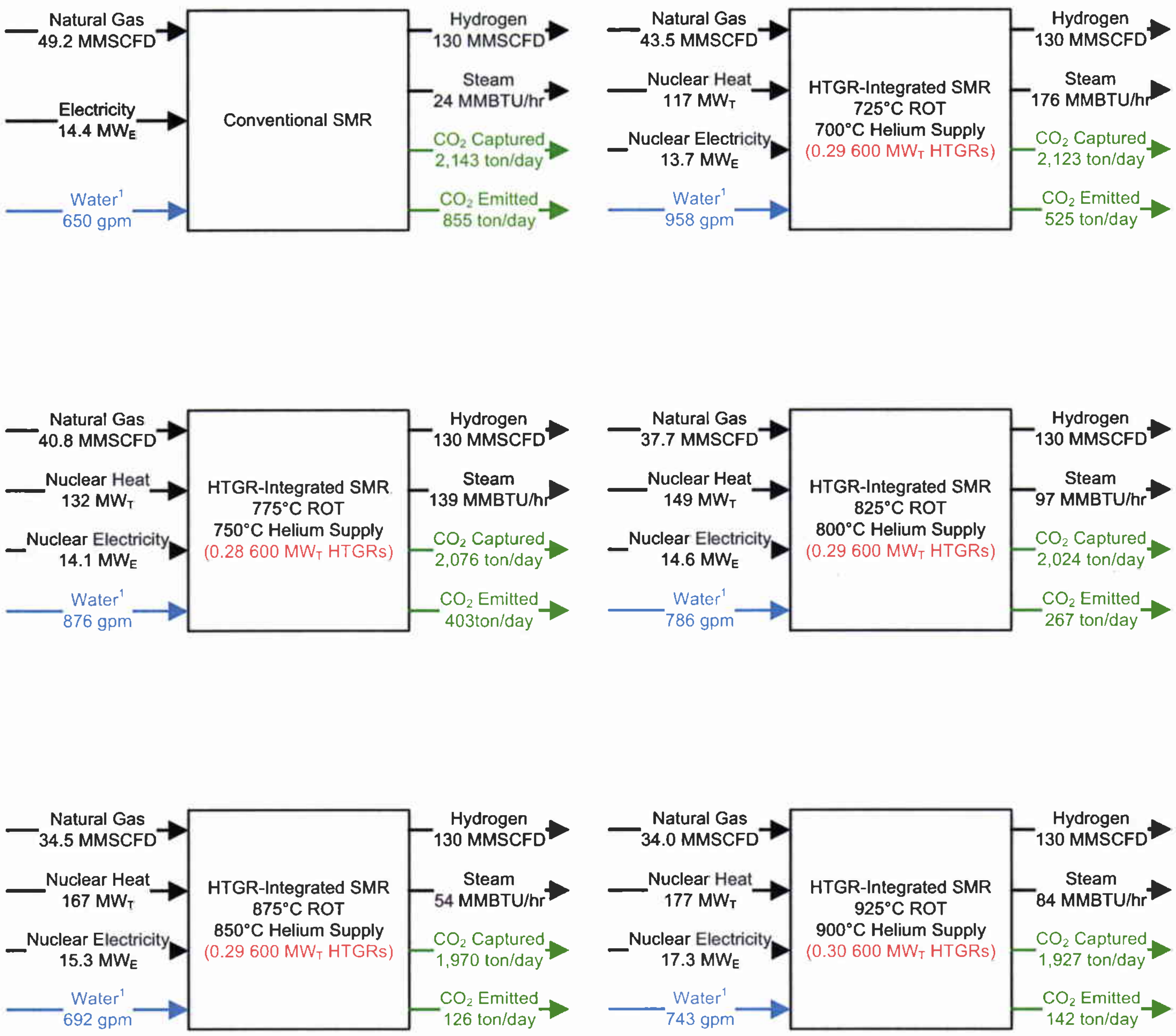
[2] Does not include heat rejection for the nuclear plant; does not include credit for export steam condensate return.

[3] Interpolated from TEV-981.

[4] Based on the calculated helium flowrate and the calculated and ideal helium return temperatures

[5] Based on the excess heat available and power generation efficiency.

[6] A negative value indicates that a small amount of power would need to be imported from the grid, or the reactor size could be increased accordingly.

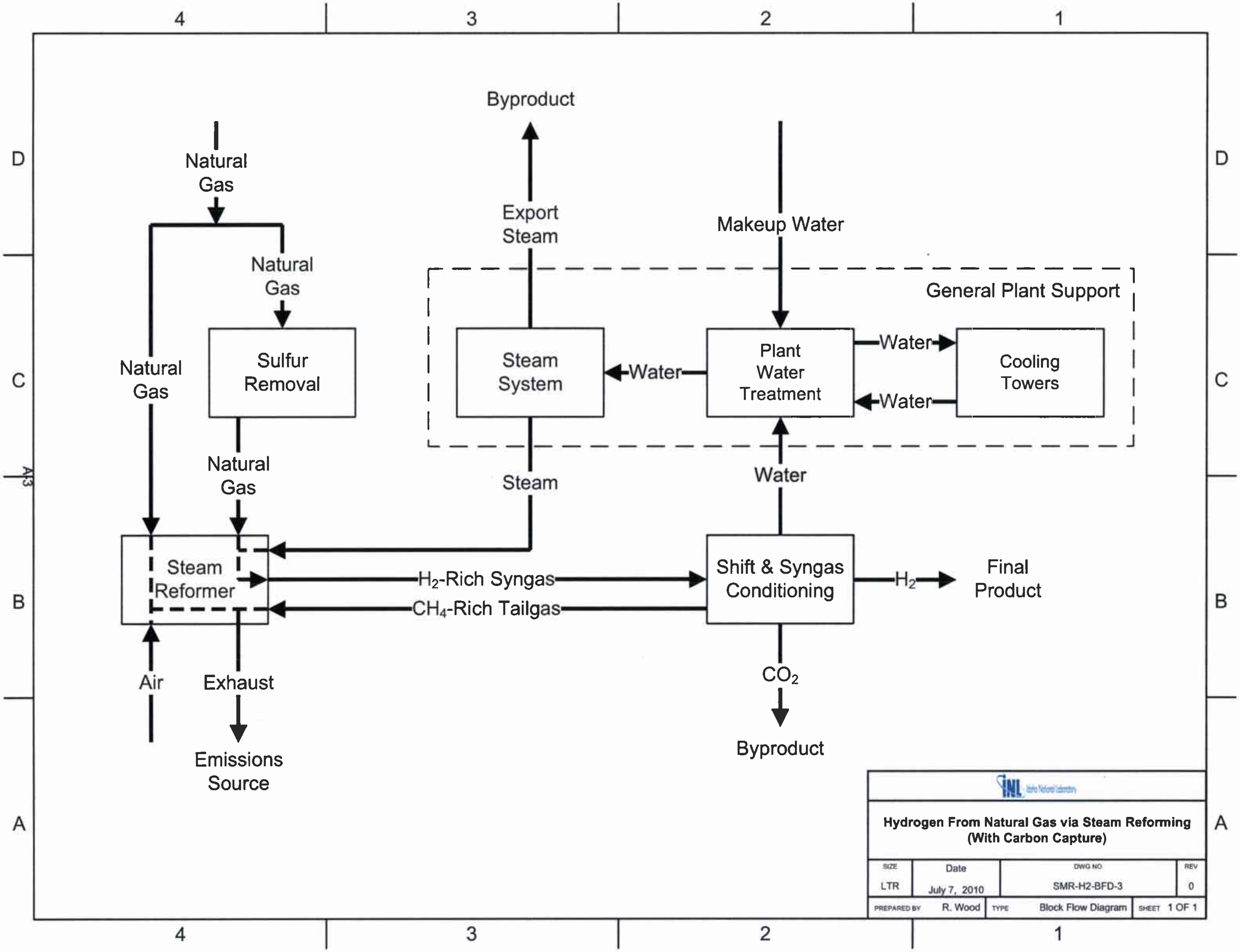


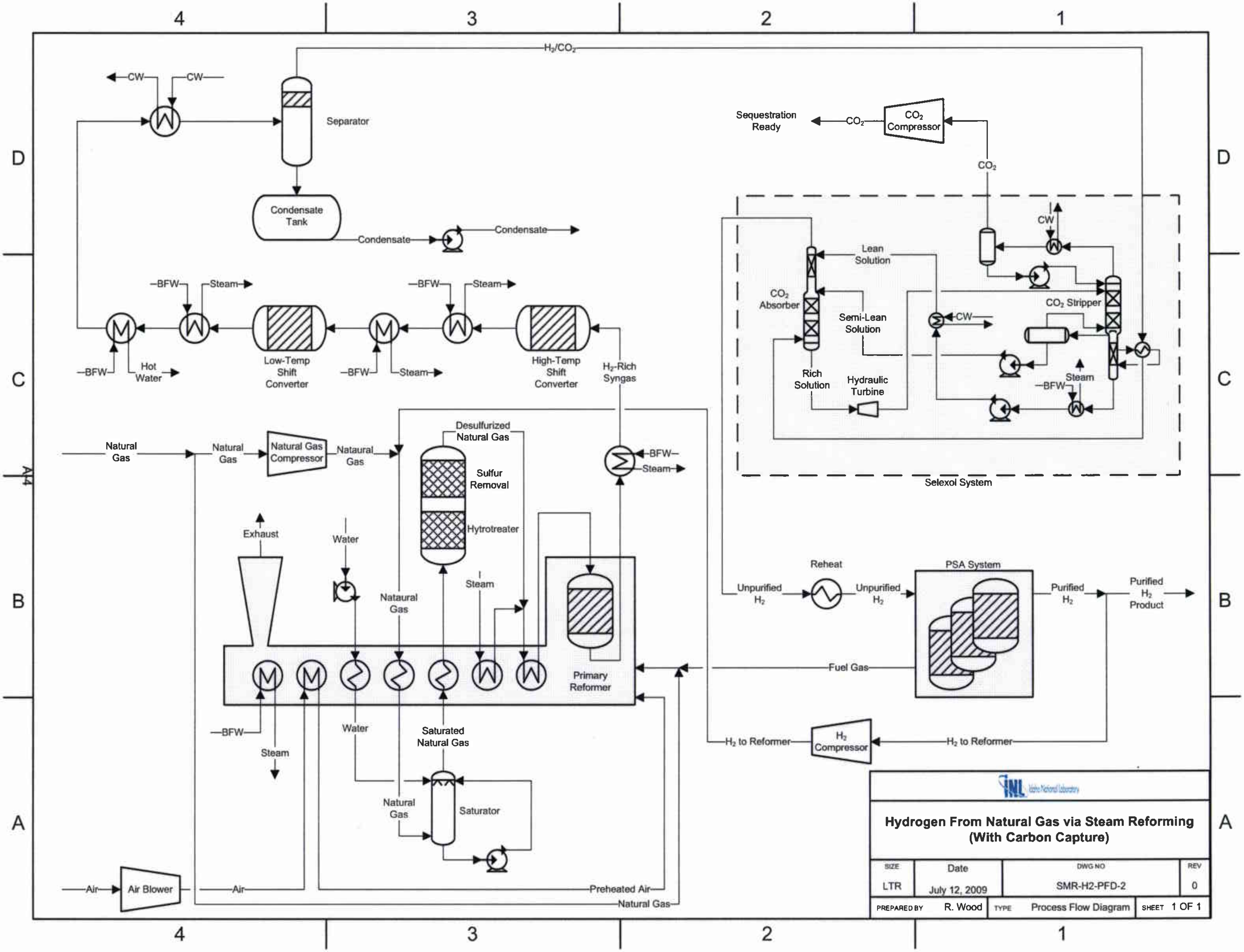
[1]Does not include heat rejection requirement for the nuclear plant.

SMR Hydrogen Production Modeling
Temperature Sensitivity Results

SIZE	Date	DWG NO	REV
LTR	July 22, 2010	SMR-TS-SUM-1	0

PREPARED BY R. Wood | TYPE Summary Diagram | SHEET 1 OF 1


Byproduct
Natural Gas
Export Steam
Makeup Water
Natural Gas
General Plant Support
Natural Gas
Sulfur Removal
Steam System
Water
Plant Water Treatment
Water
Water
Cooling Towers
Natural Gas
Steam
Water
Steam Reformer
H_2-Rich Syngas
CH_4-Rich Tailgas
Shift & Syngas Conditioning
H_2
Final Product
Air
Exhaust
CO_2
Emissions Source
Byproduct
INL Idaho National Laboratory
Hydrogen From Natural Gas via Steam Reforming (With Carbon Capture)
SIZE LTR
Date July 7, 2010
DWG NO SMR-H2-BFD-3
REV 0
PREPARED BY R. Wood
TYPE Block Flow Diagram
SHEET 1 OF 1



H2/CO2
CW
CW
Separator
Condensate Tank
Condensate
Condensate
Sequestration Ready
CO2
CO2 Compressor
CO2
CW
Lean Solution
CO2 Absorber
Semi-Lean Solution
CW
CO2 Stripper
Rich Solution
Hydraulic Turbine
Steam
BFW
Selexol System
BFW
Steam
BFW
Hot Water
Low-Temp Shift Converter
BFW
Steam
BFW
Steam
High-Temp Shift Converter
H2-Rich Syngas
BFW
Steam
Natural Gas
Natural Gas
Natural Gas Compressor
Nataural Gas
Desulfurized Natural Gas
Sulfur Removal
Hytrotreater
Exhaust
Water
Nataural Gas
Steam
Primary Reformer
BFW
Steam
Water
Saturated Natural Gas
Natural Gas
Saturator
Air
Air Blower
Air
Preheated Air
Natural Gas
Reheat
Unpurified H2
Unpurified H2
PSA System
Purified H2
Purified H2 Product
Fuel Gas
H2 to Reformer
H2 Compressor
H2 to Reformer
Hydrogen From Natural Gas via Steam Reforming (With Carbon Capture)
SIZE
LTR
Date
July 12, 2009
DWG NO
SMR-H2-PFD-2
REV
0
PREPARED BY
R. Wood
TYPE
Process Flow Diagram
SHEET
1 OF 1

Case 1 - Conventional SMR

Calculator Block SUMMARY

FEED SUMMARY:

NATURAL GAS PROPERTIES:

MASS FLOW =	1115. TON/DY
VOLUME FLOW =	49.2 MMSCFD @ 60°F
HHV =	23063. BTU/LB
HHV =	1044. BTU/SCF @ 60°F
ENERGY FLOW =	51411. MMBTU/DY

COMPOSITION:

METHANE =	93.571 MOL.%
ETHANE =	3.749 MOL.%
PROPANE =	0.920 MOL.%
BUTANE =	0.260 MOL.%
PENTANE =	0.040 MOL.%
HEXANE =	0.010 MOL.%
NITROGEN =	1.190 MOL.%
OXYGEN =	0.010 MOL.%
CO2 =	0.250 MOL.%
C4H10S =	1. PPMV
C2H6S =	0. PPMV
H2S =	0. PPMV

INTERMEDIATE PRODUCT SUMMARY:

RAW SYNGAS MASS FLOW =	364878. LB/HR
RAW SYNGAS VOLUME FLOW =	263. MMSCFD @ 60°F
RAW SYNGAS COMPOSITION:	
H2	47.7 MOL.%
CO	9.2 MOL.%
CO2	5.3 MOL.%
N2	0.2 MOL.%
H2O	34.2 MOL.%
CH4	3.5 MOL.%

FINAL PRODUCT SUMMARY:

HYDROGEN MASS FLOW =	29000. LB/HR
HYDROGEN VOLUME FLOW =	130. MMSCFD @ 60°F
HYDROGEN COMPOSITION:	
H2	99.9 MOL.%
N2	0.0 MOL.%
CH4	0.1 MOL.%
CO	11. PPMV
CO2	3. PPMV
H2O	0. PPMV

EXPORT HP STEAM FLOW =	23097. LB/HR
EXPORT HP STEAM CREDIT =	23.6 MMBTU/HR
STEAM PRESSURE =	615. PSIA
STEAM TEMPERATURE =	489. DEG. F
STEAM ENTHALPY (FOR CREDIT) =	1023. BTU/LB

CONDENSED TO LIQUID AT 1 ATM AT BOILING POINT

CARBON DIOXIDE MASS FLOW =	178876. LB/HR
CARBON DIOXIDE VOLUME FLOW =	37. MMSCFD @ 60°F
CARBON DIOXIDE COMPOSITION:	
CO2	99.1 MOL.%
H2	0.6 MOL.%
N2	0. PPMV
CH4	2458. PPMV

CO	187. PPMV
H2O	221. PPMV

POWER SUMMARY:

ELECTRICAL CONSUMERS:	
NG REFORMER POWER CONSUMPTION =	3.3 MW
GAS CLEANING POWER CONSUMPTION =	2.3 MW
STEAM SYSTEM POWER CONSUMPTION =	0.2 MW
CO2 COMPRESSION POWER CONSUMPTION =	7.1 MW
COOLING TOWER POWER CONSUMPTION =	0.1 MW
WATER TREATMENT POWER CONSUMPTION =	1.4 MW
CONSUMER SUBTOTAL =	14.4 MW
NET PLANT POWER CONSUMPTION =	14.4 MW

WATER BALANCE:

EVAPORATIVE LOSSES:	
COOLING TOWER EVAPORATION =	238.3 GPM
ZLD SYSTEM EVAPORATION =	102.8 GPM
TOTAL EVAPORATIVE LOSSES =	341.1 GPM
WATER CONSUMED:	
BOILER FEED WATER MAKEUP =	582.5 GPM
COOLING TOWER MAKEUP =	250.9 GPM
TOTAL WATER CONSUMED =	833.5 GPM
WATER GENERATED:	
GAS CLEANING CONDENSATE =	237.2 GPM
COOLING TOWER BLOWDOWN =	49.3 GPM
TOTAL WATER GENERATED =	286.5 GPM
PLANT WATER SUMMARY:	
NET MAKEUP WATER REQUIRED =	649.7 GPM
WATER CONSUMED / NG FED =	3.50 LB/LB

CO2 BALANCE:

CO2 EMITTED (TOTAL) =	855. TON/DY
CO2 EMITTED (TOTAL) =	15. MMSCFD @ 60°F
SEQUESTRATION READY CO2 =	2143. TON/DY
SEQUESTRATION READY CO2 =	37. MMSCFD @ 60°F
CO2 EMITTED / NG FED =	0.77 LB/LB

EFFICIENCY CALCULATIONS:

OVERALL PROCESS THERMAL EFFICIENCY:

ASSUMPTIONS:

(1) FOR STEAM EXPORT - HEAT RECOVERY CREDIT ASSUMES SATURATED LIQUID AT ATMOSPHERIC PRESSURE

(2) FOR ELECTRICITY IMPORT - ELECTRICAL GENERATION EFFICIENCY OF 33%

HHV BASIS =	77.8%
LHV BASIS =	72.6%

OVERALL PROCESS COLD GAS EFFICIENCY:

```
                    Case 1 - Conventional SMR
      (INCLUDES ONLY NATURAL GAS FEED AND HYDROGEN PRODUCT)

      HHV BASIS =                              82.1%
      LHV BASIS =                              76.9%

    OTHER PERFORMANCE METRICS:

      HYDROGEN PRODUCT TO NATURAL GAS FEED = 2.64 SCF/SCF
      (SHOULD BE AROUND 2.5)

      STEAM EXPORT TO HYDROGEN PRODUCT =      0.80 TON/TON
      (SHOULD BE BETWEEN 5 AND 18)


Calculator Block AIRPROPS

   HUMIDITY DATA FOR STREAM PRI-AIR:
     HUMIDITY RATIO =                          43.5 GRAINS/LB
     RELATIVE HUMIDITY =                       39.0 %


Calculator Block NG-RFMR  Hierarchy: REFORMER

   SULFUR REMOVAL CONDITIONS:

     INLET BED TEMPERATURE =                 734. °F

   PRIMARY REFORMER CONDITIONS:

     INLET TEMPERATURE =                    1292. °F
     STEAM TO CARBON MOLAR RATIO =             3.00
     NATURAL GAS BURNED FOR HEAT =             9.02 %
     OUTLET TEMPERATURE =                   1600. °F
     METHANE CONVERSION =                     78.1 %


Calculator Block GASCLEAN Hierarchy: GAS-CLN

   WATER GAS SHIFT CONDITIONS:

     HIGH-TEMPERATURE SHIFT REACTOR:

       INLET TEMPERATURE =                   635. °F
         (MINIMUM ALLOWABLE = 600°F)

       INLET STEAM:DRY GAS RATIO =             0.52
         (MINIMUM ALLOWABLE = 0.4)

       OUTLET TEMPERATURE =                  769. °F

       OUTLET CO (DRY BASIS) =                 3.23 MOL.%

     LOW-TEMPERATURE SHIFT REACTOR:

       INLET DEW TEMPERATURE =               332. °F

       INLET TEMPERATURE =                   375. °F
         (SHOULD BE AT LEAST 375°F)
         (SHOULD BE AT LEAST 27°F ABOVE DEW TEMPERATURE)

       INLET STEAM:DRY GAS RATIO =             0.38
         (MINIMUM ALLOWABLE = 0.3)

       OUTLET TEMPERATURE =                  418. °F
```

Case 1 - Conventional SMR

OUTLET CO (DRY BASIS) =	0.35 MOL.%

SELEXOL PERFORMANCE:

INLET CO2 CONCENTRATION =	18.9 %
OUTLET CO2 CONCENTRATION =	0.2 %
CO2 CAPTURE =	99.0 %
CO2 PURITY =	99.1 %
SELEXOL UTILITY REQUIREMENTS:	
ELECTRICITY USAGE =	2.3 MW
STEAM USAGE =	72959. LB/HR

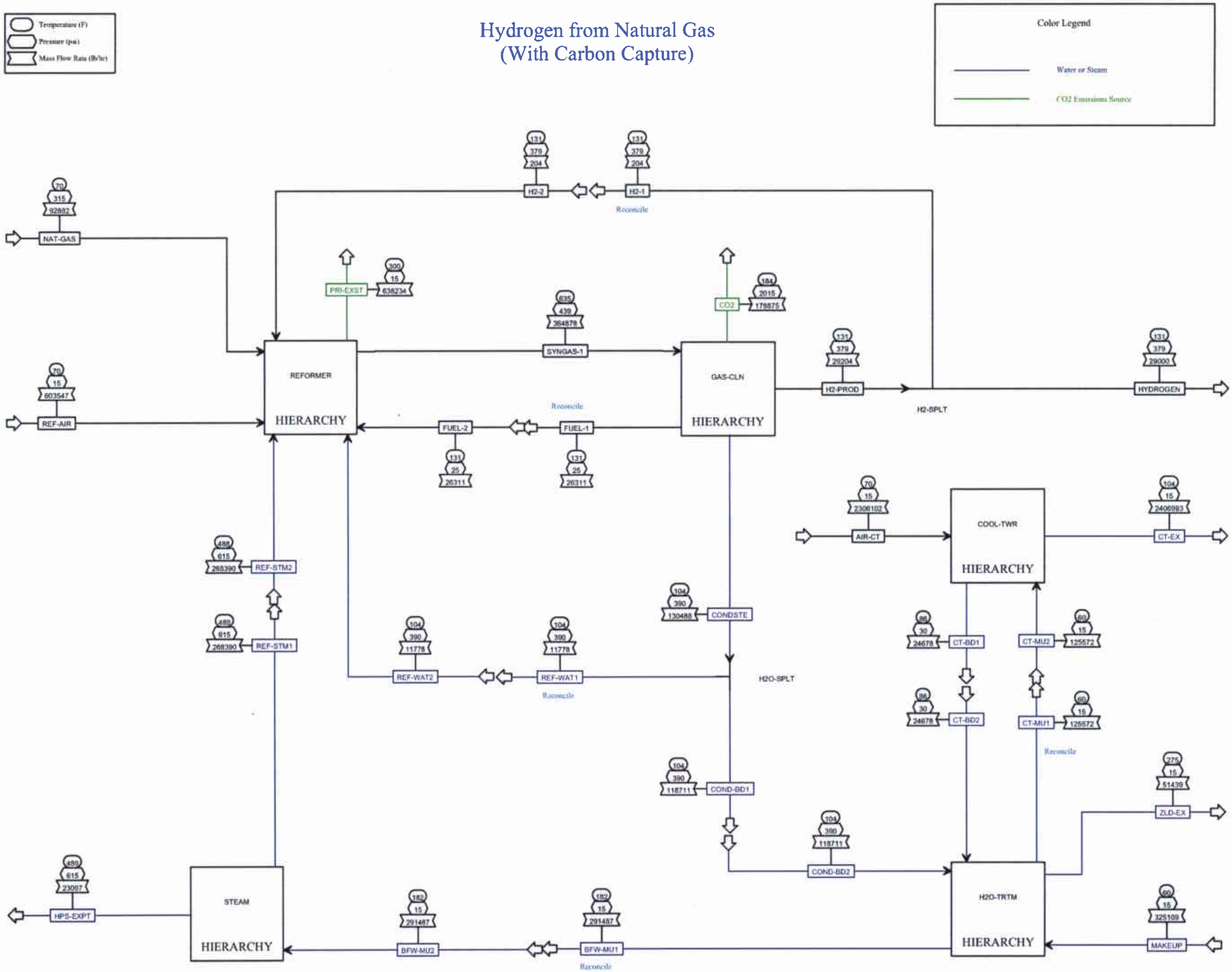
CO2 COMPRESSION:

PRESSURE =	2015. PSIA
ELECTRICITY USAGE =	7.1 MW

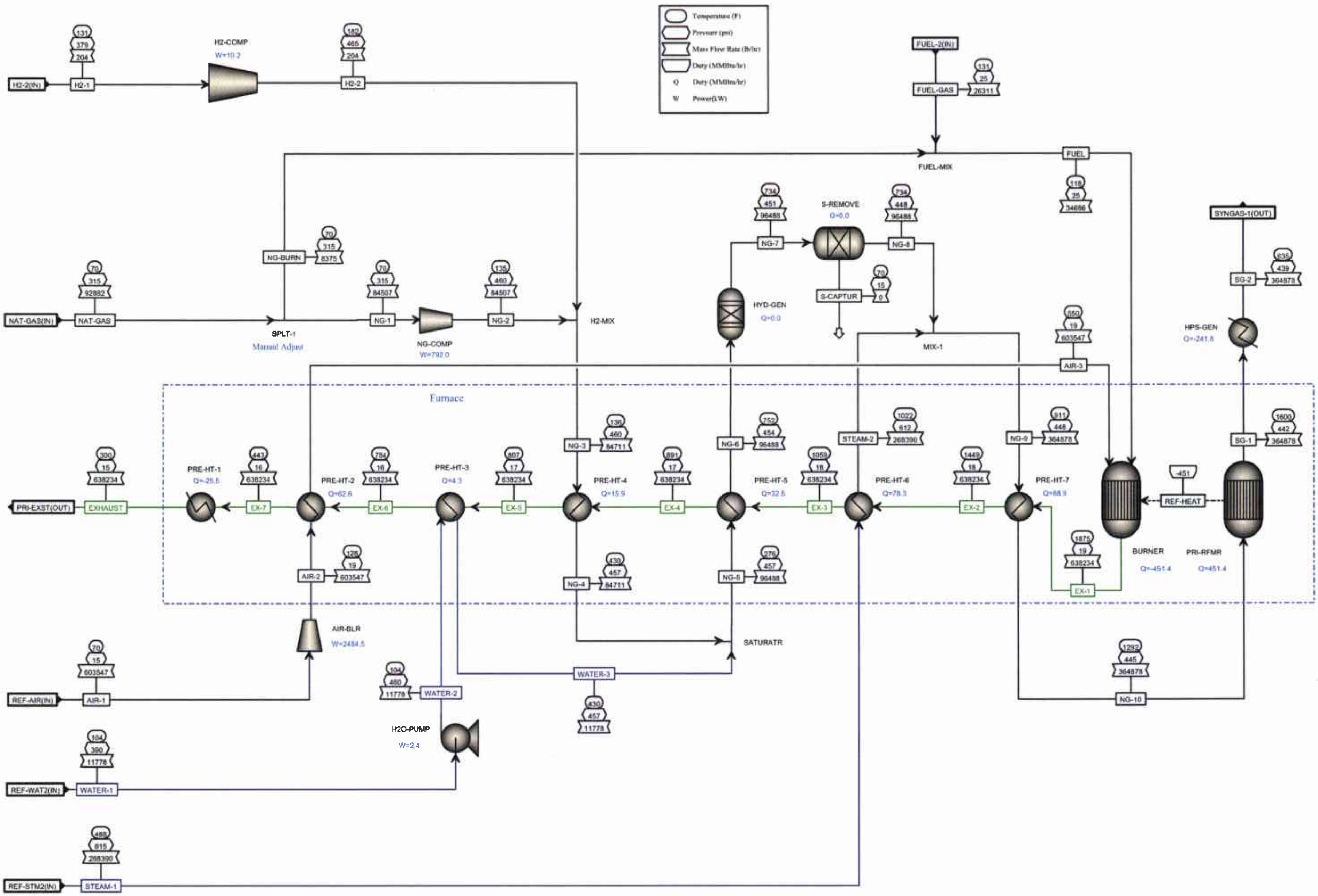
PSA PERFORMANCE:

HYDROGEN RECOVERY =	88.0 %
HYDROGEN PURITY =	99.90 %

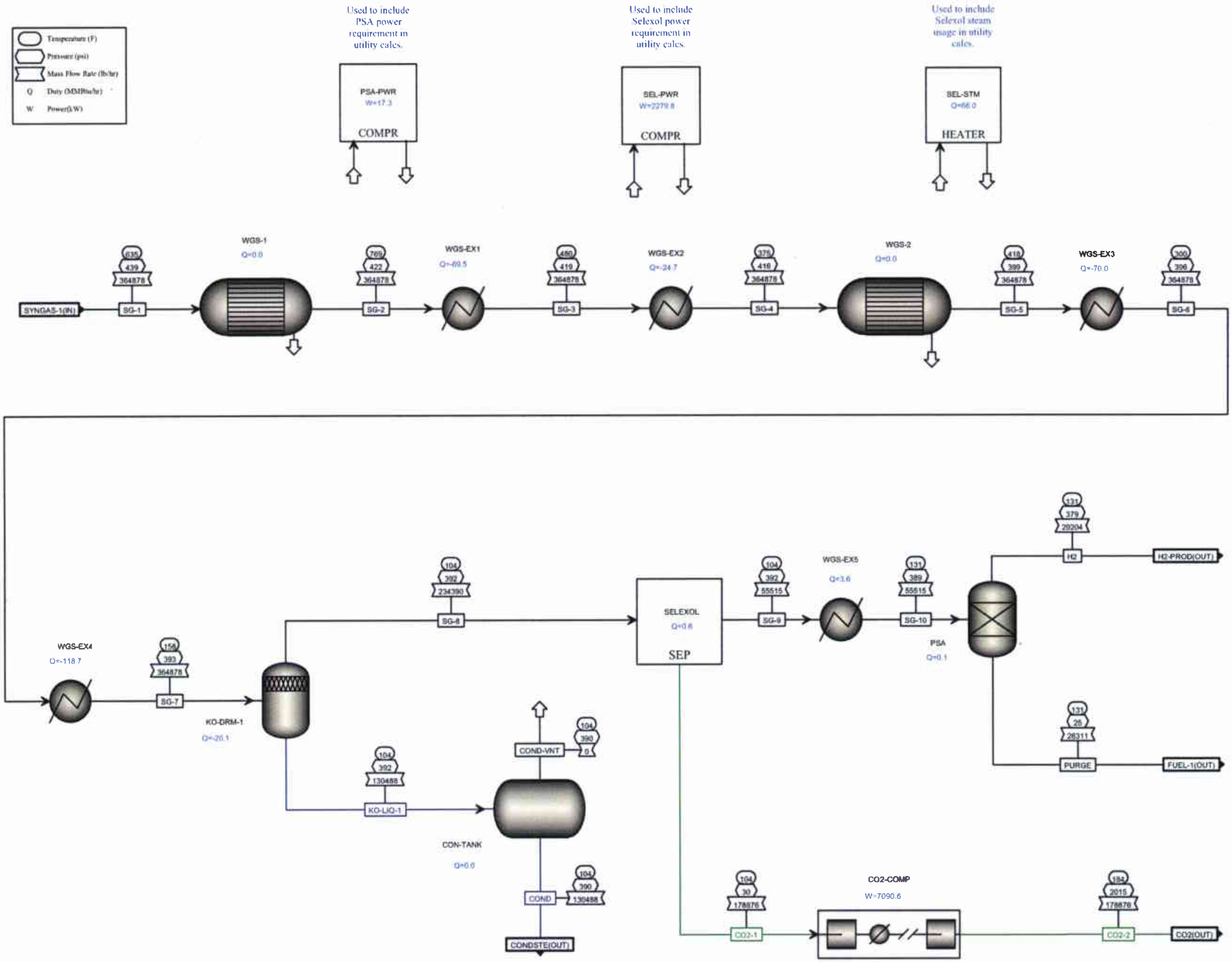
Hydrogen from Natural Gas (With Carbon Capture)



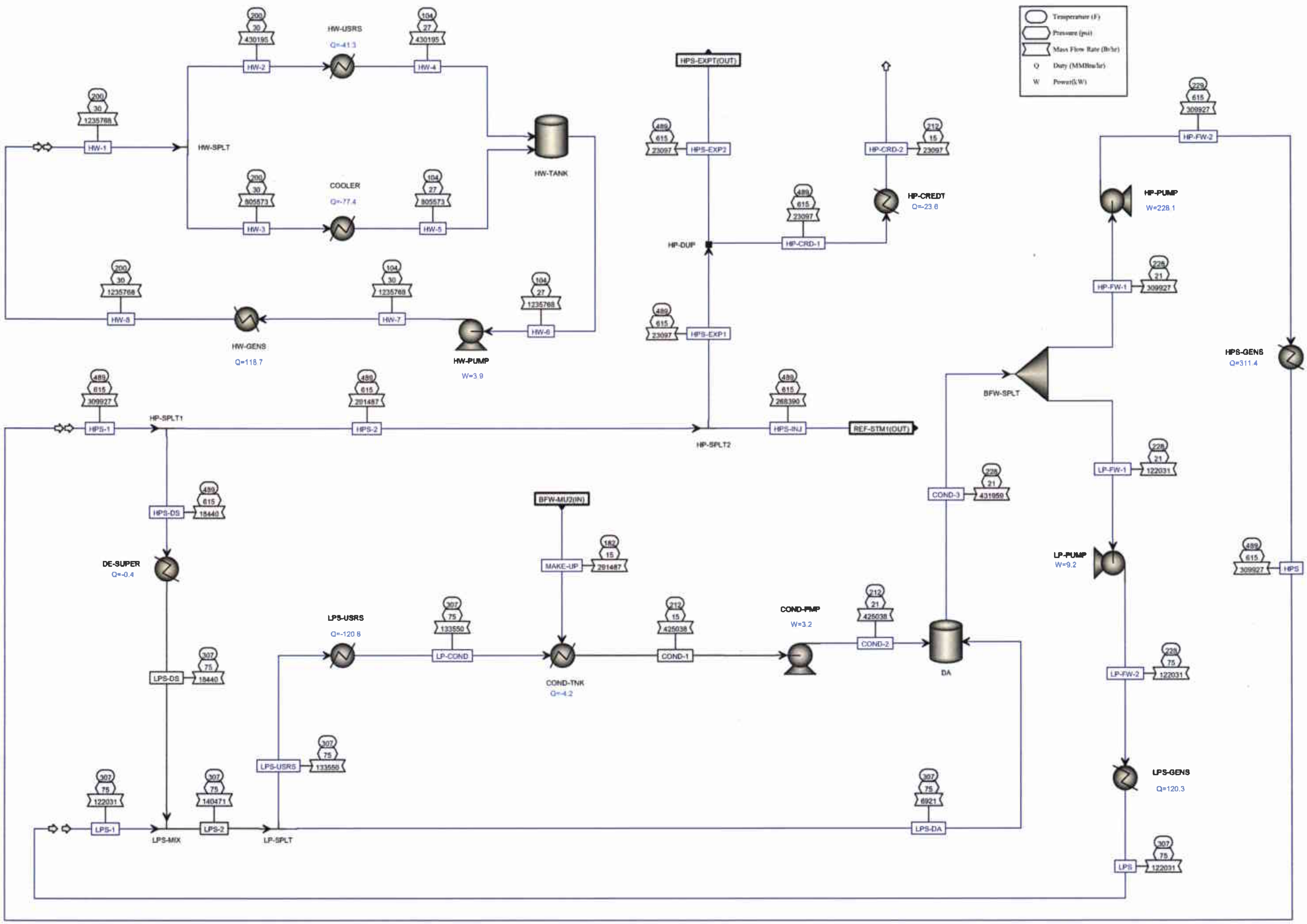
Natural Gas Steam Reforming



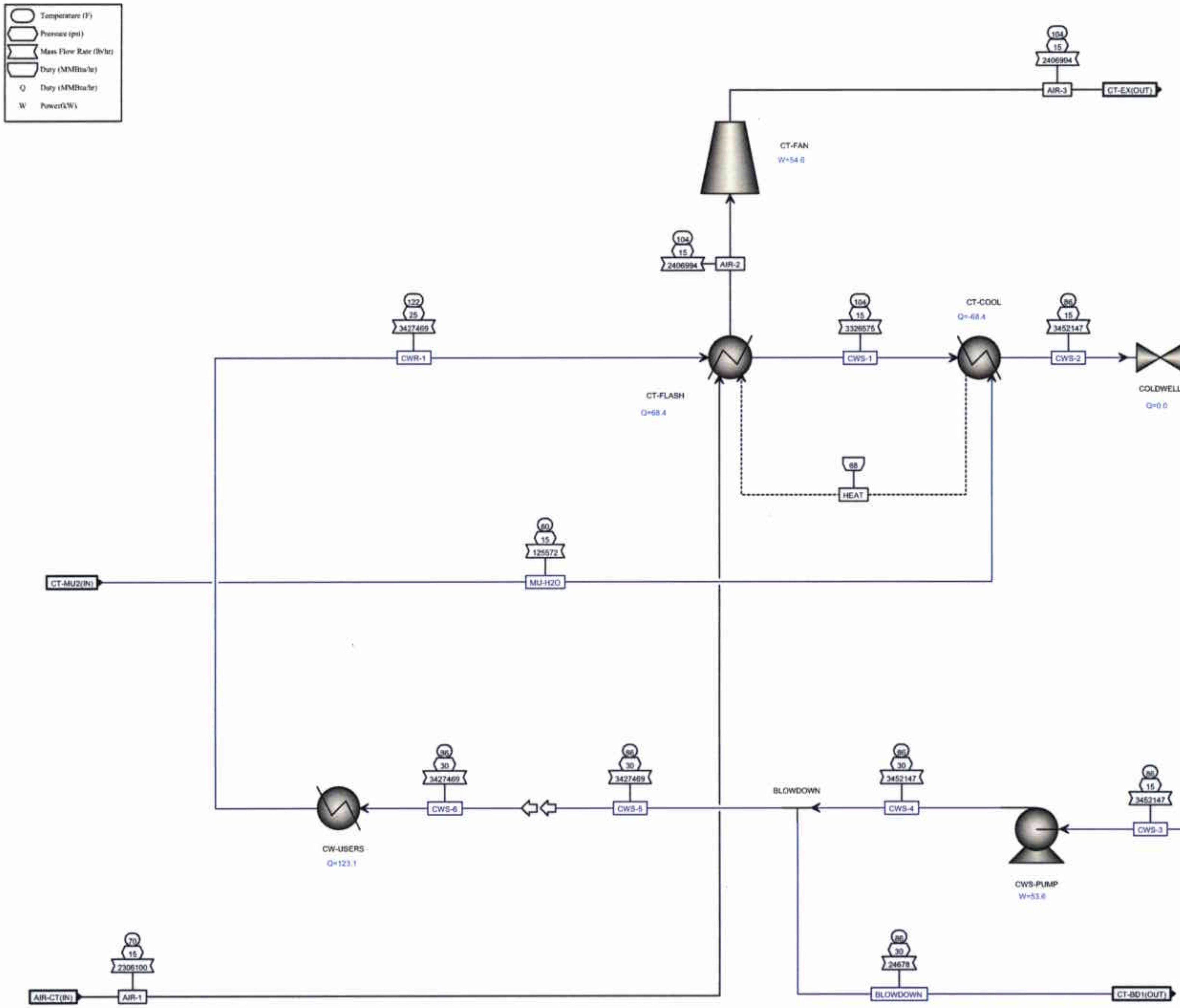
Syngas Cleaning & Conditioning



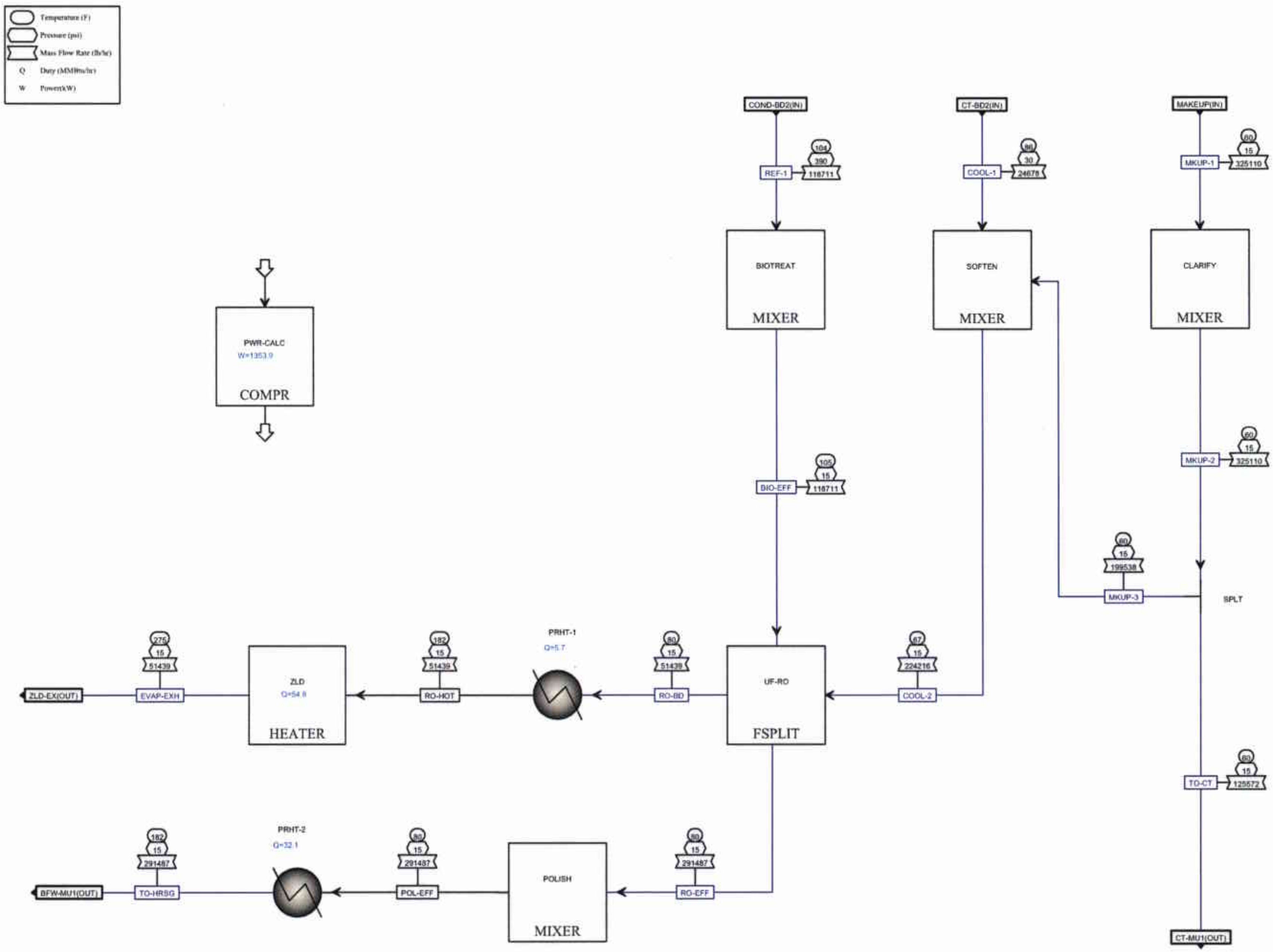
Steam System

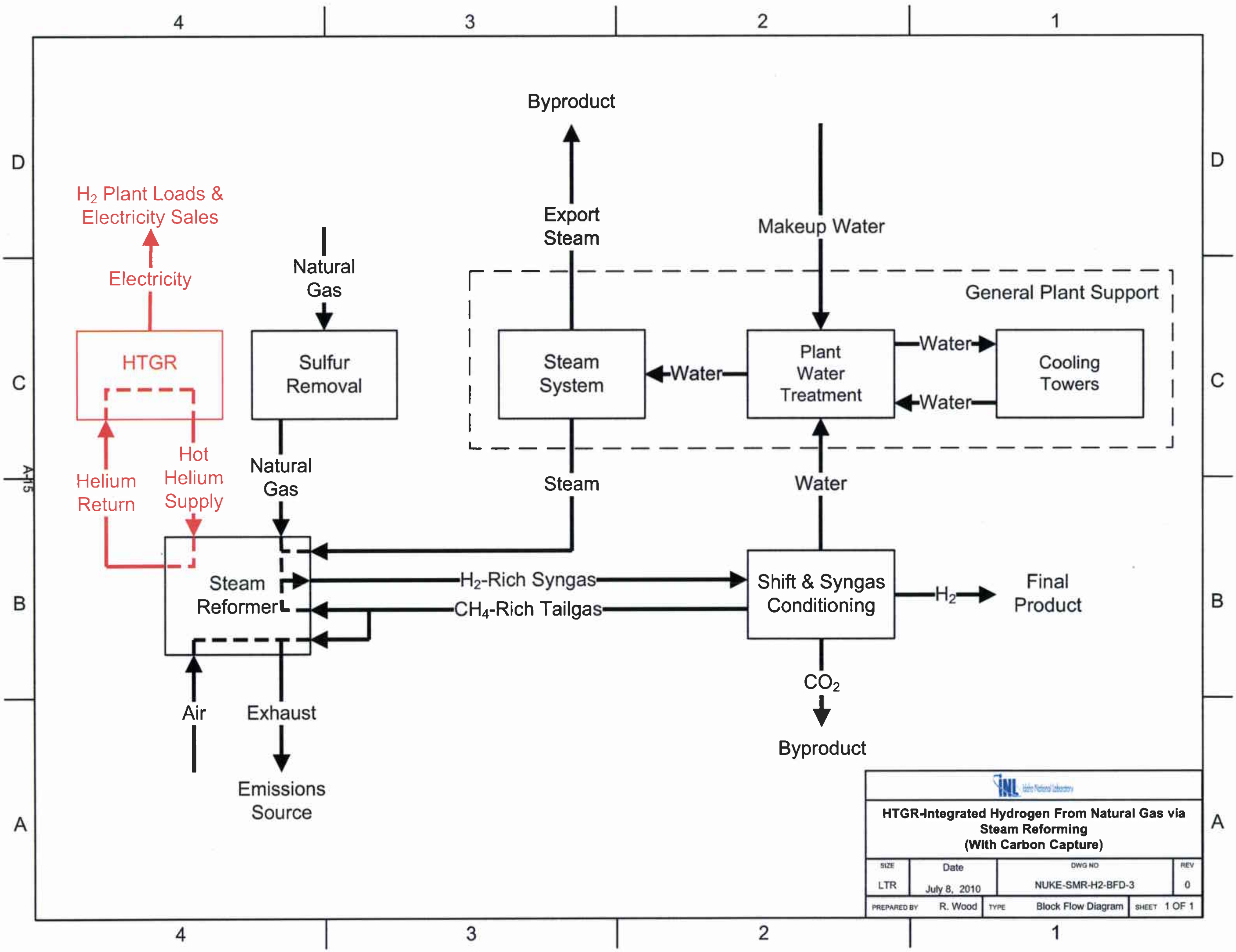


Cooling Tower

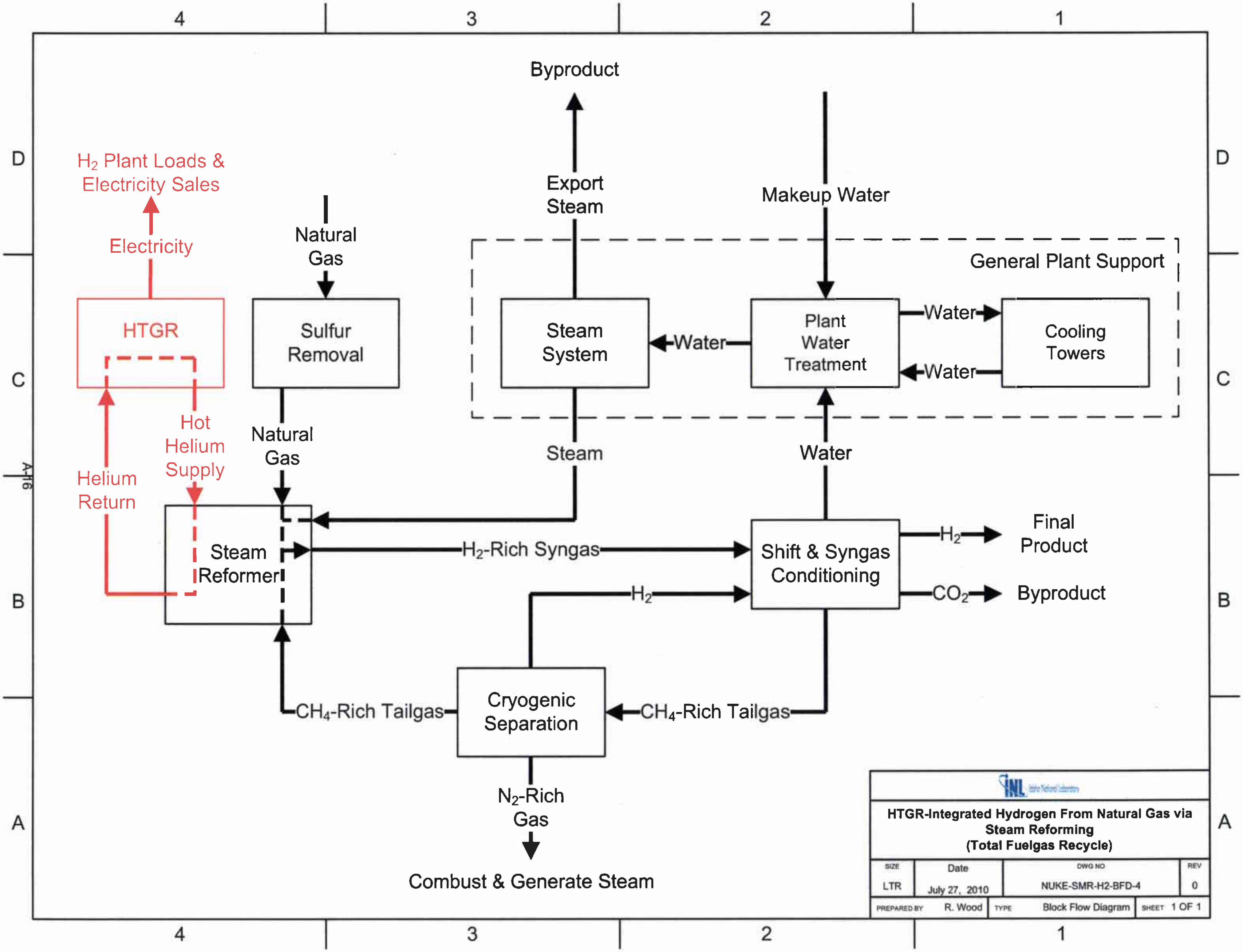


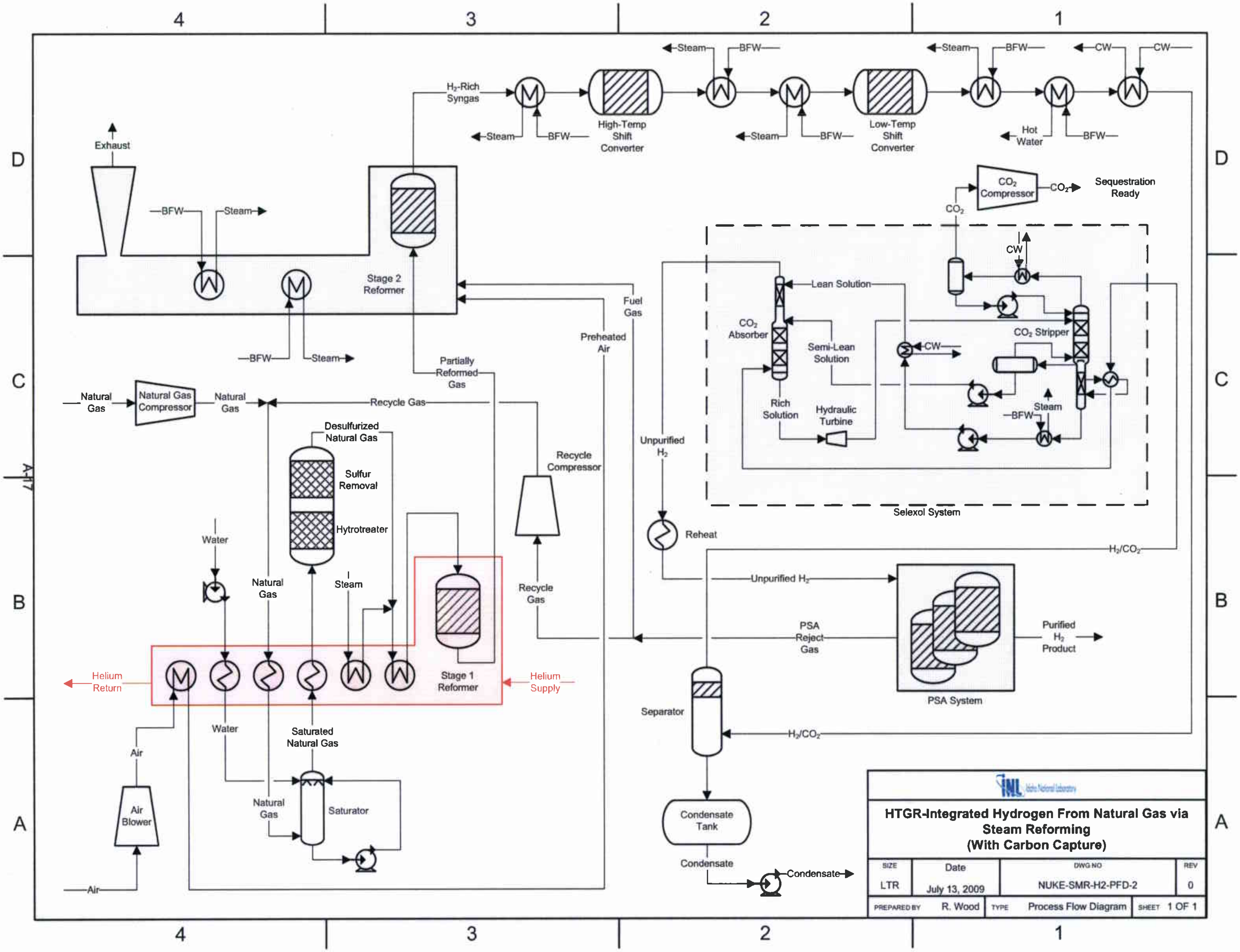
Simplified Water Treatment



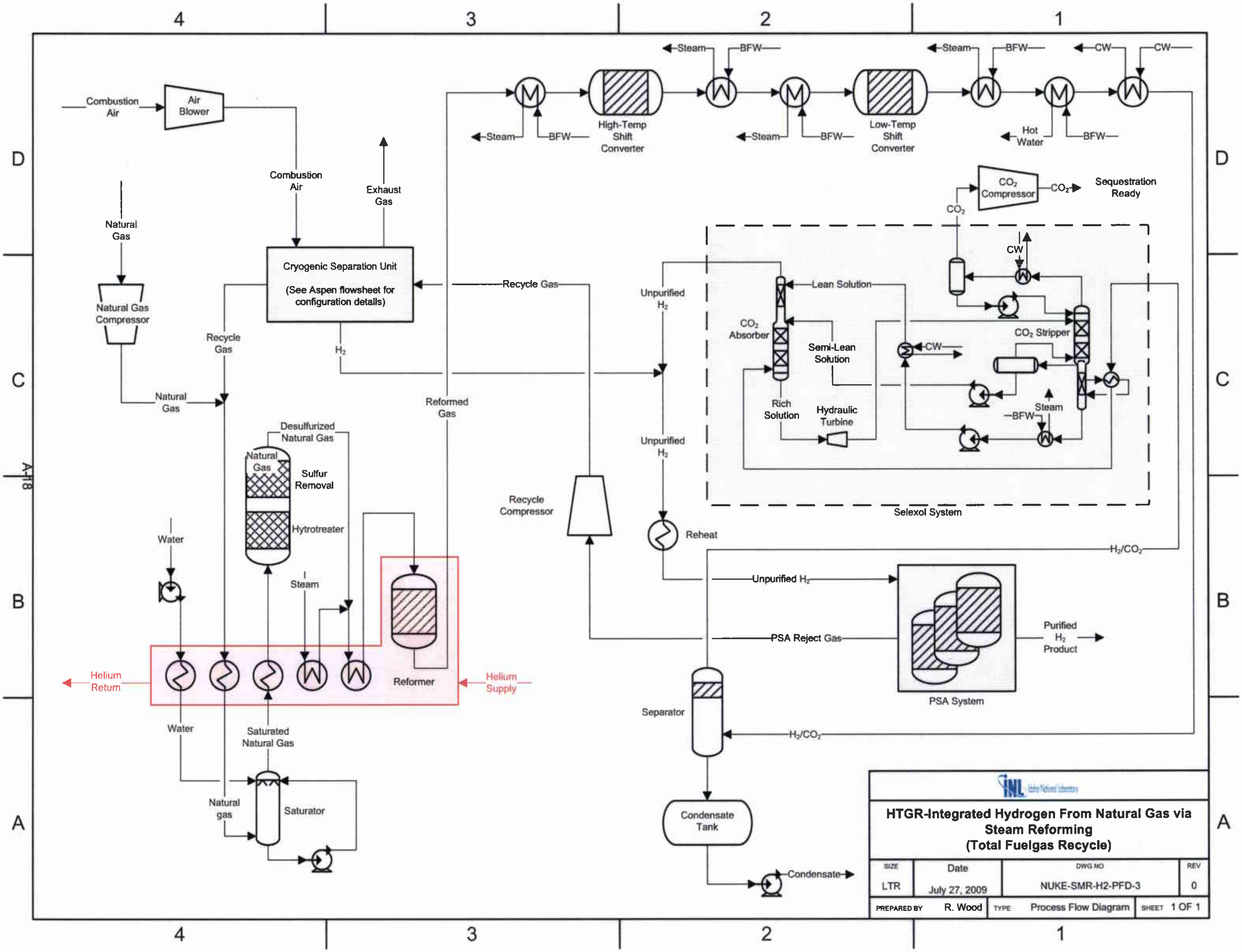


4
3
2
1
D
C
B
A
A-15
H_2 Plant Loads &
Electricity Sales
Electricity
HTGR
Helium Return
Hot Helium Supply
Natural Gas
Sulfur Removal
Natural Gas
Steam Reformer
Air
Exhaust
Emissions Source
Byproduct
Export Steam
Makeup Water
General Plant Support
Steam System
Water
Plant Water Treatment
Water
Water
Cooling Towers
Steam
Water
H_2-Rich Syngas
CH_4-Rich Tailgas
Shift & Syngas Conditioning
H_2
Final Product
CO_2
Byproduct
INL
HTGR-Integrated Hydrogen From Natural Gas via Steam Reforming (With Carbon Capture)
SIZE LTR
Date July 8, 2010
DWG NO NUKE-SMR-H2-BFD-3
REV 0
PREPARED BY R. Wood
TYPE Block Flow Diagram
SHEET 1 OF 1


4
3
2
1
D
C
B
A
Byproduct
Export Steam
Makeup Water
H_2 Plant Loads & Electricity Sales
Electricity
Natural Gas
General Plant Support
HTGR
Sulfur Removal
Steam System
Water
Plant Water Treatment
Water
Cooling Towers
Water
Hot Helium Supply
Helium Return
Natural Gas
Steam
Water
Final Product
Steam Reformer
H_2-Rich Syngas
Shift & Syngas Conditioning
H_2
H_2
CO_2
Byproduct
CH_4-Rich Tailgas
Cryogenic Separation
CH_4-Rich Tailgas
N_2-Rich Gas
Combust & Generate Steam
HTGR-Integrated Hydrogen From Natural Gas via Steam Reforming (Total Fuelgas Recycle)
SIZE LTR
Date July 27, 2010
DWG NO NUKE-SMR-H2-BFD-4
REV 0
PREPARED BY R. Wood
TYPE Block Flow Diagram
SHEET 1 OF 1

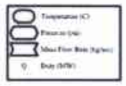


Exhaust
BFW
Steam
Stage 2 Reformer
H_2-Rich Syngas
High-Temp Shift Converter
Low-Temp Shift Converter
Hot Water
CW
CO_2 Compressor
Sequestration Ready
CO_2
Fuel Gas
Preheated Air
Partially Reformed Gas
Natural Gas
Natural Gas Compressor
Recycle Gas
Recycle Compressor
Desulfurized Natural Gas
Sulfur Removal
Hytrotreater
Water
Steam
Stage 1 Reformer
Helium Return
Helium Supply
Saturated Natural Gas
Saturator
Air
Air Blower
CO_2 Absorber
Lean Solution
Semi-Lean Solution
Rich Solution
Hydraulic Turbine
CO_2 Stripper
Selexol System
Unpurified H_2
Reheat
H_2/CO_2
PSA Reject Gas
PSA System
Purified H_2 Product
Separator
Condensate Tank
Condensate
INL Idaho National Laboratory
HTGR-Integrated Hydrogen From Natural Gas via Steam Reforming (With Carbon Capture)
SIZE LTR
Date July 13, 2009
DWG NO NUKE-SMR-H2-PFD-2
REV 0
PREPARED BY R. Wood
TYPE Process Flow Diagram
SHEET 1 OF 1

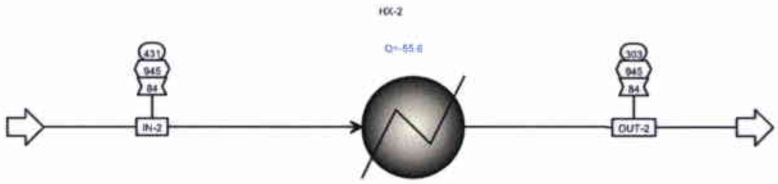


Combustion Air
Air Blower
Combustion Air
Exhaust Gas
Natural Gas
Natural Gas Compressor
Cryogenic Separation Unit
(See Aspen flowsheet for configuration details)
Recycle Gas
H_2
Natural Gas
Reformed Gas
Recycle Gas
Steam
BFW
High-Temp Shift Converter
Low-Temp Shift Converter
Hot Water
CW
CO_2 Compressor
CO_2
Sequestration Ready
Unpurified H_2
CO_2 Absorber
Lean Solution
Semi-Lean Solution
CO_2 Stripper
Rich Solution
Hydraulic Turbine
Selexol System
Desulfurized Natural Gas
Natural Gas
Sulfur Removal
Hytrotreater
Water
Recycle Compressor
Reheat
H_2/CO_2
Unpurified H_2
PSA Reject Gas
Purified H_2 Product
PSA System
Reformer
Helium Return
Helium Supply
Water
Saturated Natural Gas
Natural gas
Saturator
Separator
Condensate Tank
Condensate
INL Idaho National Laboratory
HTGR-Integrated Hydrogen From Natural Gas via Steam Reforming (Total Fuelgas Recycle)
SIZE LTR
Date July 27, 2009
DWG NO NUKE-SMR-H2-PFD-3
REV 0
PREPARED BY R. Wood
TYPE Process Flow Diagram
SHEET 1 OF 1

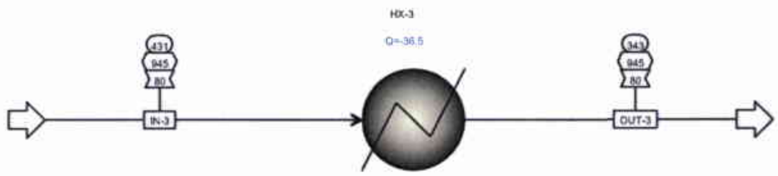
Calculation of Excess Heat Available for Power Generation



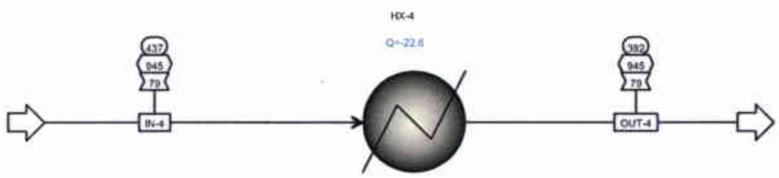
Case 2



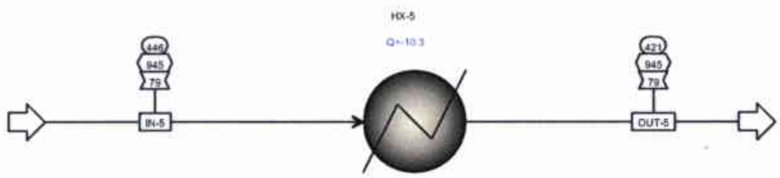
Case 3



Case 4



Case 5



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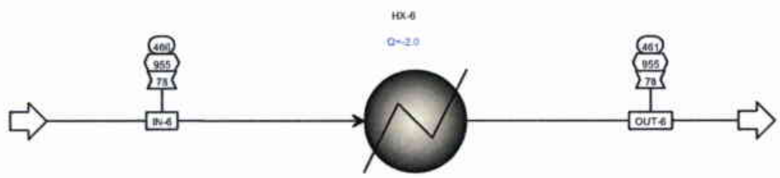

Case 2 - 725C ROT

Calculator Block SUMMARY

FEED SUMMARY:

NATURAL GAS PROPERTIES:

MASS FLOW =	985. TON/DY
VOLUME FLOW =	43.5 MMSCFD @ 60°F
HHV =	23063. BTU/LB
HHV =	1044. BTU/SCF @ 60°F
ENERGY FLOW =	45434. MMBTU/DY
COMPOSITION:	
METHANE =	93.571 MOL.%
ETHANE =	3.749 MOL.%
PROPANE =	0.920 MOL.%
BUTANE =	0.260 MOL.%
PENTANE =	0.040 MOL.%
HEXANE =	0.010 MOL.%
NITROGEN =	1.190 MOL.%
OXYGEN =	0.010 MOL.%
CO2 =	0.250 MOL.%
C4H10S =	1. PPMV
C2H6S =	0. PPMV
H2S =	0. PPMV

INTERMEDIATE PRODUCT SUMMARY:

RAW SYNGAS MASS FLOW =	361400. LB/HR
RAW SYNGAS VOLUME FLOW =	261. MMSCFD @ 60°F
RAW SYNGAS COMPOSITION:	
H2	47.8 MOL.%
CO	9.2 MOL.%
CO2	5.3 MOL.%
N2	0.2 MOL.%
H2O	34.1 MOL.%
CH4	3.5 MOL.%

FINAL PRODUCT SUMMARY:

HYDROGEN MASS FLOW =	29000. LB/HR
HYDROGEN VOLUME FLOW =	130. MMSCFD @ 60°F
HYDROGEN COMPOSITION:	
H2	99.9 MOL.%
N2	0.0 MOL.%
CH4	0.1 MOL.%
CO	11. PPMV
CO2	3. PPMV
H2O	0. PPMV

EXPORT HP STEAM FLOW =	172213. LB/HR
EXPORT HP STEAM CREDIT =	176.2 MMBTU/HR
STEAM PRESSURE =	615. PSIA
STEAM TEMPERATURE =	489. DEG. F
STEAM ENTHALPY (FOR CREDIT) =	1023. BTU/LB
CONDENSED TO LIQUID AT 1 ATM AT BOILING POINT	

CARBON DIOXIDE MASS FLOW =	177159. LB/HR
CARBON DIOXIDE VOLUME FLOW =	37. MMSCFD @ 60°F
CARBON DIOXIDE COMPOSITION:	
CO2	99.1 MOL.%
H2	0.6 MOL.%
N2	0. PPMV
CH4	2442. PPMV

CO	188. PPMV
H2O	223. PPMV

POWER SUMMARY:

ELECTRICAL CONSUMERS:	
NG REFORMER POWER CONSUMPTION =	2.0 MW
GAS CLEANING POWER CONSUMPTION =	2.3 MW
POWER BLOCK POWER CONSUMPTION =	0.4 MW
CO2 PROCESSING POWER CONSUMPTION =	7.0 MW
COOLING TOWER POWER CONSUMPTION =	0.1 MW
WATER TREATMENT POWER CONSUMPTION =	2.0 MW
CONSUMER SUBTOTAL =	13.7 MW
NET PLANT POWER CONSUMPTION =	13.7 MW

WATER BALANCE:

EVAPORATIVE LOSSES:	
COOLING TOWER EVAPORATION =	193.3 GPM
ZLD SYSTEM EVAPORATION =	154.3 GPM
TOTAL EVAPORATIVE LOSSES =	347.7 GPM
WATER CONSUMED:	
BOILER FEED WATER MAKEUP =	874.5 GPM
COOLING TOWER MAKEUP =	203.7 GPM
TOTAL WATER CONSUMED =	1078.2 GPM
WATER GENERATED:	
GAS CLEANING CONDENSATE =	234.7 GPM
COOLING TOWER BLOWDOWN =	40.0 GPM
TOTAL WATER GENERATED =	274.7 GPM
PLANT WATER SUMMARY:	
NET MAKEUP WATER REQUIRED =	957.7 GPM
WATER CONSUMED / NG FED =	5.84 LB/LB

CO2 BALANCE:

CO2 EMITTED (TOTAL) =	525. TON/DY
CO2 EMITTED (TOTAL) =	9. MMSCFD @ 60°F
SEQUESTRATION READY CO2 =	2123. TON/DY
SEQUESTRATION READY CO2 =	37. MMSCFD @ 60°F
CO2 EMITTED / NG FED =	0.53 LB/LB

NUCLEAR INTEGRATION REQUIREMENTS:

TOTAL ELECTRICITY DEMAND =	13.7 MW
TOTAL HEAT DEMAND =	116.9 MW
TOTAL HEAT DEMAND =	398.8 MMBTU/HR
HELIUM FLOWRATE REQUIRED =	663671. LB/HR
HELIUM FLOWRATE REQUIRED =	83.62 KG/S
HELIUM SUPPLY TEMPERATURE =	1292. DEG. F.
HELIUM SUPPLY TEMPERATURE =	700. DEG. C.

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HELIUM RETURN TEMPERATURE =          807. DEG. F.
HELIUM RETURN TEMPERATURE =          431. DEG. C.


EFFICIENCY CALCULATIONS:

  OVERALL PROCESS THERMAL EFFICIENCY:
    ASSUMPTIONS:
      (1) FOR STEAM EXPORT - HEAT RECOVERY CREDIT
          ASSUMES SATURATED LIQUID AT ATMOSPHERIC PRESSURE
      (2) FOR ELECTRICITY IMPORT - ELECTRICAL
          GENERATION EFFICIENCY OF 38.4%

    HHV BASIS =                          80.1%
    LHV BASIS =                          74.6%

  OVERALL PROCESS COLD GAS EFFICIENCY:
    (INCLUDES ONLY NATURAL GAS FEED AND HYDROGEN PRODUCT)

    HHV BASIS =                          92.9%
    LHV BASIS =                          87.1%

  OTHER PERFORMANCE METRICS:

    HYDROGEN PRODUCT TO NATURAL GAS FEED = 2.99 SCF/SCF
    (CONVENTIONAL PROCESS IS AROUND 2.5)

    STEAM EXPORT TO HYDROGEN PRODUCT =     5.94 TON/TON
    (CONVENTIONAL PROCESS IS TYPICALLY BETWEEN 5 AND 18)


Calculator Block AIRPROPS

  HUMIDITY DATA FOR STREAM PRI-AIR:
    HUMIDITY RATIO =                     43.5 GRAINS/LB
    RELATIVE HUMIDITY =                  39.0 %


Calculator Block NG-RFMR  Hierarchy: REFORMER

  SULFUR REMOVAL CONDITIONS:

    INLET BED TEMPERATURE =             729. °F

  PRIMARY REFORMER CONDITIONS:

    STAGE 1:

      INLET TEMPERATURE =              1000. °F
      STEAM TO CARBON MOLAR RATIO =       3.00
      OUTLET TEMPERATURE =             1247. °F
      METHANE CONVERSION =               27.8 %

    STAGE 2:

      INLET TEMPERATURE =              1247. °F
      STEAM TO CARBON MOLAR RATIO =       2.37
      OUTLET TEMPERATURE =             1600. °F
      METHANE CONVERSION =               69.7 %

    OVERALL METHANE CONVERSION =         78.2 %


Calculator Block GASCLEAN Hierarchy: GAS-CLN
```

Case 2 - 725C ROT

WATER GAS SHIFT CONDITIONS:

HIGH-TEMPERATURE SHIFT REACTOR:

INLET TEMPERATURE = (MINIMUM ALLOWABLE = 600°F)	635. °F
INLET STEAM:DRY GAS RATIO = (MINIMUM ALLOWABLE = 0.4)	0.52
OUTLET TEMPERATURE =	769. °F
OUTLET CO (DRY BASIS) =	3.23 MOL.%

LOW-TEMPERATURE SHIFT REACTOR:

INLET DEW TEMPERATURE =	332. °F
INLET TEMPERATURE = (SHOULD BE AT LEAST 375°F) (SHOULD BE AT LEAST 27°F ABOVE DEW TEMPERATURE)	375. °F
INLET STEAM:DRY GAS RATIO = (MINIMUM ALLOWABLE = 0.3)	0.38
OUTLET TEMPERATURE =	418. °F
OUTLET CO (DRY BASIS) =	0.36 MOL.%

SELEXOL PERFORMANCE:

INLET CO2 CONCENTRATION =	18.9 %
OUTLET CO2 CONCENTRATION =	0.2 %
CO2 CAPTURE =	99.0 %
CO2 PURITY =	99.1 %
SELEXOL UTILITY REQUIREMENTS:	
ELECTRICITY USAGE =	2.3 MW
STEAM USAGE =	72398. LB/HR

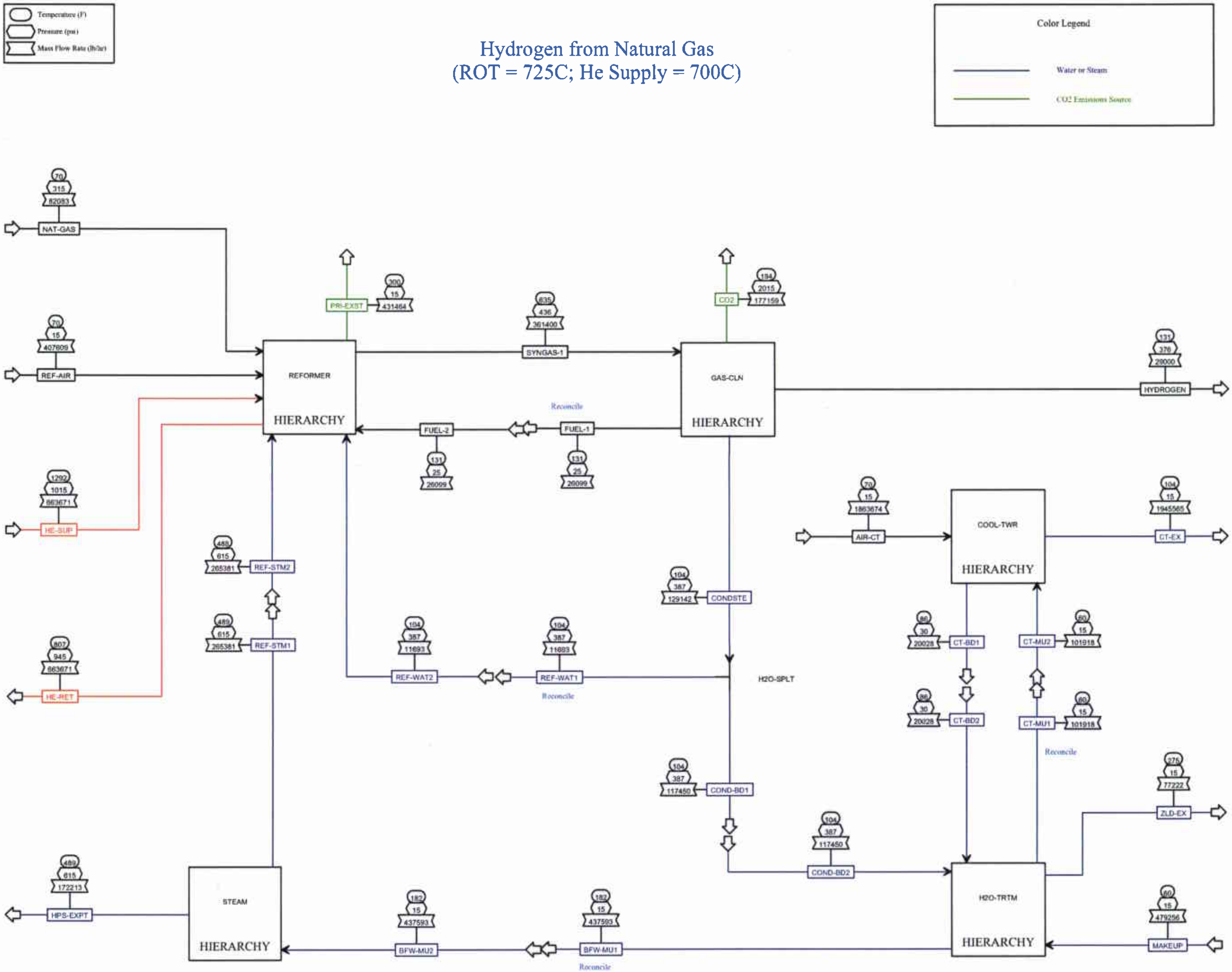
CO2 COMPRESSION:

PRESSURE =	2015. PSIA
ELECTRICITY USAGE =	7.0 MW

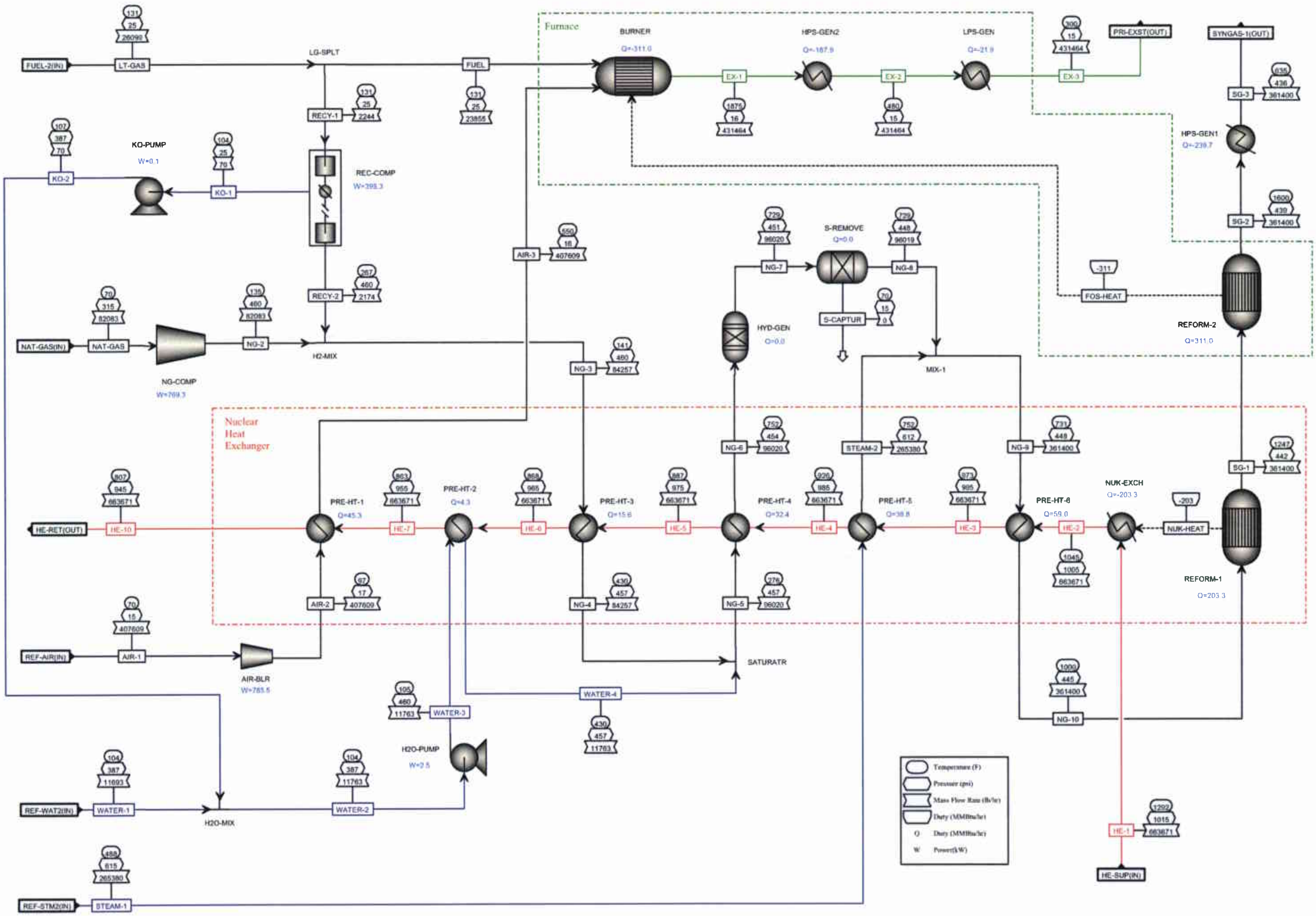
PSA PERFORMANCE:

HYDROGEN RECOVERY =	88.0 %
HYDROGEN PURITY =	99.90 %

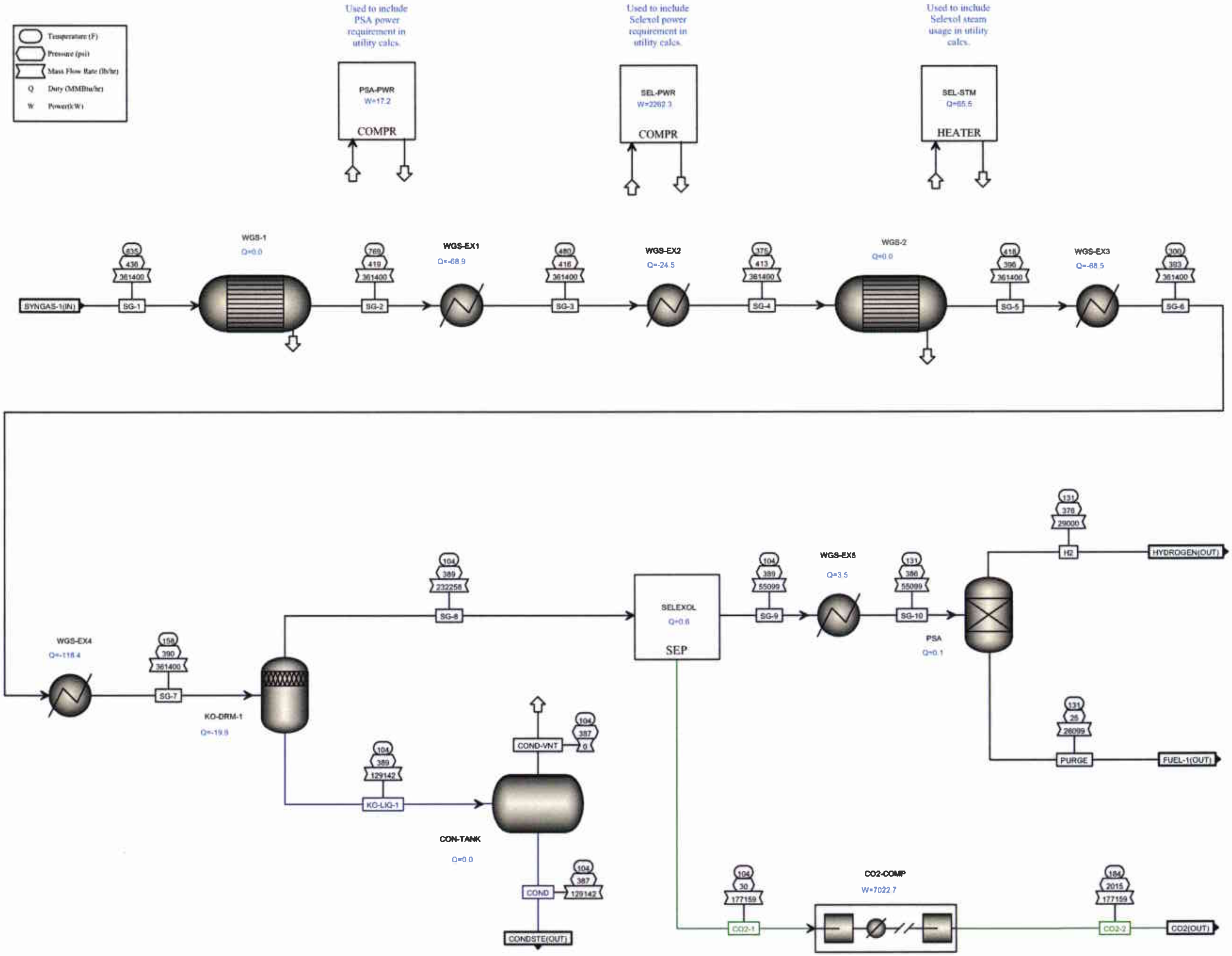
Hydrogen from Natural Gas
(ROT = 725C; He Supply = 700C)



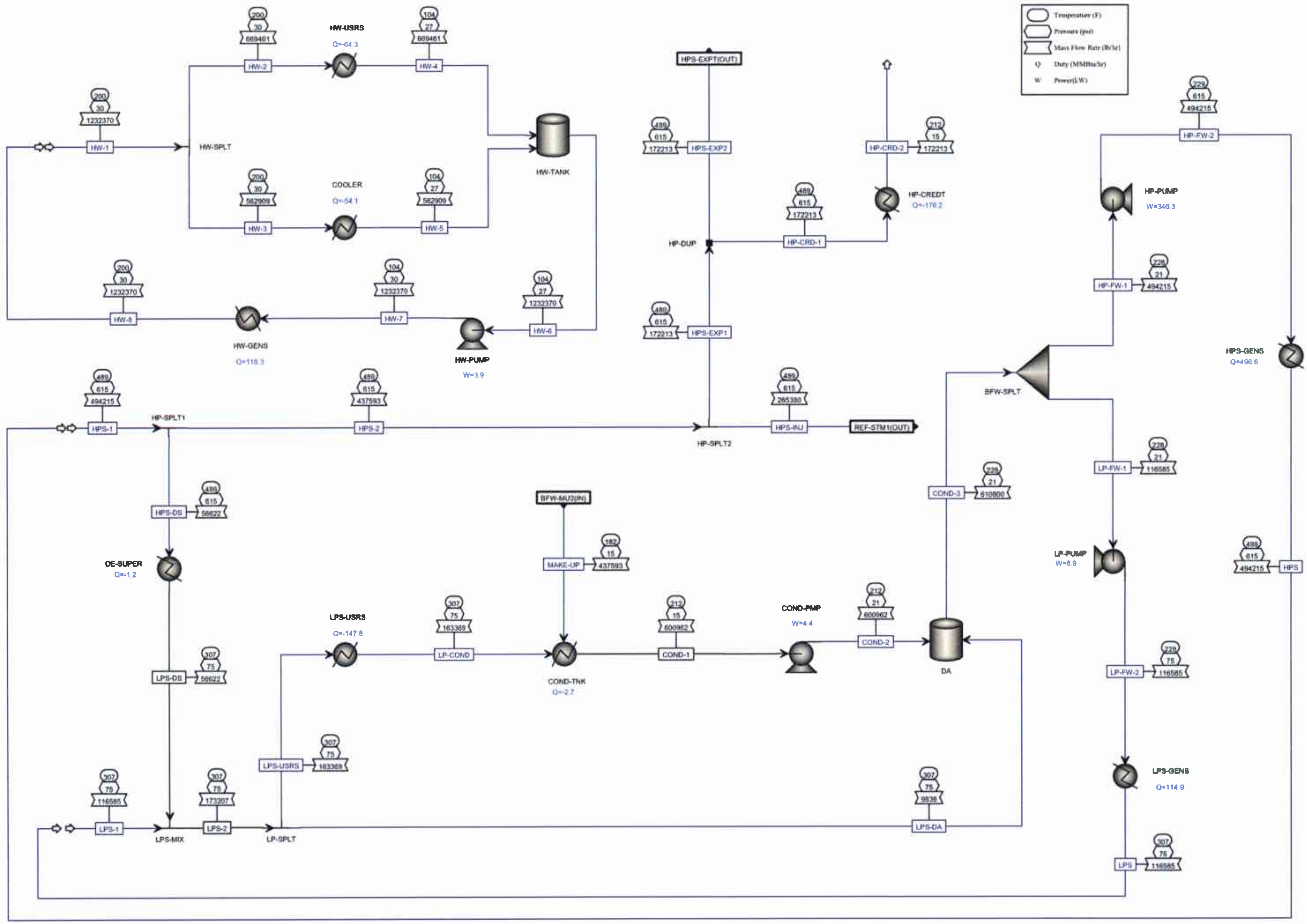
Natural Gas Steam Reforming



Syngas Cleaning & Conditioning

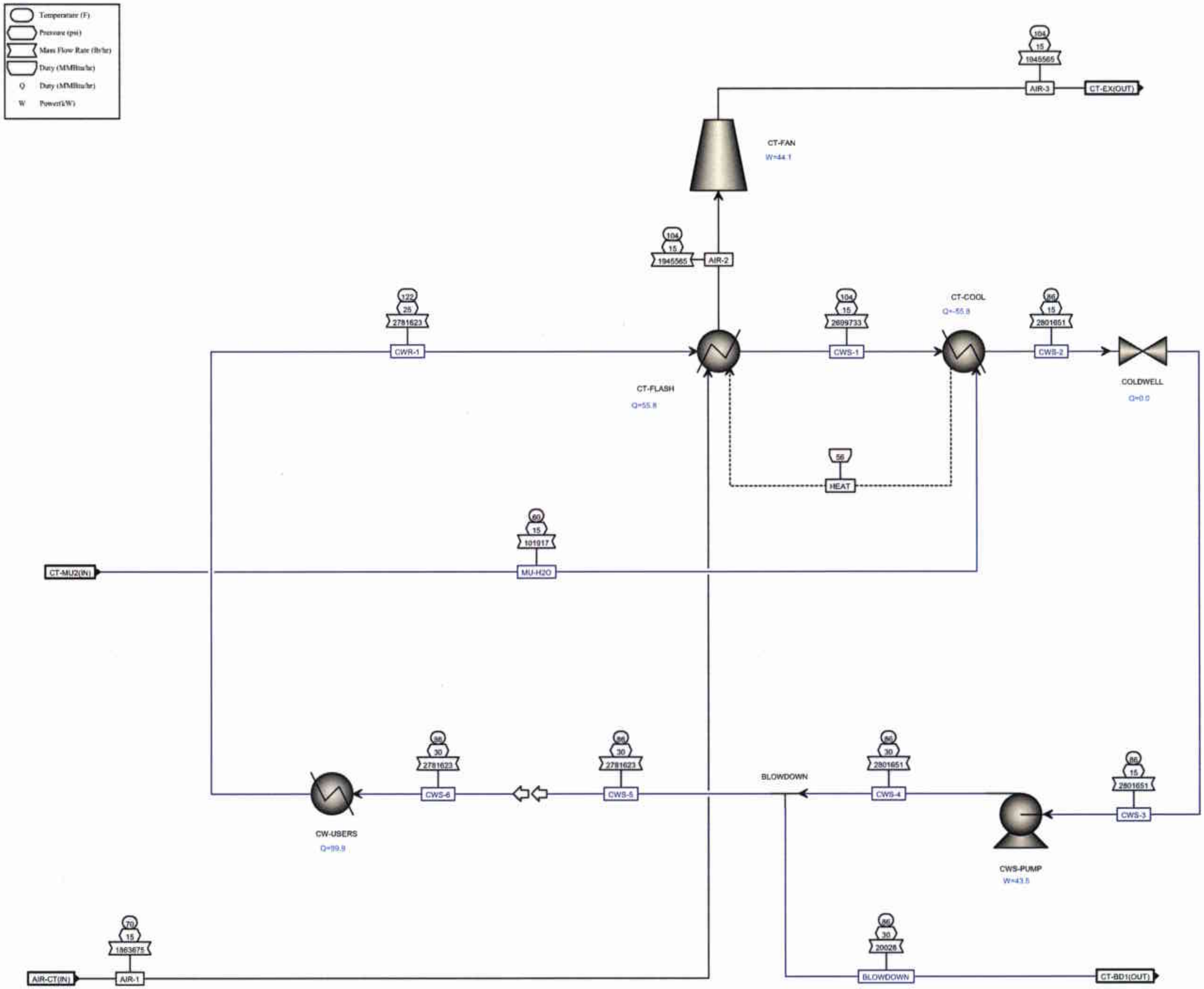


Steam System

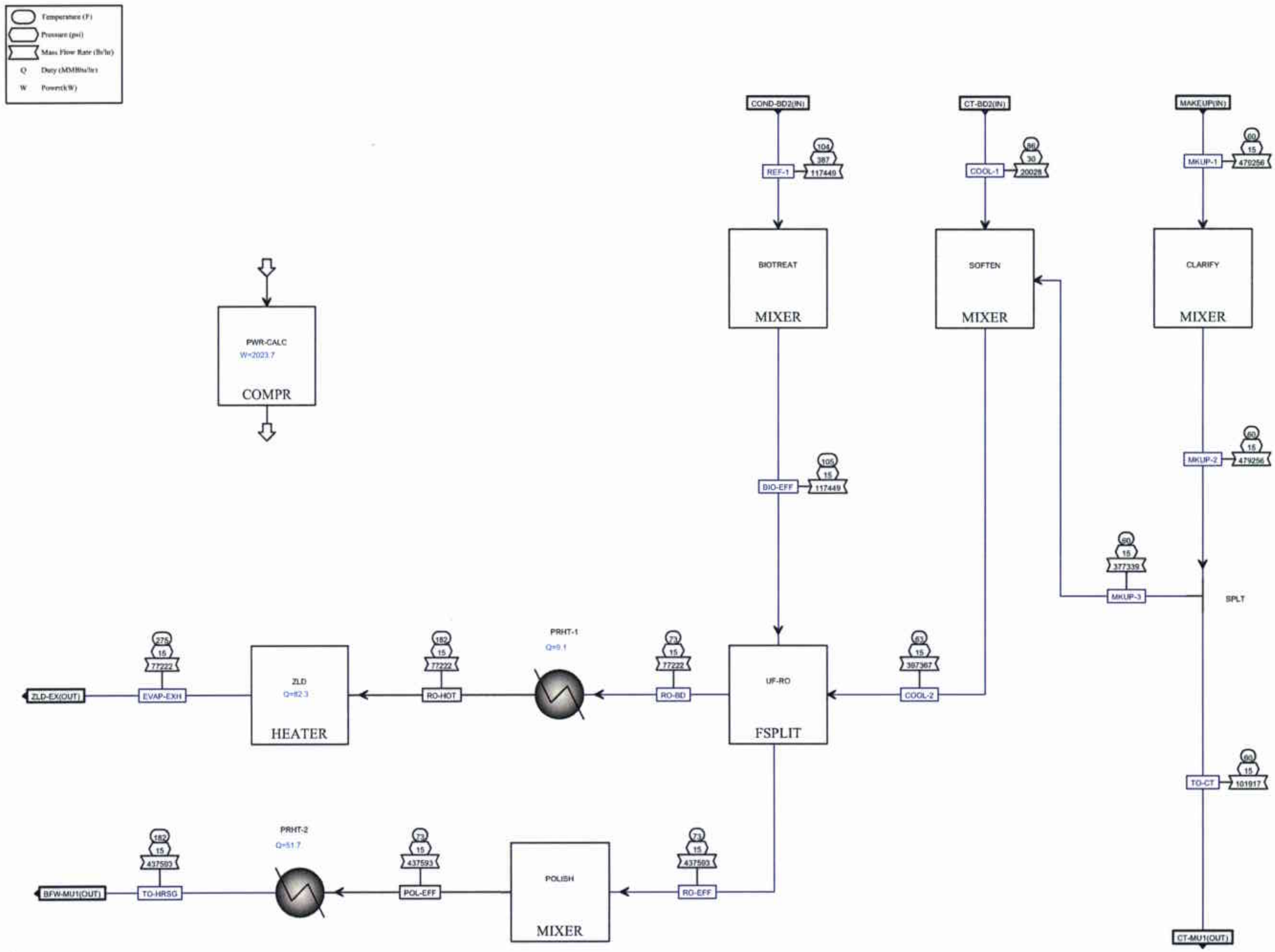


A-27

Cooling Tower



Simplified Water Treatment



Calculator Block SUMMARY

FEED SUMMARY:

NATURAL GAS PROPERTIES:

MASS FLOW =	922. TON/DY
VOLUME FLOW =	40.8 MMSCFD @ 60°F
HHV =	23063. BTU/LB
HHV =	1044. BTU/SCF @ 60°F
ENERGY FLOW =	42551. MMBTU/DY

COMPOSITION:

METHANE =	93.571 MOL.%
ETHANE =	3.749 MOL.%
PROPANE =	0.920 MOL.%
BUTANE =	0.260 MOL.%
PENTANE =	0.040 MOL.%
HEXANE =	0.010 MOL.%
NITROGEN =	1.190 MOL.%
OXYGEN =	0.010 MOL.%
CO2 =	0.250 MOL.%
C4H10S =	1. PPMV
C2H6S =	0. PPMV
H2S =	0. PPMV

INTERMEDIATE PRODUCT SUMMARY:

RAW SYNGAS MASS FLOW =	357219. LB/HR
RAW SYNGAS VOLUME FLOW =	260. MMSCFD @ 60°F
RAW SYNGAS COMPOSITION:	
H2	48.1 MOL.%
CO	9.0 MOL.%
CO2	5.1 MOL.%
N2	0.3 MOL.%
H2O	34.0 MOL.%
CH4	3.5 MOL.%

FINAL PRODUCT SUMMARY:

HYDROGEN MASS FLOW =	29000. LB/HR
HYDROGEN VOLUME FLOW =	130. MMSCFD @ 60°F
HYDROGEN COMPOSITION:	
H2	99.9 MOL.%
N2	0.0 MOL.%
CH4	0.1 MOL.%
CO	10. PPMV
CO2	3. PPMV
H2O	0. PPMV

EXPORT HP STEAM FLOW =	135666. LB/HR
EXPORT HP STEAM CREDIT =	138.8 MMBTU/HR
STEAM PRESSURE =	615. PSIA
STEAM TEMPERATURE =	489. DEG. F
STEAM ENTHALPY (FOR CREDIT) =	1023. BTU/LB

CONDENSED TO LIQUID AT 1 ATM AT BOILING POINT

CARBON DIOXIDE MASS FLOW =	173265. LB/HR
CARBON DIOXIDE VOLUME FLOW =	36. MMSCFD @ 60°F
CARBON DIOXIDE COMPOSITION:	
CO2	99.1 MOL.%
H2	0.7 MOL.%
N2	0. PPMV
CH4	2517. PPMV

CO	187. PPMV
H2O	227. PPMV

POWER SUMMARY:

ELECTRICAL CONSUMERS:	
NG REFORMER POWER CONSUMPTION =	2.7 MW
GAS CLEANING POWER CONSUMPTION =	2.3 MW
POWER BLOCK POWER CONSUMPTION =	0.3 MW
CO2 PROCESSING POWER CONSUMPTION =	6.9 MW
COOLING TOWER POWER CONSUMPTION =	0.1 MW
WATER TREATMENT POWER CONSUMPTION =	1.8 MW
CONSUMER SUBTOTAL =	14.1 MW
NET PLANT POWER CONSUMPTION =	14.1 MW

WATER BALANCE:

EVAPORATIVE LOSSES:	
COOLING TOWER EVAPORATION =	210.3 GPM
ZLD SYSTEM EVAPORATION =	139.6 GPM
TOTAL EVAPORATIVE LOSSES =	349.9 GPM
WATER CONSUMED:	
BOILER FEED WATER MAKEUP =	791.3 GPM
COOLING TOWER MAKEUP =	221.5 GPM
TOTAL WATER CONSUMED =	1012.8 GPM
WATER GENERATED:	
GAS CLEANING CONDENSATE =	232.7 GPM
COOLING TOWER BLOWDOWN =	43.5 GPM
TOTAL WATER GENERATED =	276.2 GPM
PLANT WATER SUMMARY:	
NET MAKEUP WATER REQUIRED =	876.3 GPM
WATER CONSUMED / NG FED =	5.70 LB/LB

CO2 BALANCE:

CO2 EMITTED (TOTAL) =	403. TON/DY
CO2 EMITTED (TOTAL) =	7. MMSCFD @ 60°F
SEQUESTRATION READY CO2 =	2076. TON/DY
SEQUESTRATION READY CO2 =	36. MMSCFD @ 60°F
CO2 EMITTED / NG FED =	0.44 LB/LB

NUCLEAR INTEGRATION REQUIREMENTS:

TOTAL ELECTRICITY DEMAND =	14.1 MW
TOTAL HEAT DEMAND =	132.2 MW
TOTAL HEAT DEMAND =	450.9 MMBTU/HR
HELIUM FLOWRATE REQUIRED =	633142. LB/HR
HELIUM FLOWRATE REQUIRED =	79.78 KG/S
HELIUM SUPPLY TEMPERATURE =	1382. DEG. F.
HELIUM SUPPLY TEMPERATURE =	750. DEG. C.

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HELIUM RETURN TEMPERATURE =           808. DEG. F.
HELIUM RETURN TEMPERATURE =           431. DEG. C.


EFFICIENCY CALCULATIONS:

  OVERALL PROCESS THERMAL EFFICIENCY:
    ASSUMPTIONS:
      (1) FOR STEAM EXPORT - HEAT RECOVERY CREDIT
          ASSUMES SATURATED LIQUID AT ATMOSPHERIC PRESSURE
      (2) FOR ELECTRICITY IMPORT - ELECTRICAL
          GENERATION EFFICIENCY OF 38.4%

    HHV BASIS =                                80.7%
    LHV BASIS =                                74.7%

  OVERALL PROCESS COLD GAS EFFICIENCY:
    (INCLUDES ONLY NATURAL GAS FEED AND HYDROGEN PRODUCT)

    HHV BASIS =                                99.2%
    LHV BASIS =                                93.0%

  OTHER PERFORMANCE METRICS:

    HYDROGEN PRODUCT TO NATURAL GAS FEED = 3.19 SCF/SCF
    (CONVENTIONAL PROCESS IS AROUND 2.5)

    STEAM EXPORT TO HYDROGEN PRODUCT =     4.68 TON/TON
    (CONVENTIONAL PROCESS IS TYPICALLY BETWEEN 5 AND 18)


Calculator Block AIRPROPS

  HUMIDITY DATA FOR STREAM PRI-AIR:
    HUMIDITY RATIO =                           43.5 GRAINS/LB
    RELATIVE HUMIDITY =                        39.0 %


Calculator Block NG-RFMR  Hierarchy: REFORMER

  SULFUR REMOVAL CONDITIONS:

    INLET BED TEMPERATURE =                 719. °F

  PRIMARY REFORMER CONDITIONS:

    STAGE 1:

      INLET TEMPERATURE =                  1000. °F
      STEAM TO CARBON MOLAR RATIO =           3.00
      OUTLET TEMPERATURE =                 1337. °F
      METHANE CONVERSION =                   38.3 %

    STAGE 2:

      INLET TEMPERATURE =                  1337. °F
      STEAM TO CARBON MOLAR RATIO =           2.27
      OUTLET TEMPERATURE =                 1600. °F
      METHANE CONVERSION =                   63.7 %

    OVERALL METHANE CONVERSION =             77.6 %


Calculator Block GASCLEAN Hierarchy: GAS-CLN
```

Case 3 - 775C ROT

WATER GAS SHIFT CONDITIONS:

HIGH-TEMPERATURE SHIFT REACTOR:

INLET TEMPERATURE = (MINIMUM ALLOWABLE = 600°F)	635. °F
INLET STEAM:DRY GAS RATIO = (MINIMUM ALLOWABLE = 0.4)	0.51
OUTLET TEMPERATURE =	767. °F
OUTLET CO (DRY BASIS) =	3.17 MOL.%

LOW-TEMPERATURE SHIFT REACTOR:

INLET DEW TEMPERATURE =	332. °F
INLET TEMPERATURE = (SHOULD BE AT LEAST 375°F) (SHOULD BE AT LEAST 27°F ABOVE DEW TEMPERATURE)	375. °F
INLET STEAM:DRY GAS RATIO = (MINIMUM ALLOWABLE = 0.3)	0.37
OUTLET TEMPERATURE =	417. °F
OUTLET CO (DRY BASIS) =	0.35 MOL.%

SELEXOL PERFORMANCE:

INLET CO2 CONCENTRATION =	18.5 %
OUTLET CO2 CONCENTRATION =	0.2 %
CO2 CAPTURE =	99.0 %
CO2 PURITY =	99.1 %
SELEXOL UTILITY REQUIREMENTS:	
ELECTRICITY USAGE =	2.3 MW
STEAM USAGE =	72158. LB/HR

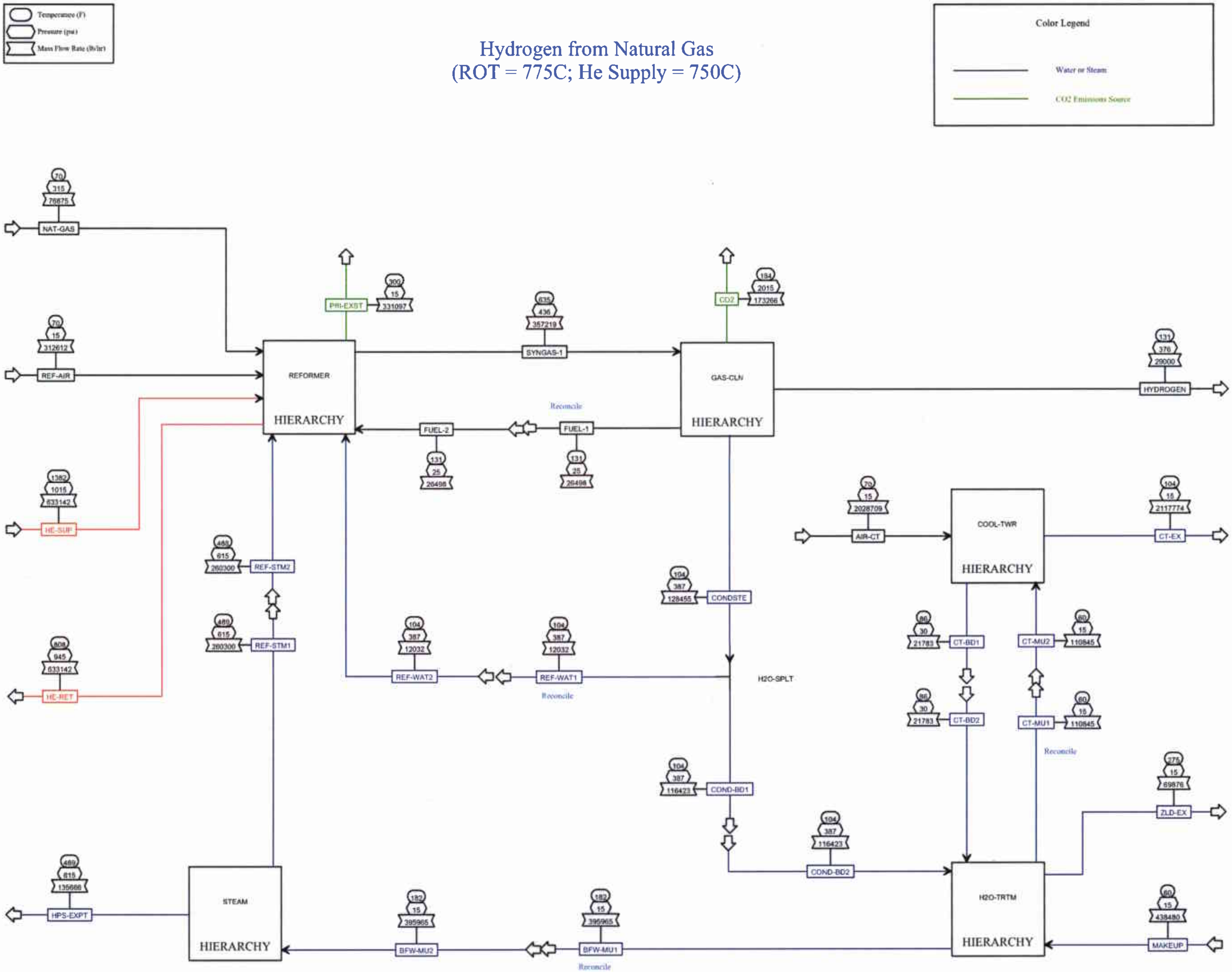
CO2 COMPRESSION:

PRESSURE =	2015. PSIA
ELECTRICITY USAGE =	6.9 MW

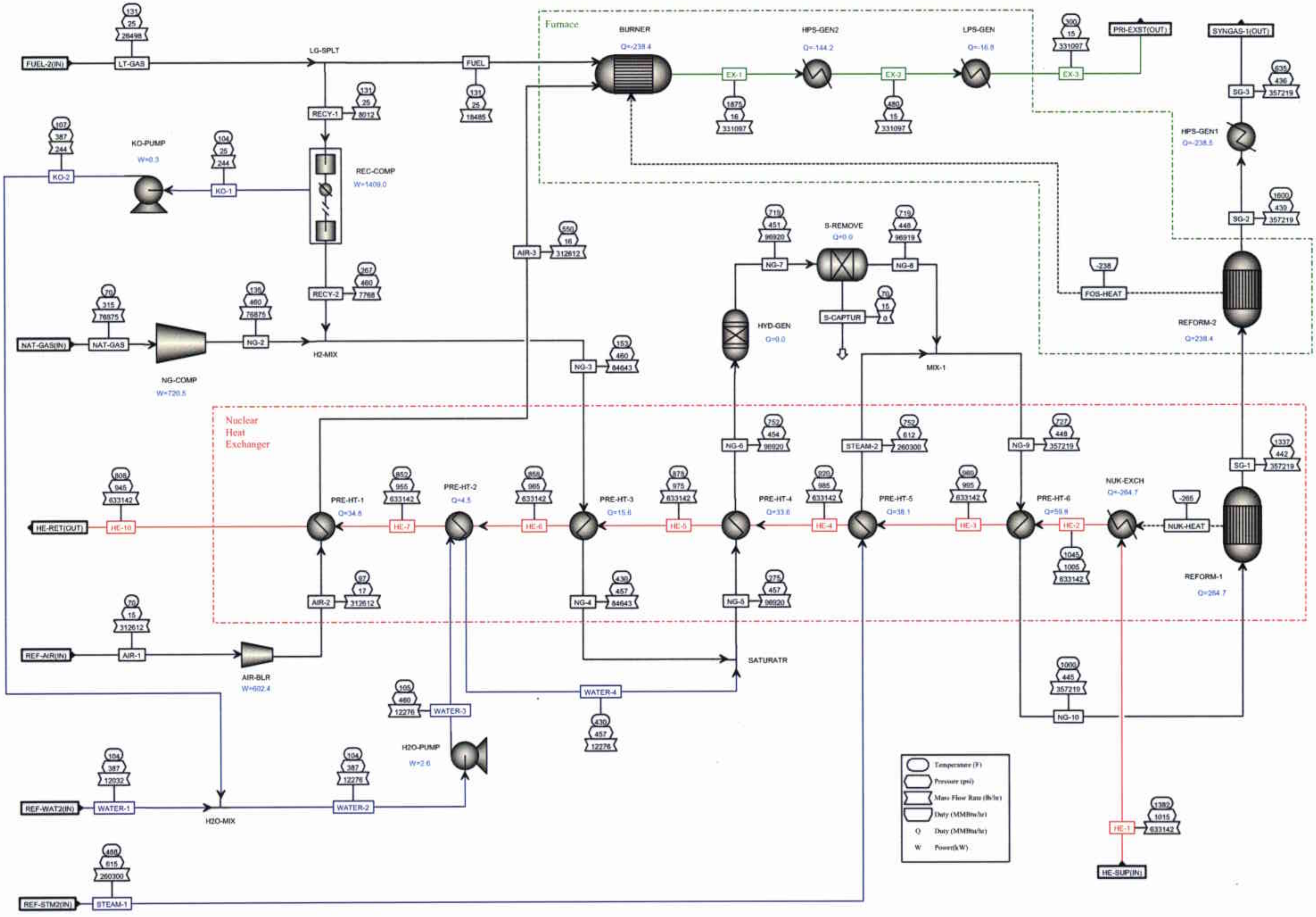
PSA PERFORMANCE:

HYDROGEN RECOVERY =	88.0 %
HYDROGEN PURITY =	99.90 %

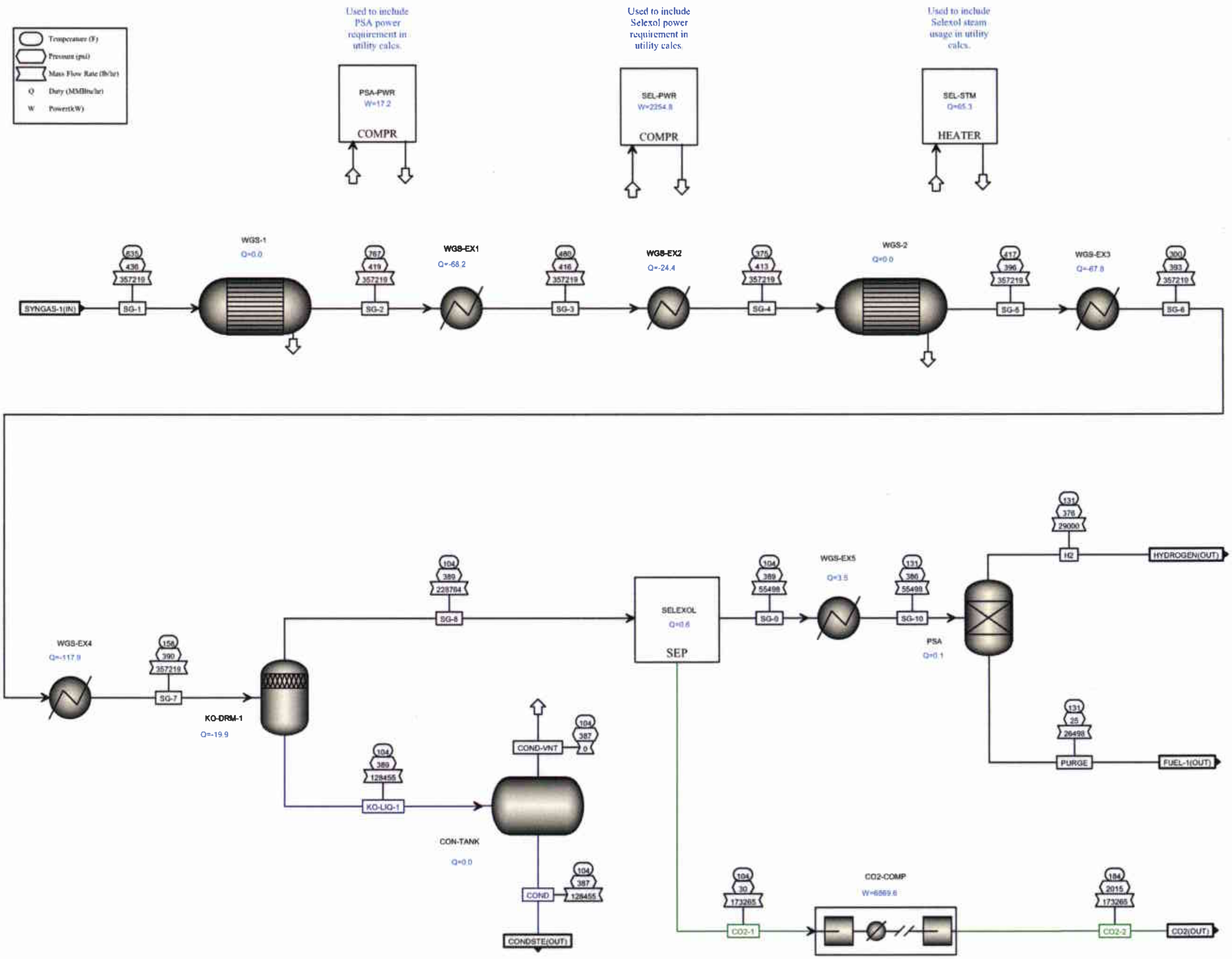
Hydrogen from Natural Gas
(ROT = 775C; He Supply = 750C)



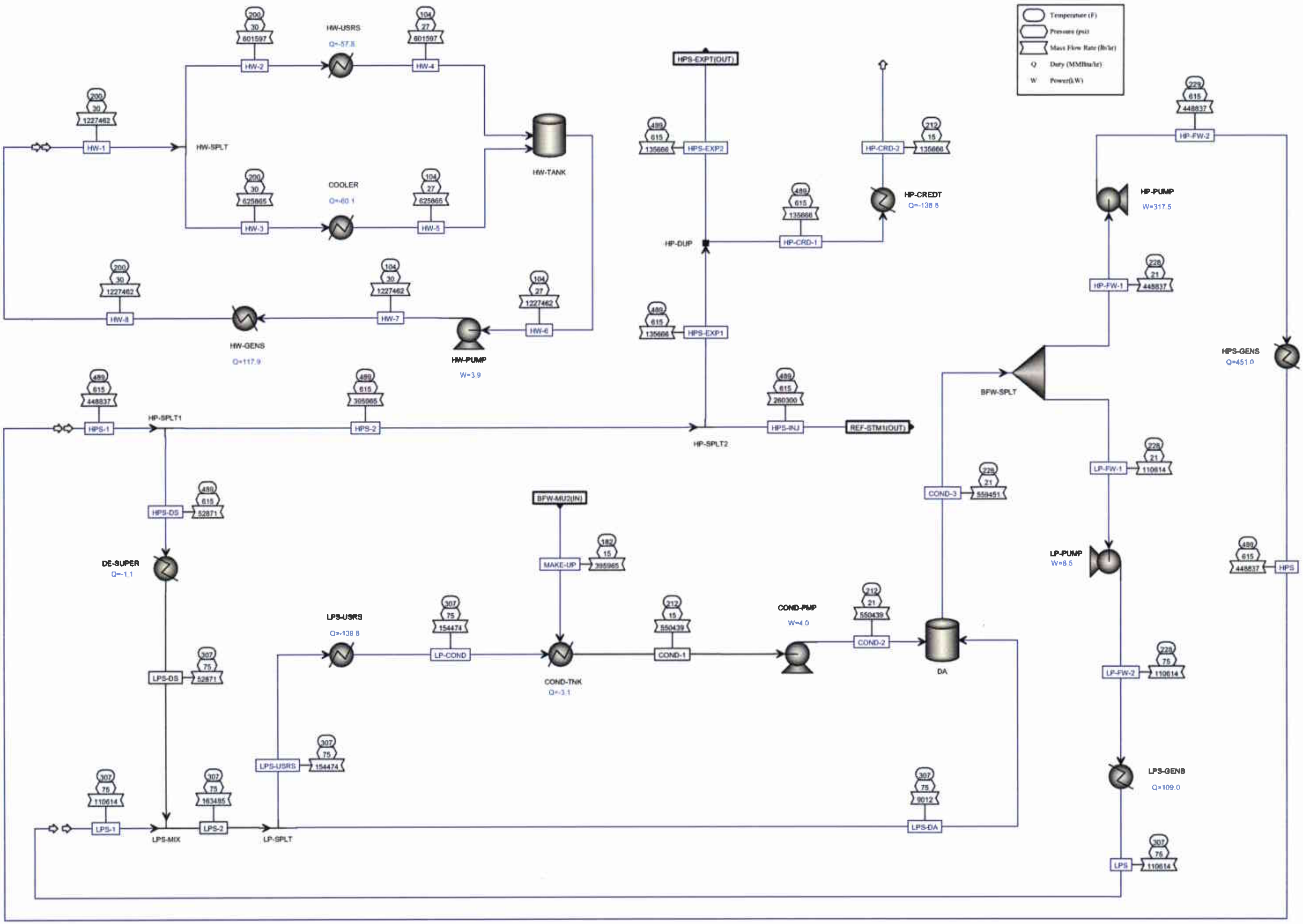
Natural Gas Steam Reforming



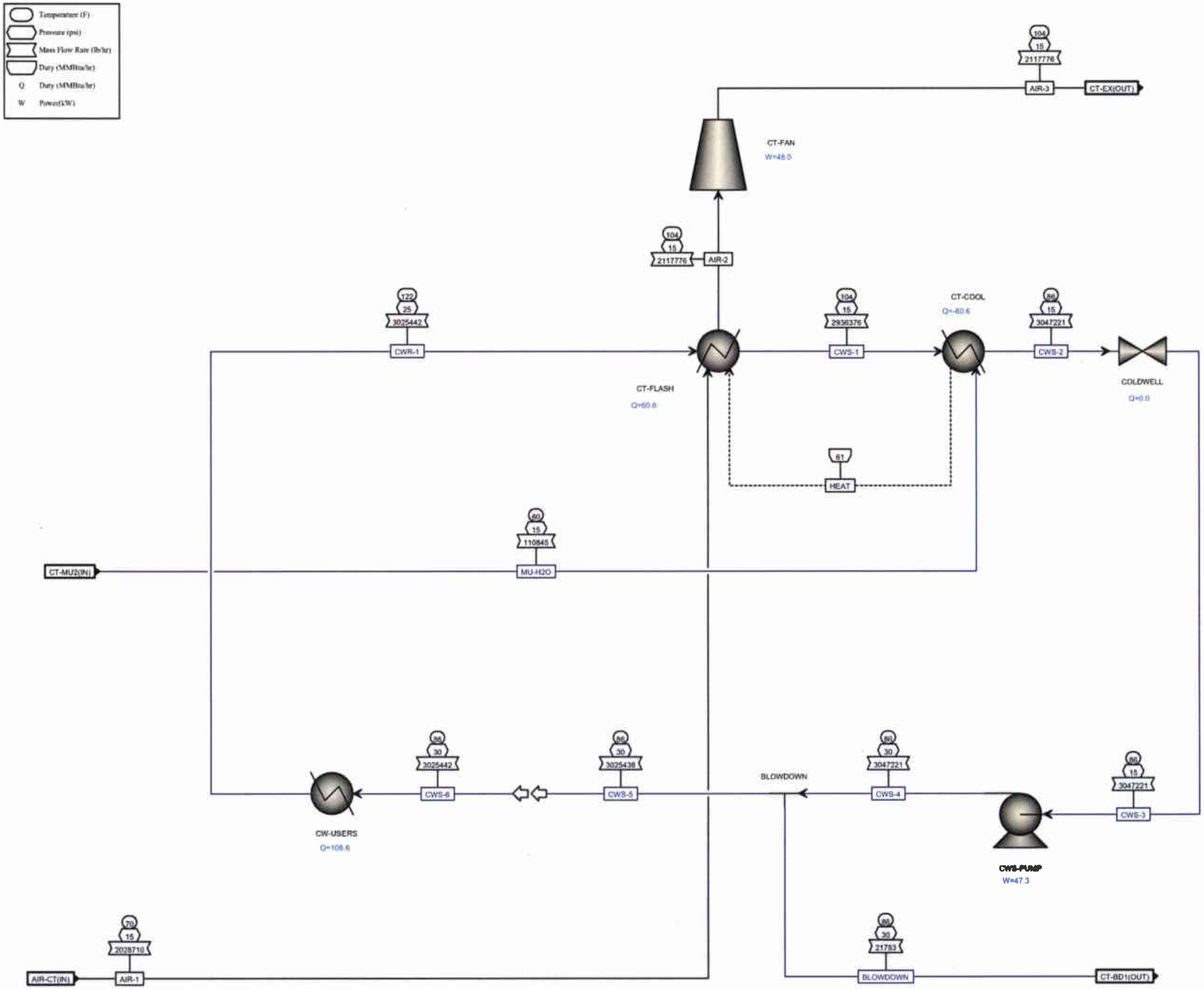
Syngas Cleaning & Conditioning



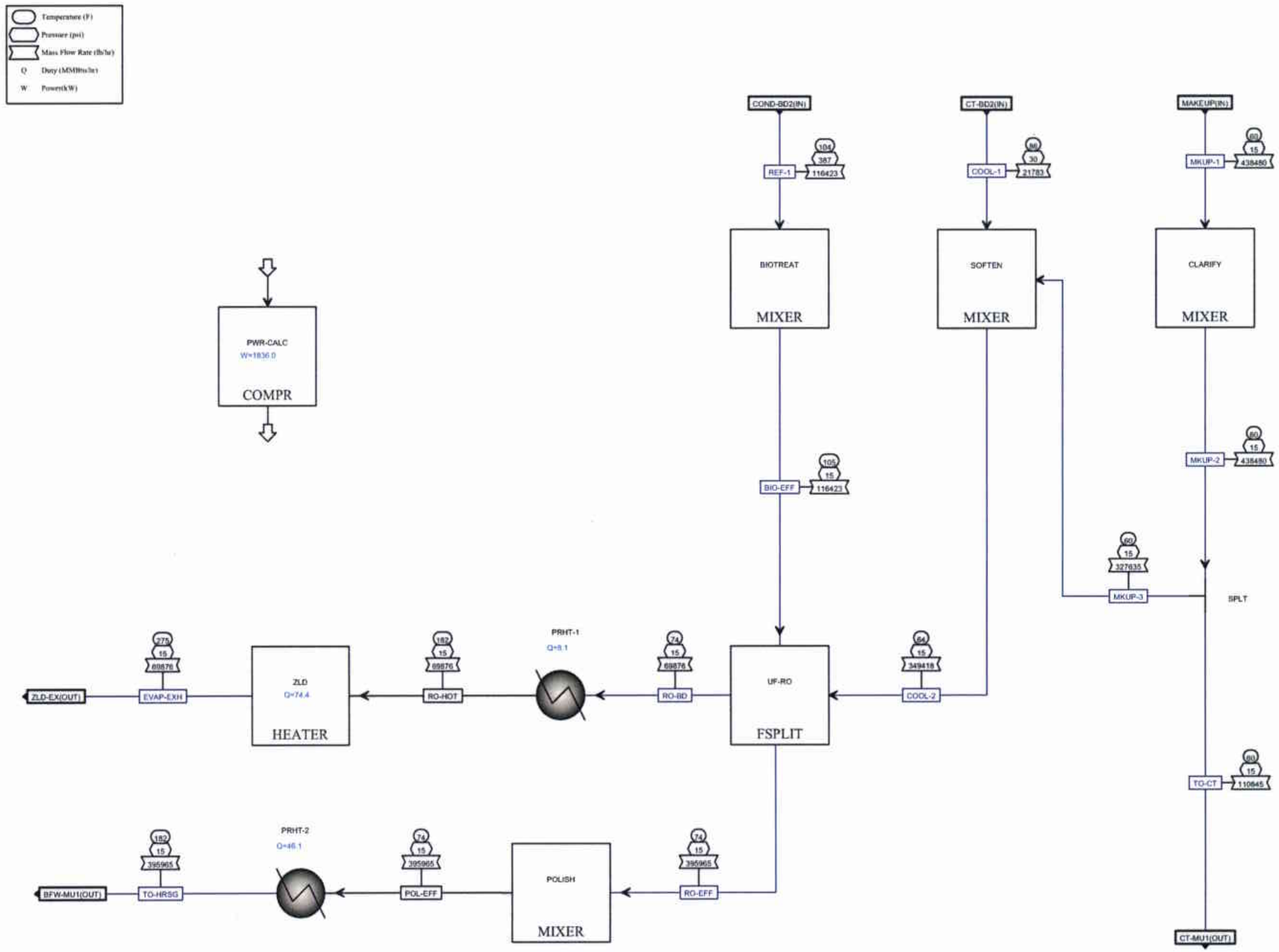
Steam System



Cooling Tower



Simplified Water Treatment



Calculator Block SUMMARY

FEED SUMMARY:

NATURAL GAS PROPERTIES:

MASS FLOW =	853. TON/DY
VOLUME FLOW =	37.7 MMSCFD @ 60°F
HHV =	23063. BTU/LB
HHV =	1044. BTU/SCF @ 60°F
ENERGY FLOW =	39350. MMBTU/DY

COMPOSITION:

METHANE =	93.571 MOL.%
ETHANE =	3.749 MOL.%
PROPANE =	0.920 MOL.%
BUTANE =	0.260 MOL.%
PENTANE =	0.040 MOL.%
HEXANE =	0.010 MOL.%
NITROGEN =	1.190 MOL.%
OXYGEN =	0.010 MOL.%
CO2 =	0.250 MOL.%
C4H10S =	1. PPMV
C2H6S =	0. PPMV
H2S =	0. PPMV

INTERMEDIATE PRODUCT SUMMARY:

RAW SYNGAS MASS FLOW =	352864. LB/HR
RAW SYNGAS VOLUME FLOW =	259. MMSCFD @ 60°F
RAW SYNGAS COMPOSITION:	
H2	48.5 MOL.%
CO	8.9 MOL.%
CO2	5.0 MOL.%
N2	0.4 MOL.%
H2O	33.7 MOL.%
CH4	3.5 MOL.%

FINAL PRODUCT SUMMARY:

HYDROGEN MASS FLOW =	29000. LB/HR
HYDROGEN VOLUME FLOW =	130. MMSCFD @ 60°F
HYDROGEN COMPOSITION:	
H2	99.9 MOL.%
N2	0.0 MOL.%
CH4	0.1 MOL.%
CO	10. PPMV
CO2	3. PPMV
H2O	0. PPMV

EXPORT HP STEAM FLOW =	95152. LB/HR
EXPORT HP STEAM CREDIT =	97.4 MMBTU/HR
STEAM PRESSURE =	615. PSIA
STEAM TEMPERATURE =	489. DEG. F
STEAM ENTHALPY (FOR CREDIT) =	1023. BTU/LB

CONDENSED TO LIQUID AT 1 ATM AT BOILING POINT

CARBON DIOXIDE MASS FLOW =	168932. LB/HR
CARBON DIOXIDE VOLUME FLOW =	35. MMSCFD @ 60°F
CARBON DIOXIDE COMPOSITION:	
CO2	99.0 MOL.%
H2	0.7 MOL.%
N2	0. PPMV
CH4	2601. PPMV

CO	187. PPMV
H2O	232. PPMV

POWER SUMMARY:

ELECTRICAL CONSUMERS:	
NG REFORMER POWER CONSUMPTION =	3.6 MW
GAS CLEANING POWER CONSUMPTION =	2.3 MW
POWER BLOCK POWER CONSUMPTION =	0.3 MW
CO2 PROCESSING POWER CONSUMPTION =	6.7 MW
COOLING TOWER POWER CONSUMPTION =	0.1 MW
WATER TREATMENT POWER CONSUMPTION =	1.6 MW
CONSUMER SUBTOTAL =	14.6 MW
NET PLANT POWER CONSUMPTION =	14.6 MW

WATER BALANCE:

EVAPORATIVE LOSSES:	
COOLING TOWER EVAPORATION =	229.3 GPM
ZLD SYSTEM EVAPORATION =	123.3 GPM
TOTAL EVAPORATIVE LOSSES =	352.7 GPM
WATER CONSUMED:	
BOILER FEED WATER MAKEUP =	699.0 GPM
COOLING TOWER MAKEUP =	241.5 GPM
TOTAL WATER CONSUMED =	940.4 GPM
WATER GENERATED:	
GAS CLEANING CONDENSATE =	230.2 GPM
COOLING TOWER BLOWDOWN =	47.5 GPM
TOTAL WATER GENERATED =	277.7 GPM
PLANT WATER SUMMARY:	
NET MAKEUP WATER REQUIRED =	786.1 GPM
WATER CONSUMED / NG FED =	5.53 LB/LB

CO2 BALANCE:

CO2 EMITTED (TOTAL) =	267. TON/DY
CO2 EMITTED (TOTAL) =	5. MMSCFD @ 60°F
SEQUESTRATION READY CO2 =	2024. TON/DY
SEQUESTRATION READY CO2 =	35. MMSCFD @ 60°F
CO2 EMITTED / NG FED =	0.31 LB/LB

NUCLEAR INTEGRATION REQUIREMENTS:

TOTAL ELECTRICITY DEMAND =	14.6 MW
TOTAL HEAT DEMAND =	149.1 MW
TOTAL HEAT DEMAND =	508.9 MMBTU/HR
HELIUM FLOWRATE REQUIRED =	628657. LB/HR
HELIUM FLOWRATE REQUIRED =	79.21 KG/S
HELIUM SUPPLY TEMPERATURE =	1472. DEG. F.
HELIUM SUPPLY TEMPERATURE =	800. DEG. C.

HELIUM RETURN TEMPERATURE = 819. DEG. F.
HELIUM RETURN TEMPERATURE = 437. DEG. C.

EFFICIENCY CALCULATIONS:

OVERALL PROCESS THERMAL EFFICIENCY:
ASSUMPTIONS:
(1) FOR STEAM EXPORT - HEAT RECOVERY CREDIT ASSUMES SATURATED LIQUID AT ATMOSPHERIC PRESSURE
(2) FOR ELECTRICITY IMPORT - ELECTRICAL GENERATION EFFICIENCY OF 38.7%

HHV BASIS = 81.5%
LHV BASIS = 74.8%

OVERALL PROCESS COLD GAS EFFICIENCY:
(INCLUDES ONLY NATURAL GAS FEED AND HYDROGEN PRODUCT)

HHV BASIS = 107.2%
LHV BASIS = 100.5%

OTHER PERFORMANCE METRICS:

HYDROGEN PRODUCT TO NATURAL GAS FEED = 3.45 SCF/SCF
(CONVENTIONAL PROCESS IS AROUND 2.5)

STEAM EXPORT TO HYDROGEN PRODUCT = 3.28 TON/TON
(CONVENTIONAL PROCESS IS TYPICALLY BETWEEN 5 AND 18)

Calculator Block AIRPROPS

HUMIDITY DATA FOR STREAM PRI-AIR:
HUMIDITY RATIO = 43.5 GRAINS/LB
RELATIVE HUMIDITY = 39.0 %

Calculator Block NG-RFMR Hierarchy: REFORMER

SULFUR REMOVAL CONDITIONS:

INLET BED TEMPERATURE = 709. °F

PRIMARY REFORMER CONDITIONS:

STAGE 1:

INLET TEMPERATURE = 1000. °F
STEAM TO CARBON MOLAR RATIO = 3.00
OUTLET TEMPERATURE = 1427. °F
METHANE CONVERSION = 50.7 %

STAGE 2:

INLET TEMPERATURE = 1427. °F
STEAM TO CARBON MOLAR RATIO = 2.16
OUTLET TEMPERATURE = 1600. °F
METHANE CONVERSION = 53.3 %

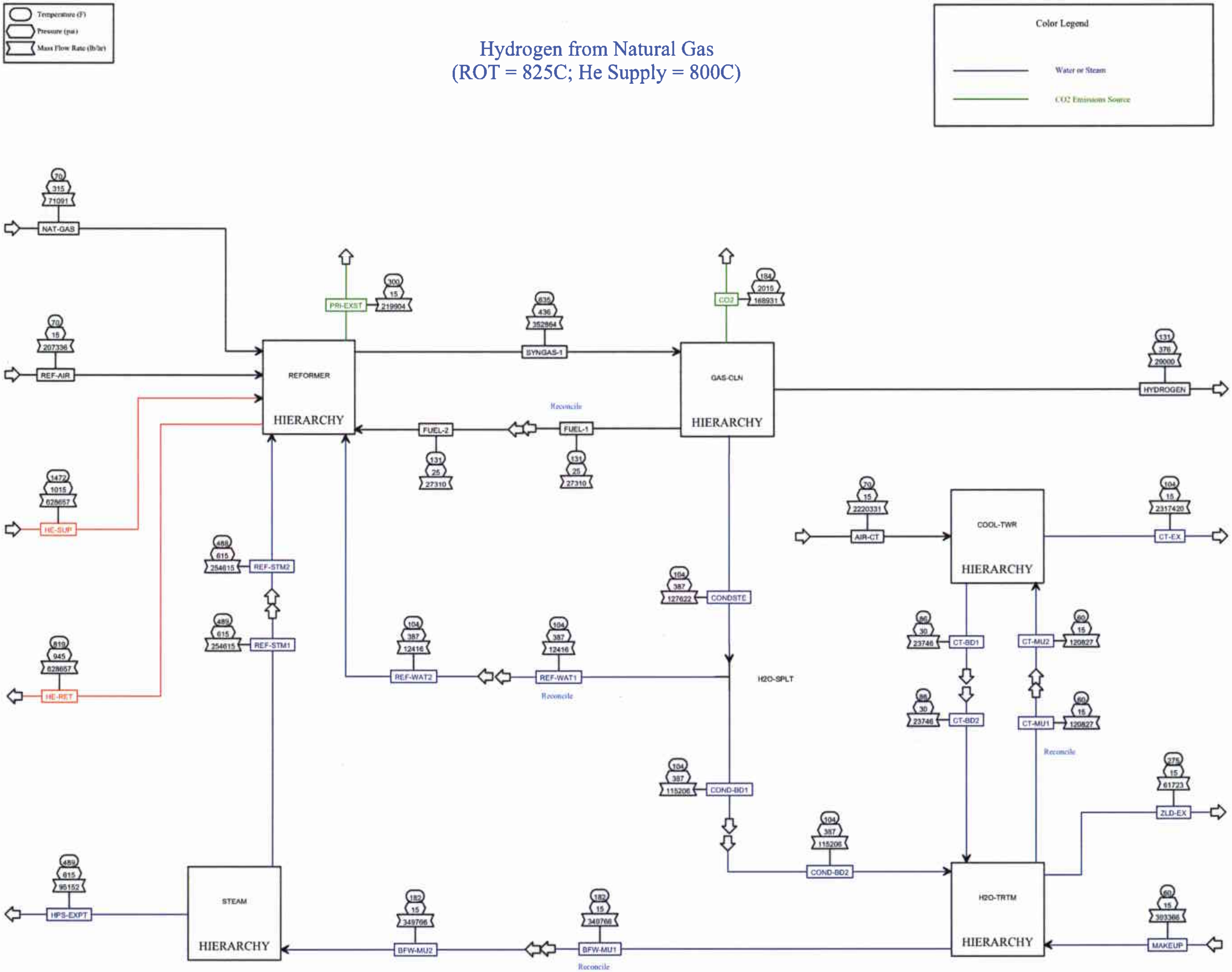
OVERALL METHANE CONVERSION = 77.0 %

Calculator Block GASCLEAN Hierarchy: GAS-CLN

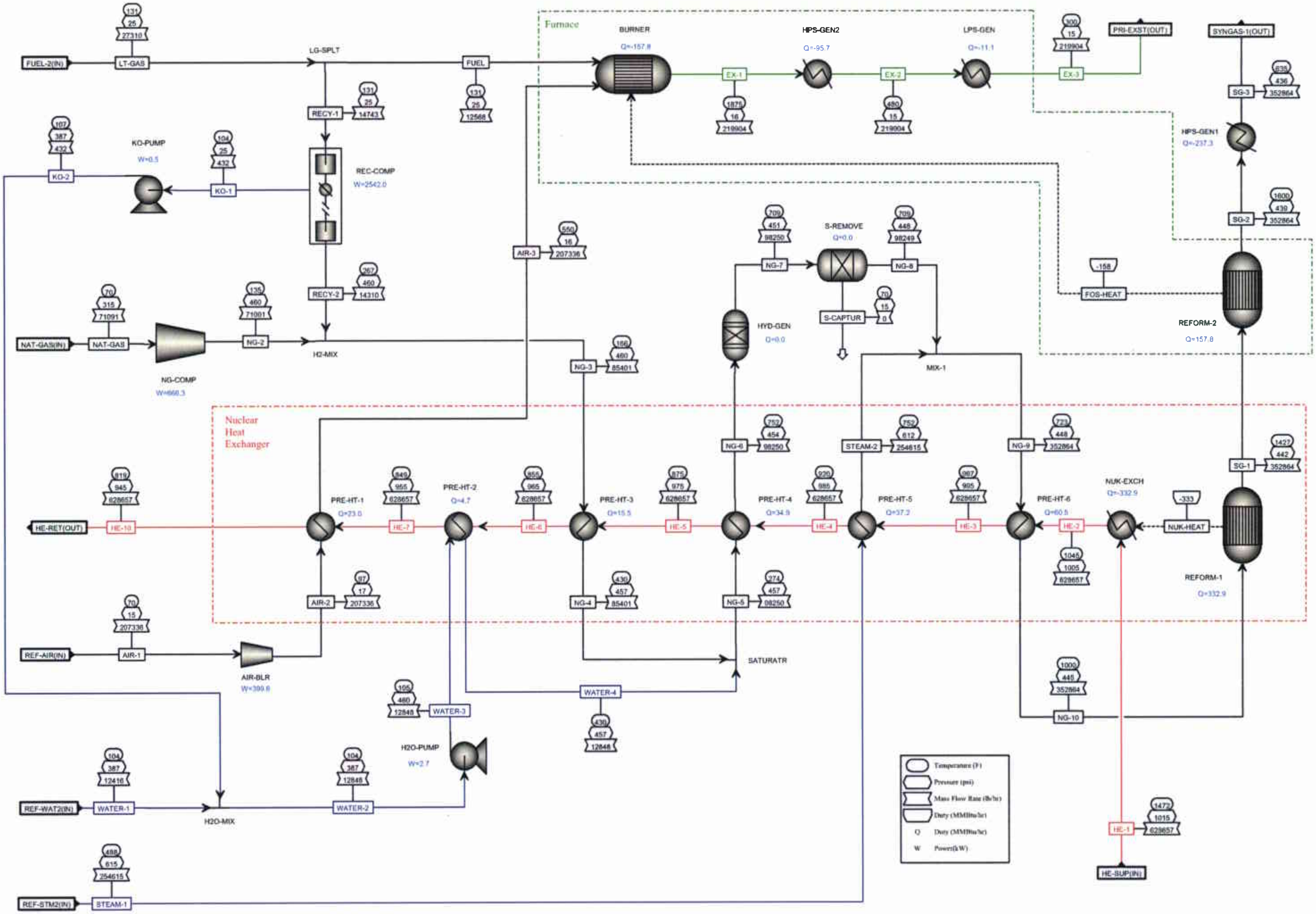
Case 4 - 825C ROT

WATER GAS SHIFT CONDITIONS:	
HIGH-TEMPERATURE SHIFT REACTOR:	
INLET TEMPERATURE = (MINIMUM ALLOWABLE = 600°F)	635. °F
INLET STEAM:DRY GAS RATIO = (MINIMUM ALLOWABLE = 0.4)	0.51
OUTLET TEMPERATURE =	766. °F
OUTLET CO (DRY BASIS) =	3.10 MOL.%
LOW-TEMPERATURE SHIFT REACTOR:	
INLET DEW TEMPERATURE =	331. °F
INLET TEMPERATURE = (SHOULD BE AT LEAST 375°F) (SHOULD BE AT LEAST 27°F ABOVE DEW TEMPERATURE)	375. °F
INLET STEAM:DRY GAS RATIO = (MINIMUM ALLOWABLE = 0.3)	0.37
OUTLET TEMPERATURE =	416. °F
OUTLET CO (DRY BASIS) =	0.34 MOL.%
SELEXOL PERFORMANCE:	
INLET CO2 CONCENTRATION =	18.1 %
OUTLET CO2 CONCENTRATION =	0.2 %
CO2 CAPTURE =	99.0 %
CO2 PURITY =	99.0 %
SELEXOL UTILITY REQUIREMENTS:	
ELECTRICITY USAGE =	2.2 MW
STEAM USAGE =	71932. LB/HR
CO2 COMPRESSION:	
PRESSURE =	2015. PSIA
ELECTRICITY USAGE =	6.7 MW
PSA PERFORMANCE:	
HYDROGEN RECOVERY =	88.0 %
HYDROGEN PURITY =	99.90 %

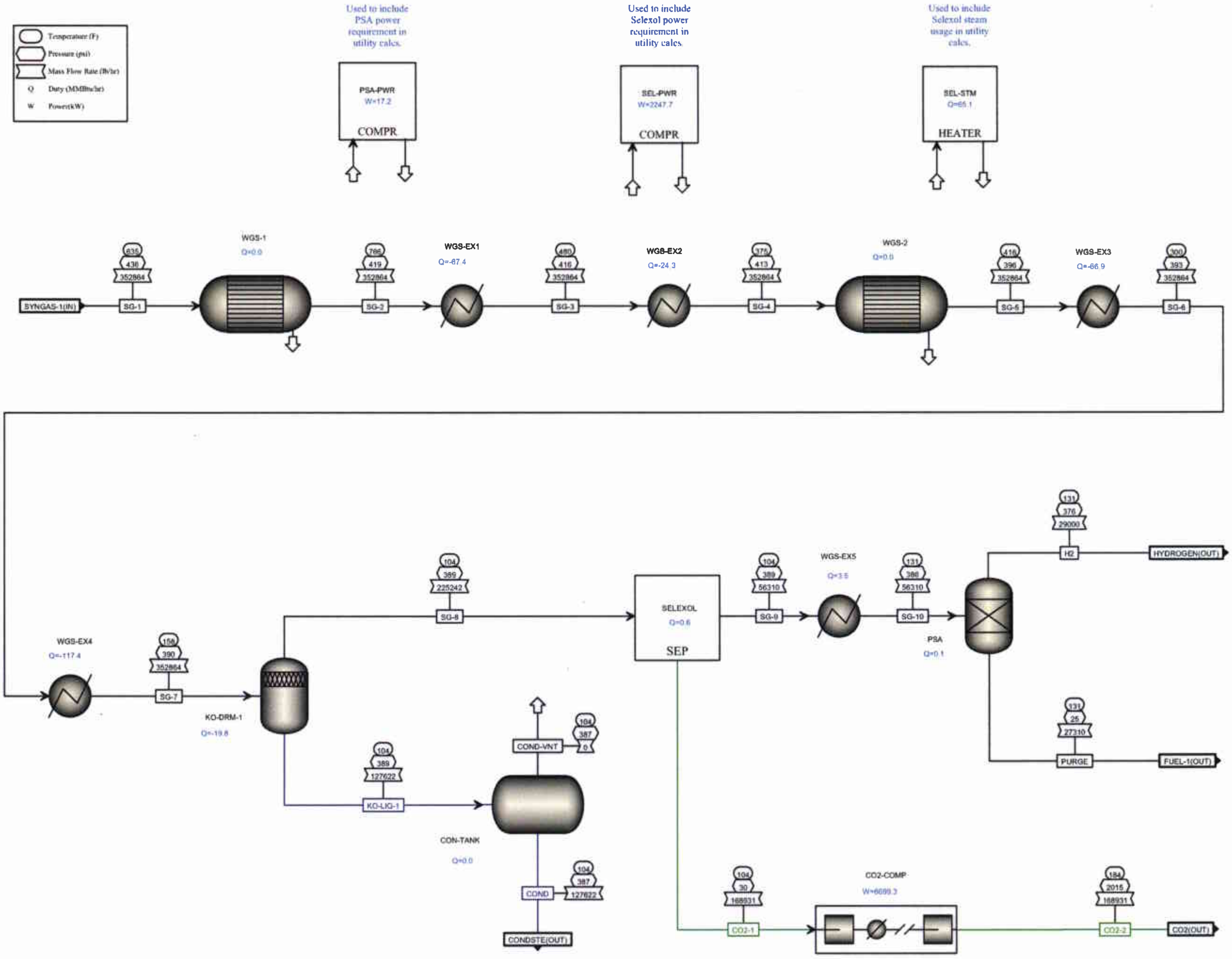
Hydrogen from Natural Gas
(ROT = 825C; He Supply = 800C)



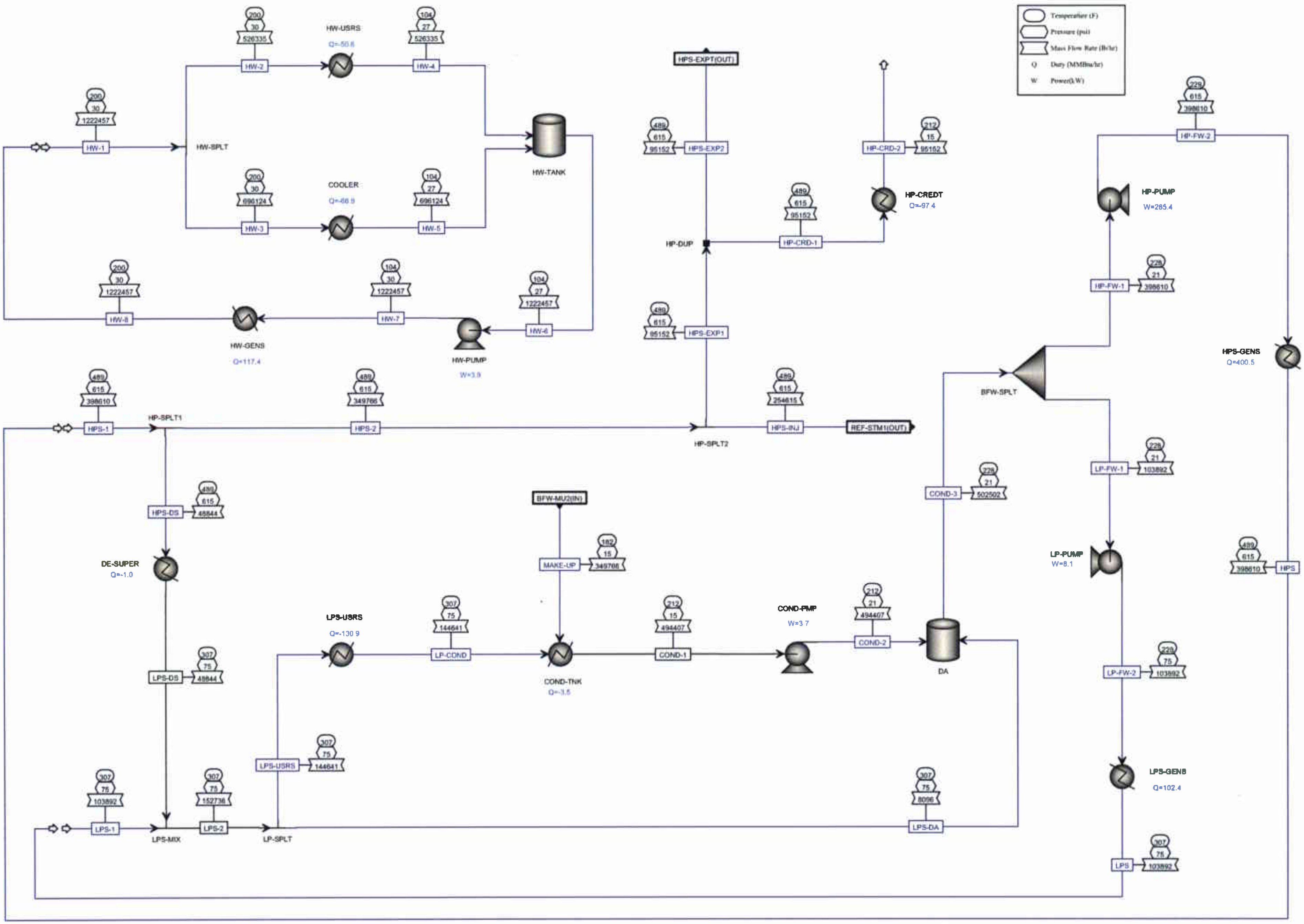
Natural Gas Steam Reforming



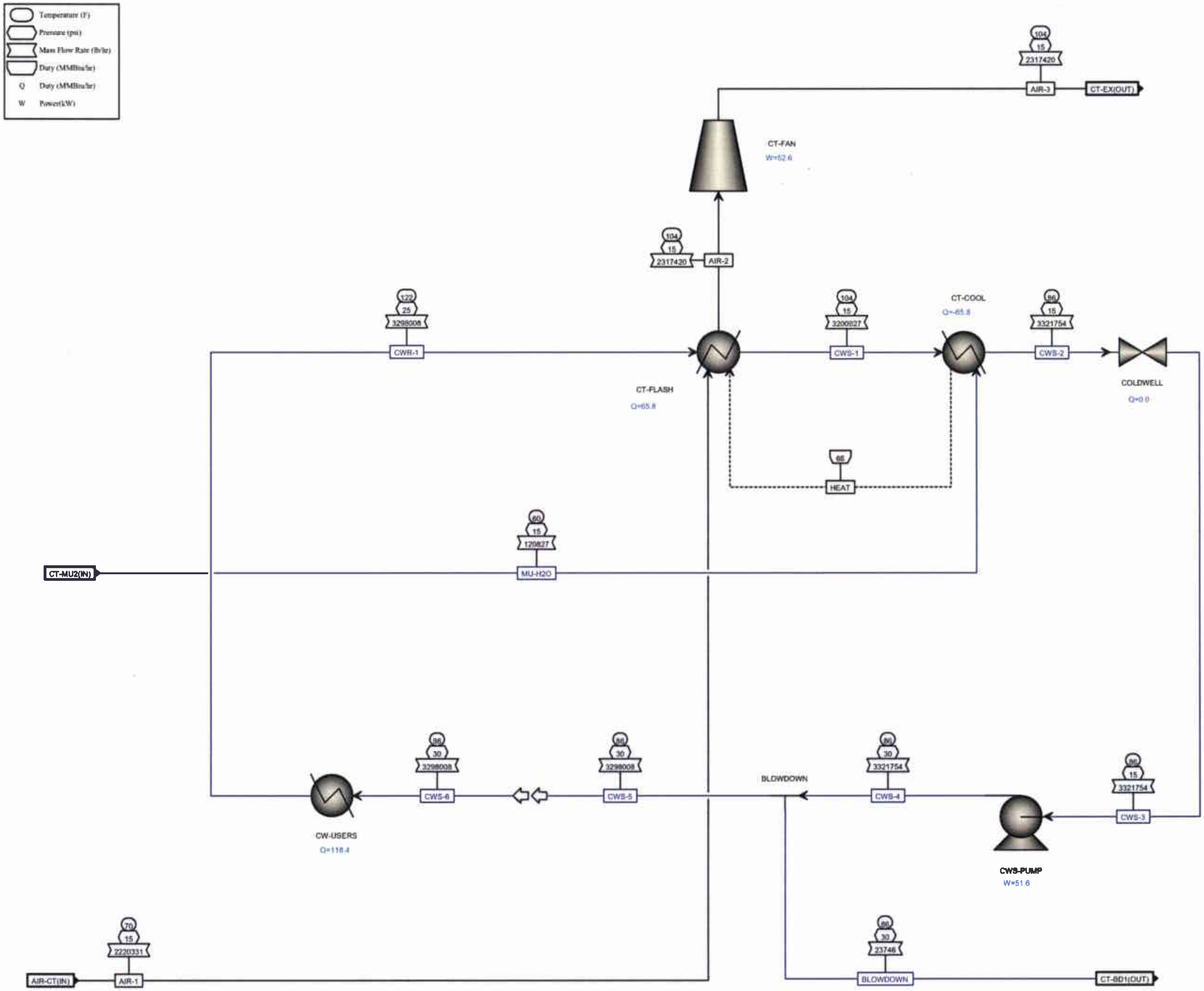
Syngas Cleaning & Conditioning



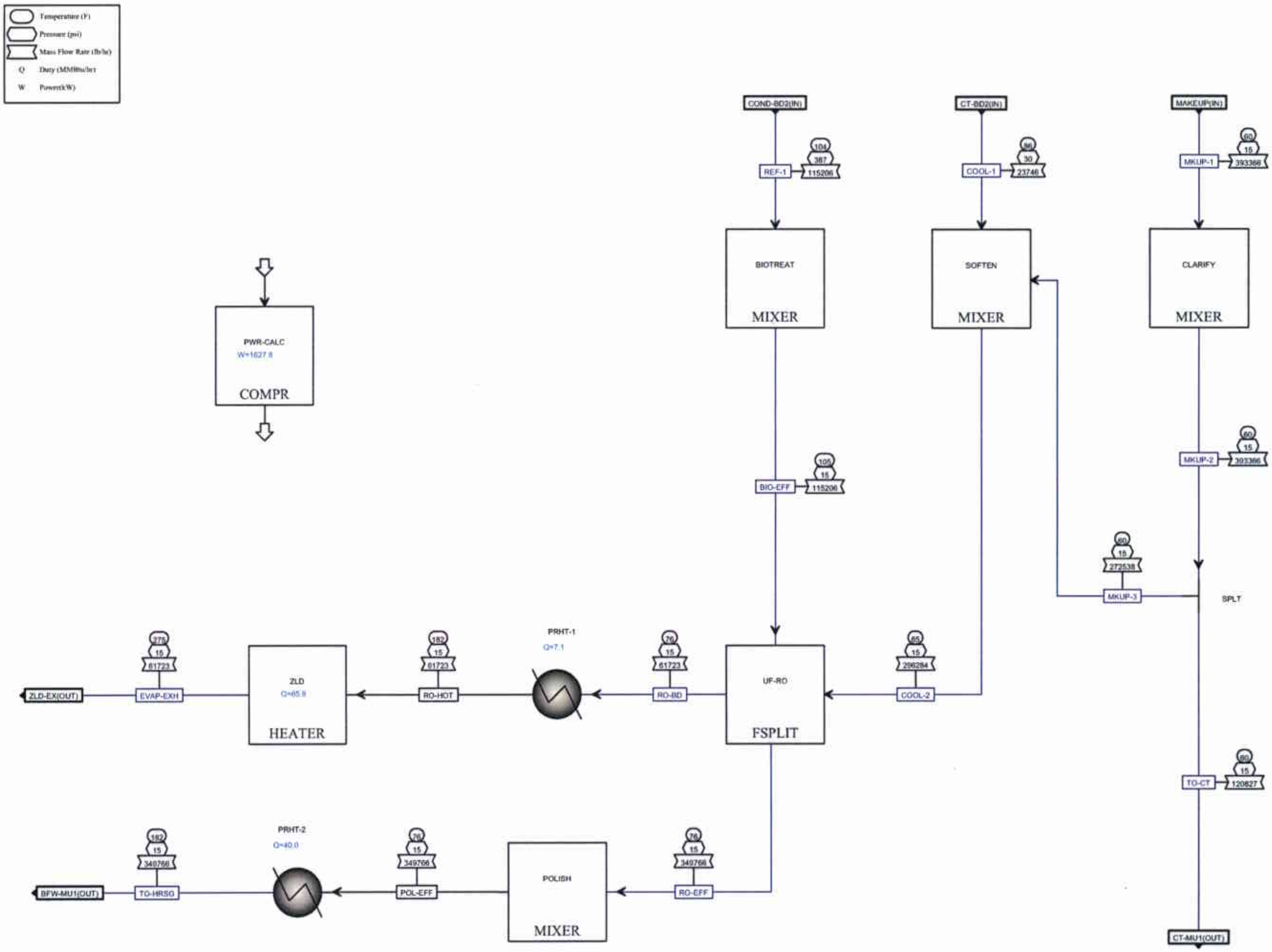
Steam System



Cooling Tower



Simplified Water Treatment



Case 5 - 875C ROT

Calculator Block SUMMARY

FEED SUMMARY:

NATURAL GAS PROPERTIES:

MASS FLOW =	781. TON/DY
VOLUME FLOW =	34.5 MMSCFD @ 60°F
HHV =	23063. BTU/LB
HHV =	1044. BTU/SCF @ 60°F
ENERGY FLOW =	36004. MMBTU/DY

COMPOSITION:

METHANE =	93.571 MOL.%
ETHANE =	3.749 MOL.%
PROPANE =	0.920 MOL.%
BUTANE =	0.260 MOL.%
PENTANE =	0.040 MOL.%
HEXANE =	0.010 MOL.%
NITROGEN =	1.190 MOL.%
OXYGEN =	0.010 MOL.%
CO2 =	0.250 MOL.%
C4H10S =	1. PPMV
C2H6S =	0. PPMV
H2S =	0. PPMV

INTERMEDIATE PRODUCT SUMMARY:

RAW SYNGAS MASS FLOW =	349724. LB/HR
RAW SYNGAS VOLUME FLOW =	258. MMSCFD @ 60°F
RAW SYNGAS COMPOSITION:	
H2	48.8 MOL.%
CO	8.7 MOL.%
CO2	4.8 MOL.%
N2	0.7 MOL.%
H2O	33.4 MOL.%
CH4	3.6 MOL.%

FINAL PRODUCT SUMMARY:

HYDROGEN MASS FLOW =	29000. LB/HR
HYDROGEN VOLUME FLOW =	130. MMSCFD @ 60°F
HYDROGEN COMPOSITION:	
H2	99.9 MOL.%
N2	0.0 MOL.%
CH4	0.1 MOL.%
CO	10. PPMV
CO2	3. PPMV
H2O	0. PPMV

EXPORT HP STEAM FLOW =	53100. LB/HR
EXPORT HP STEAM CREDIT =	54.3 MMBTU/HR
STEAM PRESSURE =	615. PSIA
STEAM TEMPERATURE =	489. DEG. F
STEAM ENTHALPY (FOR CREDIT) =	1023. BTU/LB

CONDENSED TO LIQUID AT 1 ATM AT BOILING POINT

CARBON DIOXIDE MASS FLOW =	164385. LB/HR
CARBON DIOXIDE VOLUME FLOW =	34. MMSCFD @ 60°F
CARBON DIOXIDE COMPOSITION:	
CO2	99.0 MOL.%
H2	0.7 MOL.%
N2	0. PPMV
CH4	2687. PPMV

CO	186. PPMV
H2O	238. PPMV

POWER SUMMARY:

ELECTRICAL CONSUMERS:	
NG REFORMER POWER CONSUMPTION =	4.7 MW
GAS CLEANING POWER CONSUMPTION =	2.3 MW
POWER BLOCK POWER CONSUMPTION =	0.3 MW
CO2 PROCESSING POWER CONSUMPTION =	6.5 MW
COOLING TOWER POWER CONSUMPTION =	0.1 MW
WATER TREATMENT POWER CONSUMPTION =	1.4 MW
CONSUMER SUBTOTAL =	15.3 MW
NET PLANT POWER CONSUMPTION =	15.3 MW

WATER BALANCE:

EVAPORATIVE LOSSES:	
COOLING TOWER EVAPORATION =	248.4 GPM
ZLD SYSTEM EVAPORATION =	106.3 GPM
TOTAL EVAPORATIVE LOSSES =	354.7 GPM
WATER CONSUMED:	
BOILER FEED WATER MAKEUP =	602.5 GPM
COOLING TOWER MAKEUP =	261.6 GPM
TOTAL WATER CONSUMED =	864.0 GPM
WATER GENERATED:	
GAS CLEANING CONDENSATE =	227.0 GPM
COOLING TOWER BLOWDOWN =	51.4 GPM
TOTAL WATER GENERATED =	278.4 GPM
PLANT WATER SUMMARY:	
NET MAKEUP WATER REQUIRED =	691.9 GPM
WATER CONSUMED / NG FED =	5.32 LB/LB

CO2 BALANCE:

CO2 EMITTED (TOTAL) =	126. TON/DY
CO2 EMITTED (TOTAL) =	2. MMSCFD @ 60°F
SEQUESTRATION READY CO2 =	1970. TON/DY
SEQUESTRATION READY CO2 =	34. MMSCFD @ 60°F
CO2 EMITTED / NG FED =	0.16 LB/LB

NUCLEAR INTEGRATION REQUIREMENTS:

TOTAL ELECTRICITY DEMAND =	15.3 MW
TOTAL HEAT DEMAND =	166.6 MW
TOTAL HEAT DEMAND =	568.4 MMBTU/HR
HELIUM FLOWRATE REQUIRED =	630342. LB/HR
HELIUM FLOWRATE REQUIRED =	79.42 KG/S
HELIUM SUPPLY TEMPERATURE =	1562. DEG. F.
HELIUM SUPPLY TEMPERATURE =	850. DEG. C.

```
    HELIUM RETURN TEMPERATURE =             835. DEG. F.
    HELIUM RETURN TEMPERATURE =             446. DEG. C.


  EFFICIENCY CALCULATIONS:

    OVERALL PROCESS THERMAL EFFICIENCY:
      ASSUMPTIONS:
        (1) FOR STEAM EXPORT - HEAT RECOVERY CREDIT
            ASSUMES SATURATED LIQUID AT ATMOSPHERIC PRESSURE
        (2) FOR ELECTRICITY IMPORT - ELECTRICAL
            GENERATION EFFICIENCY OF 39.0%

      HHV BASIS =                               82.2%
      LHV BASIS =                               74.9%

    OVERALL PROCESS COLD GAS EFFICIENCY:
      (INCLUDES ONLY NATURAL GAS FEED AND HYDROGEN PRODUCT)

      HHV BASIS =                              117.1%
      LHV BASIS =                              109.8%

    OTHER PERFORMANCE METRICS:

      HYDROGEN PRODUCT TO NATURAL GAS FEED = 3.77 SCF/SCF
      (CONVENTIONAL PROCESS IS AROUND 2.5)

      STEAM EXPORT TO HYDROGEN PRODUCT =     1.83 TON/TON
      (CONVENTIONAL PROCESS IS TYPICALLY BETWEEN 5 AND 18)


Calculator Block AIRPROPS

  HUMIDITY DATA FOR STREAM PRI-AIR:
    HUMIDITY RATIO =                          43.5 GRAINS/LB
    RELATIVE HUMIDITY =                       39.0 %


Calculator Block NG-RFMR  Hierarchy: REFORMER

  SULFUR REMOVAL CONDITIONS:

    INLET BED TEMPERATURE =                 700. °F

  PRIMARY REFORMER CONDITIONS:

    STAGE 1:

      INLET TEMPERATURE =                  1000. °F
      STEAM TO CARBON MOLAR RATIO =           3.00
      OUTLET TEMPERATURE =                 1517. °F
      METHANE CONVERSION =                   64.0 %

    STAGE 2:

      INLET TEMPERATURE =                  1517. °F
      STEAM TO CARBON MOLAR RATIO =           2.05
      OUTLET TEMPERATURE =                 1600. °F
      METHANE CONVERSION =                   34.4 %

    OVERALL METHANE CONVERSION =             76.3 %


Calculator Block GASCLEAN Hierarchy: GAS-CLN
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Case 5 - 875C ROT

WATER GAS SHIFT CONDITIONS:

HIGH-TEMPERATURE SHIFT REACTOR:

INLET TEMPERATURE = (MINIMUM ALLOWABLE = 600°F)	635. °F
INLET STEAM:DRY GAS RATIO = (MINIMUM ALLOWABLE = 0.4)	0.50
OUTLET TEMPERATURE =	764. °F
OUTLET CO (DRY BASIS) =	3.01 MOL.%

LOW-TEMPERATURE SHIFT REACTOR:

INLET DEW TEMPERATURE =	331. °F
INLET TEMPERATURE = (SHOULD BE AT LEAST 375°F) (SHOULD BE AT LEAST 27°F ABOVE DEW TEMPERATURE)	375. °F
INLET STEAM:DRY GAS RATIO = (MINIMUM ALLOWABLE = 0.3)	0.37
OUTLET TEMPERATURE =	415. °F
OUTLET CO (DRY BASIS) =	0.33 MOL.%

SELEXOL PERFORMANCE:

INLET CO2 CONCENTRATION =	17.7 %
OUTLET CO2 CONCENTRATION =	0.2 %
CO2 CAPTURE =	99.0 %
CO2 PURITY =	99.0 %
SELEXOL UTILITY REQUIREMENTS:	
ELECTRICITY USAGE =	2.2 MW
STEAM USAGE =	71874. LB/HR

CO2 COMPRESSION:

PRESSURE =	2015. PSIA
ELECTRICITY USAGE =	6.5 MW

PSA PERFORMANCE:

HYDROGEN RECOVERY =	88.0 %
HYDROGEN PURITY =	99.90 %

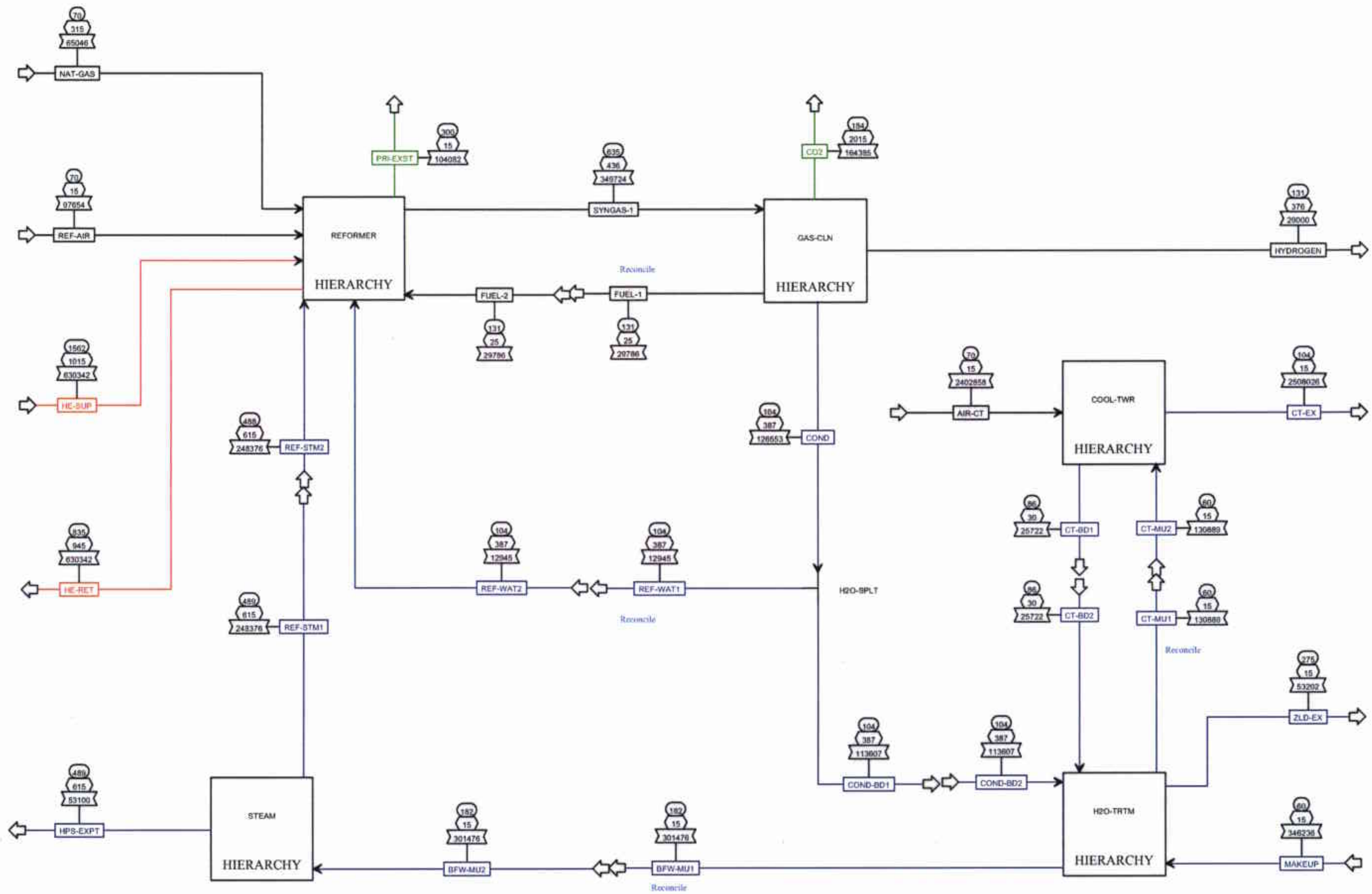
Hydrogen from Natural Gas
(With Sequestration; With Recycle)
(ROT = 875C; He Supply = 850C)

Temperature (F)
Pressure (psi)
Mass Flow Rate (lb/hr)

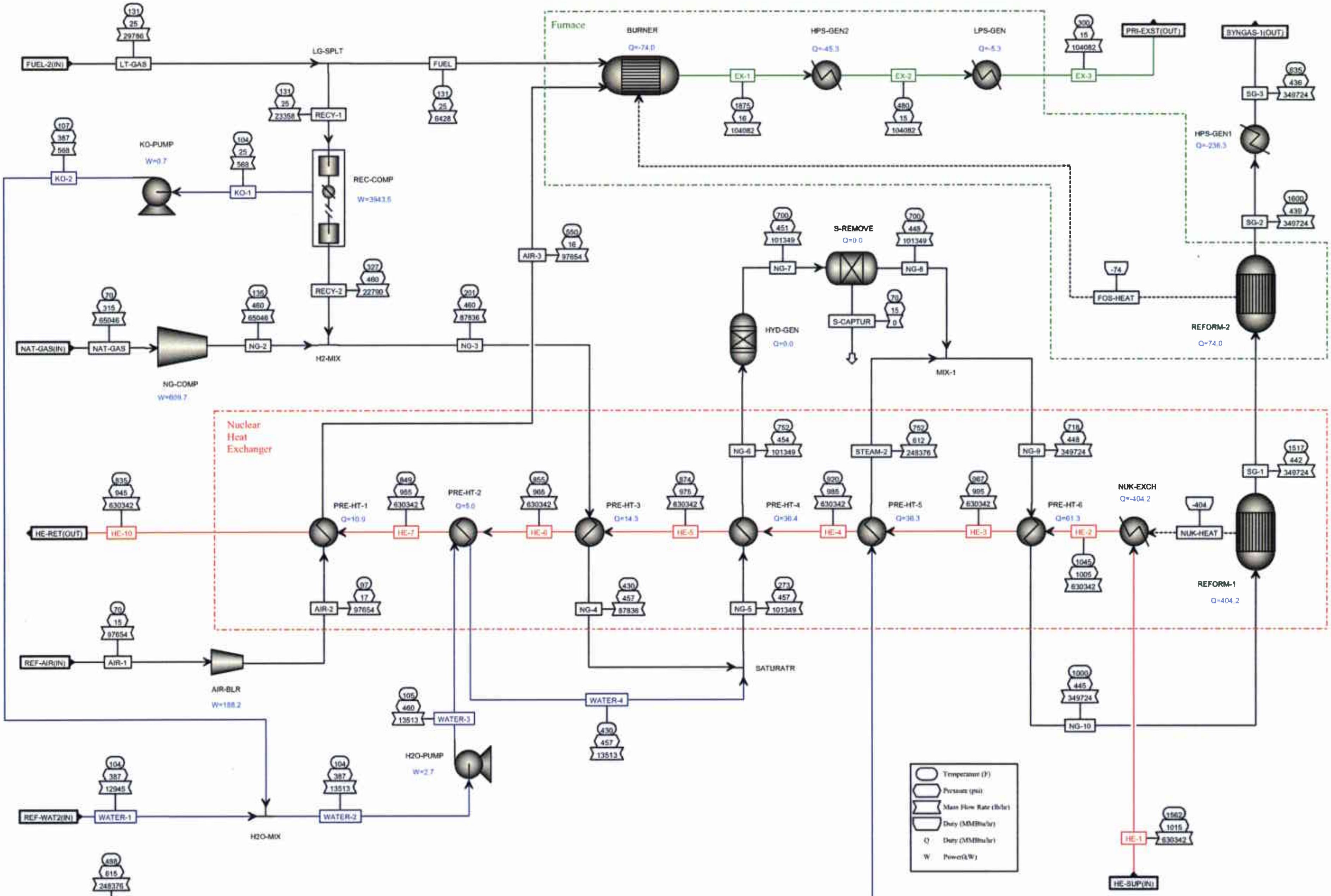
Color Legend

Water or Steam

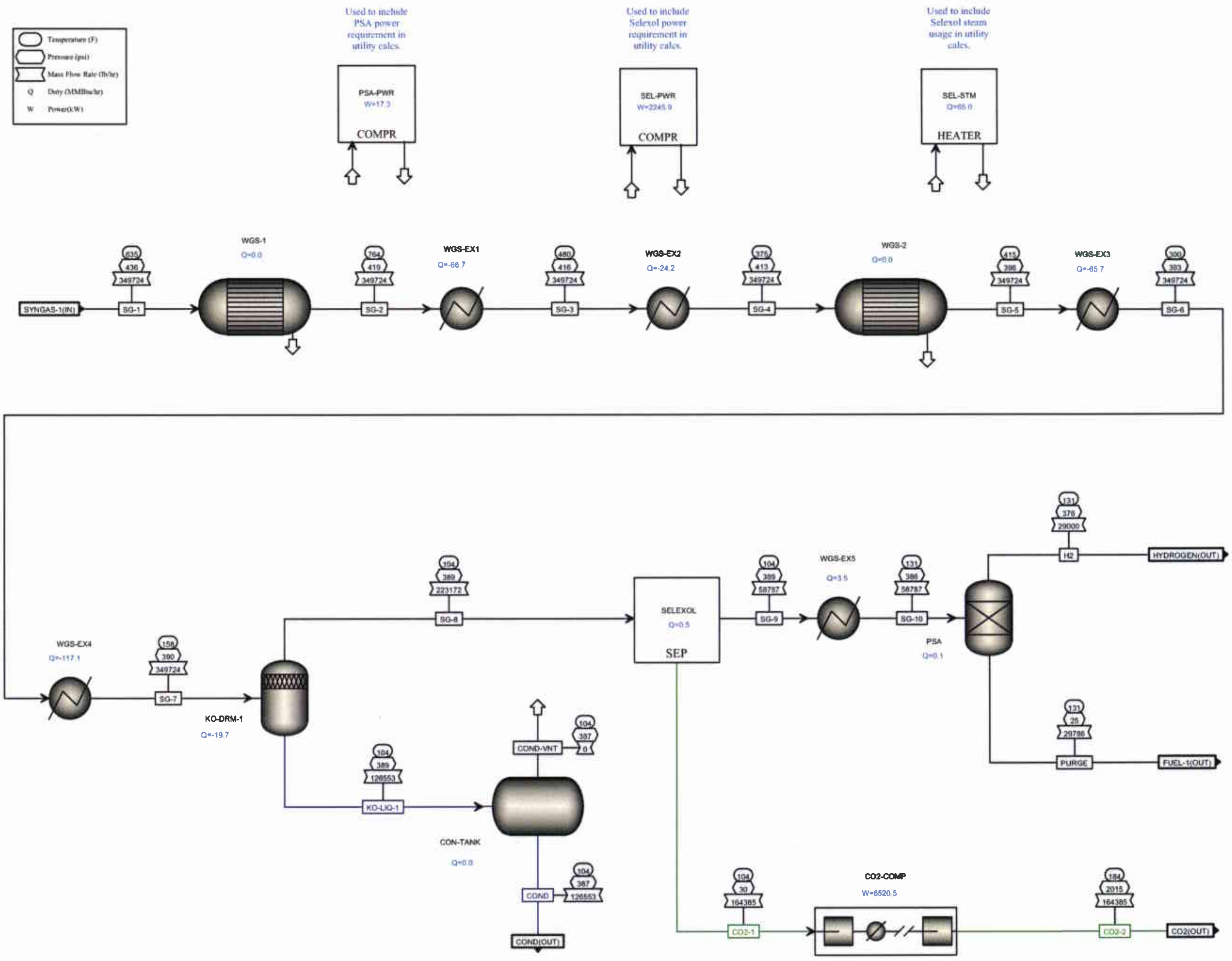
CO2 Emissions Source



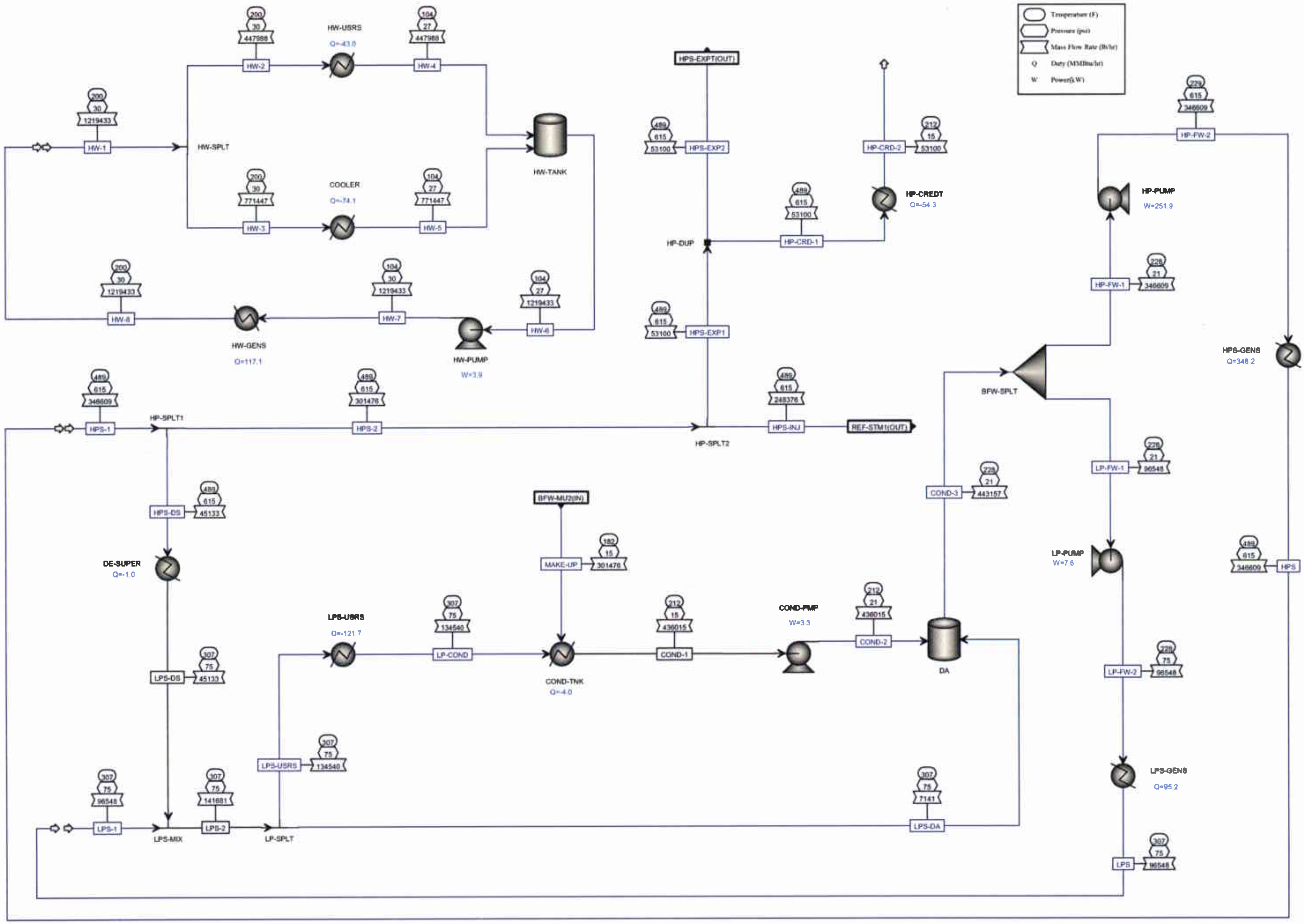
Natural Gas Steam Reforming



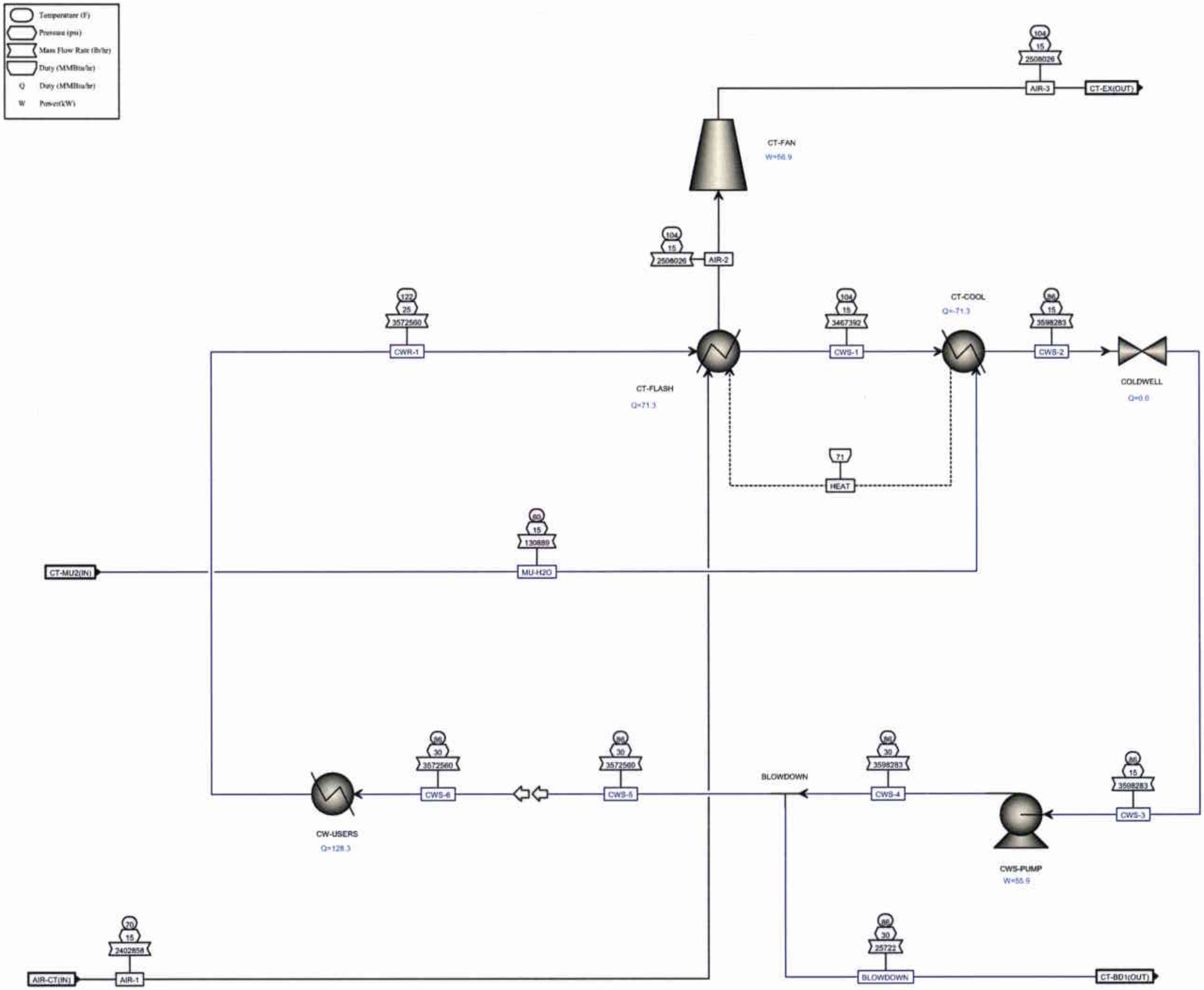
Syngas Cleaning & Conditioning



Steam System



Cooling Tower



Simplified Water Treatment