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ENGINEERING SERVICES FOR THE NEXT GENERATION NUCLEAR PLANT (NGNP) WITH HYDROGEN PRODUCTION

Nuclear Heat Supply System Point Design Study for NGNP Conceptual Design

Prepared by General Atomics
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ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
BTU	British Thermal Unit (unit of energy measure)
C	Centigrade (unit of temperature measure)
CD	Conceptual Design
F	Fahrenheit (unit of temperature measure)
ft	Feet (unit of linear measure)
hp	Horsepower (unit of power measure)
in-Hg	Inches of mercury (unit of pressure measure)
kg	Kilogram (unit of force or weight measure)
lb	Pound (unit of force or weight measure)
m	Meter (unit of linear measure)
MHTGR	Modular High Temperature Gas Reactor
mm	Mille meter (unit of linear measure)
MPa	Mega Pascal (unit of pressure measure)
MW	Mega Watt (unit of power measure)
NGNP	Next Generation Nuclear Power
PCS	Power Conversion System
psia	Pounds per square inch, absolute
sec	Second (unit of time measure)
SG or S.G.	Steam Generator
Tonne	Metric ton (1000 kilograms)

1 INTRODUCTION

The pre-conceptual design studies performed by the Next Generation Nuclear Plant (NGNP) project resulted in the conclusion that a primary mission for the NGNP should be co-generation of electricity and high-temperature process steam [INL 2007]. Also, a decision was made by the NGNP Project in October 2008 to reduce the nominal reactor outlet helium temperature for the NGNP from 950°C into the range of 750°C to 800°C with a corresponding reduction in the reactor inlet helium temperature [INL 2008] [SRM 2009].

Other key NGNP parameters for the process-steam application include reactor power level and the temperature of the steam produced by the steam generator. In the PCS Alternatives and Selection Study [PCS 2008], GA performed steam generator design evaluations for NGNP heat transport configurations having direct and indirect PCS cycles and single and dual heat transport loops. In all cases considered, the reactor power was 600 MW, the reactor outlet helium temperature was 750°C, and steam was produced at 540°C.

Prior to the start of NGNP CD, a limited-scope evaluation was performed to determine the effect of certain reactor operating parameters on a plant designed for co-generation of electricity and high-temperature process steam. The parameters and ranges addressed in this study are:

- Reactor Power Level: 350 – 600 MW
- Reactor Outlet Helium Temperature: 750°C -800°C
- Steam Temperature: 540°C - 600°C

This report provides the results of the study. The assumptions made for the study are first identified and the key evaluation criteria are itemized. A summary and discussion of the results are then given, followed by a section that summarizes the conclusions of the study.

2 ASSUMPTIONS AND EVALUATION CRITERIA

2.1 Assumptions

The key assumptions for the current limited-scope point design study are as follows:

1. Heat Transport System Configuration - The heat transport configuration is the single-loop direct steam cycle configuration with the steam generator in the primary loop as shown in Figure 1. This configuration was selected based on the results given in the PCS Alternatives and Selection Study [GA 2008], which indicate that this configuration has the best economics of the alternatives studied. The steam generator in this configuration is assumed to be a once-through, counter-flow, helical coil design similar to the MHTGR steam generator design [MHTGR 1987]. The design employs two tube bundles, an economizer, evaporator, superheater bundle with the tubes manufactured from 2¼ Cr-1Mo material and a finishing superheater bundle with the tubes manufactured from Inconel 800H material. The two bundles are interconnected by bi-metallic weld joints in the tubes between the bundles.

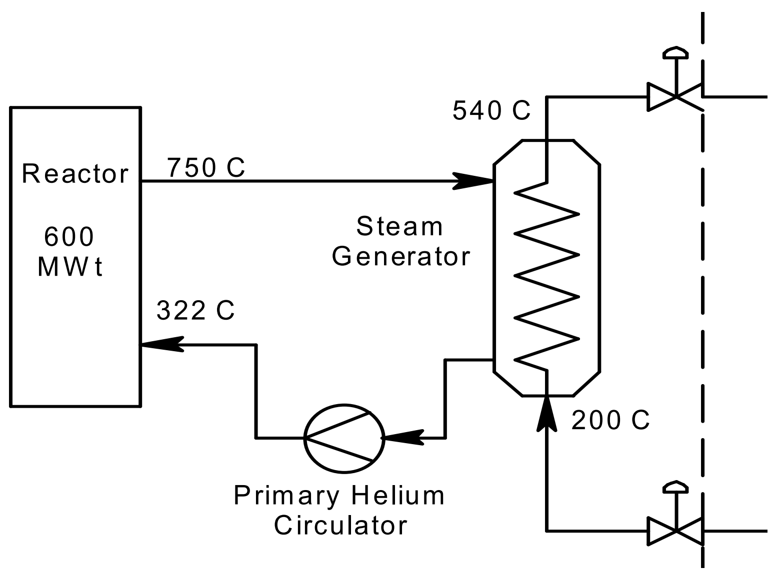

Figure 1. Heat Transport Configuration

2. Plant Application - The plant application is co-generation of process steam and electricity. In this configuration, electricity is produced by a steam turbine in the secondary system powered by steam from the steam generator in the primary loop. The process steam is produced in steam-to-steam heat exchangers (i.e., “re-boilers”) in the secondary loop. Re-boilers were assumed in order to provide physical separation of the process steam and return water supply system from the secondary system steam and water supply. Separate re-boilers could be used to supply process steam at various steam conditions (various pressures and temperatures). Secondary steam could be provided to re-boilers at conditions other than steam generator conditions by use of turbine extraction steam.

3. Multiple Module Plant – Economic applications will require multiple reactor modules and the reactor modules will be coupled to a single steam header used to provide steam to the re-boilers and to a steam turbine to generate electricity. Sufficient modules will be provided to ensure meeting process-steam availability requirements.
4. Secondary Steam Conditions – The nominal steam generator outlet superheated steam conditions were assumed to be 541°C and 17.3 MPa. These steam conditions (1005°F, 2515 psia) are the steam conditions used in most prior GA high temperature gas cooled reactor steam power plant designs, e.g. [MHTGR 1987] and correspond to steam conditions commonly used in fossil-fired steam power plants. Supercritical steam conditions of 593°C and 24.2 MPa (1100ºF, 3515 psia) were also evaluated because of the trend toward supercritical conditions for contemporary steam power plants. Steam-to-steam reheating was assumed for both the superheat and supercritical steam conditions.

2.2 Key Evaluation Criteria

The key criteria used in this point design parameter study are based on the potential for achieving a practical steam generator design. For the purposes of this evaluation, steam generator thermal-hydraulic and mechanical design parameters were selected that have been previously shown to be appropriate for the MHTGR design. Using these design parameters, steam generator designs were derived for the following alternative discrete point design conditions:

- Reactor Power: 450 MW and 600 MW
- Reactor Outlet temperature: 750°C and 800°C
- Steam Generation Conditions: a) Superheated steam (541°C, 17.3 MPa)
  b) Supercritical steam (593°C, 24.2 MPa)

A reactor power of 350 MW was not used as a design point in these calculations because the results for 450 MW envelop those for 350 MW with respect to the limiting criteria discussed below.

The most limiting resultant steam generator parameters were found to be (1) the overall shipping weight of the SG assembly, and (2) maximum SG helical coil tube wall temperature. All of the other steam generator parameters were either selected to be within an acceptable range or were computed to be within an acceptable range. The limits used in this study for the two most limiting design parameters and the basis for each is as follows

- Maximum transport weight: 665 tonne
  Basis: Transport weight demonstrated to be practical for most sites

- Maximum allowable tube wall temperature: 760°C
  Basis: Maximum allowable temperature in Section III of the ASME Boiler and Pressure Vessel Code for Incoloy 800H

3 SUMMARY AND DISCUSSION OF RESULTS

3.1 Summary of Results

The cases investigated in this study and the values determined for the two most limiting design parameters as identified in Section 2 are summarized in Table 1. Appendix A contains more detailed results.

Table 1. Steam Generation Design Cases for Alternative Point Design Conditions

Case	Reactor Power, MW	Core Outlet Temperature, °C	Steam Temperature, °C	Steam Pressure, MPa	S.G. Transport Weight, Tonne	Maximum Tube Wall Temperature, °C
1	450	750	541	17.3	402	732
2	450	800	541	17.3	376	771
3	450	750	593	24.2	641	754
4	450	800	593	24.2	578	798
5	600	750	541	17.3	467	735
6	600	800	541	17.3	437	775
7	600	750	593	24.2	788	756
8	600	800	593	24.2	711	801

Note: Highlighted parameters are parameters that do not satisfy criteria given in the previous Section (i.e., Weight ≤ 665 tonne; Maximum Incoloy 800 tube temperature ≤ 760°C.

To evaluate the merits of using supercritical steam conditions relative to those of superheated steam, a simple steam turbine cycle with steam-to-steam reheat was assumed coupled to the primary loop shown in Figure 1. Overall cycle thermal performance was derived for both 450-MW and 600-MW reactor powers and for both superheated steam conditions and supercritical steam conditions. The results are summarized in Figures 2 through 5. Detail results are provided in Appendix B.

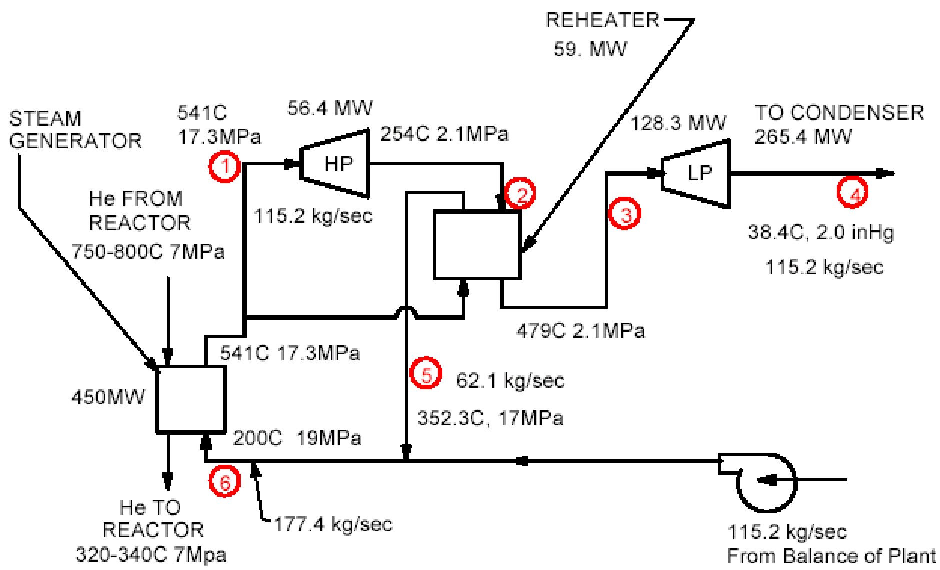

Figure 2. 450-MW Superheated Steam with Steam-to-Steam Reheat: Efficiency = 41.0%

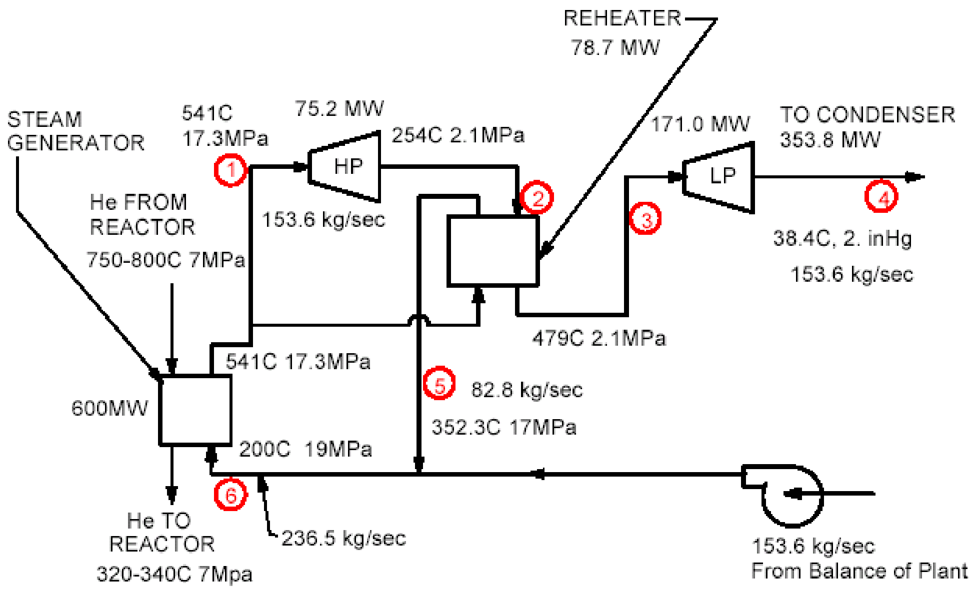

Figure 3. 600-MW Superheated Steam with Steam-to-Steam Reheat: Efficiency = 41.0%

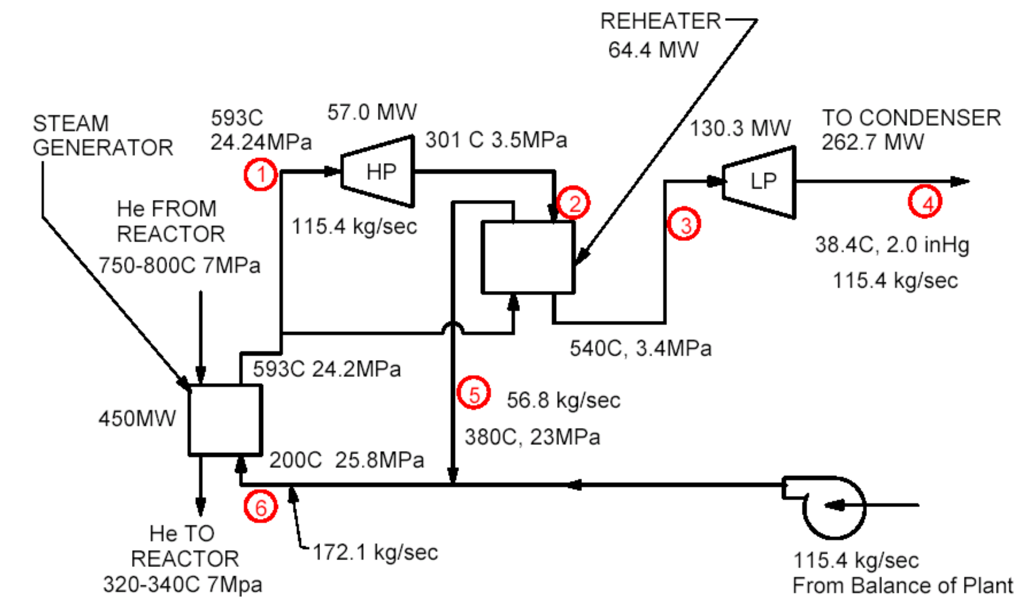

Figure 4. 450-MW Supercritical Steam with Steam-to-Steam Reheat: Efficiency = 41.6%

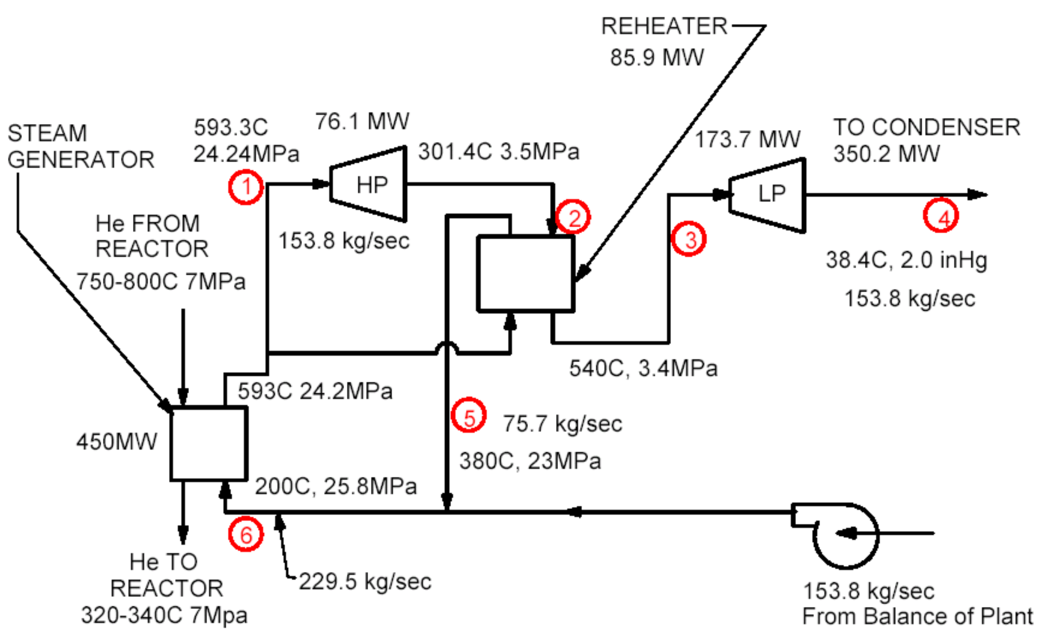

Figure 5. 600-MW Supercritical Steam with Steam-to-Steam Reheat: Efficiency = 41.6%

3.2 Discussion of Results

Table 1 shows that for all cases having a reactor outlet temperature of 800°C, the maximum tube wall temperature exceeds the maximum allowable temperature of 760°C. The maximum tube wall temperature occurs in the finishing superheater section at the steam generator steam outlet end. This is the SG region where the core outlet helium (highest temperature helium) enters the SG. The computed temperatures are at the outside of the tube wall on the helium coolant side of the tube. The computed temperatures include the following allowances for uncertainties and hot streaks:

- 60°C for water temperature
- 35°C for helium temperature
- a local 1.35 multiplying factor on the helium side heat transfer coefficient to account for circumferential variation in heat transfer coefficient
- a local 1.28 multiplying factor on the helium side heat transfer coefficient to account for a 50% local flow maldistribution effect

These allowances are based on GA's experience in the design and analysis of helical coil steam generators, including analyses of actual operating performance data accumulated over several years.

With a core outlet helium temperature of 800°C, use of Incoloy 800H material for components at the hot end of the steam generator is questionable. An alternative to 800H would be a higher-temperature material such as Inconel 617. However, use of this material, or similar high-temperature materials, would drive up technology development costs as well as capital costs. Also, the cobalt content of Inconel 617 and other high temperature materials could be an issue with regard to the impact on circulating and plateout activity in the primary circuit. There is, however, no need for an 800°C core outlet temperature to generate either superheated steam or supercritical steam at attractive conditions.

The transportation weight of steam generators to produce supercritical steam for a 600-MW reactor exceeds the selected transportation weight criteria. Dual loops could be used, but that may be economically unattractive.

The key result from the performance calculations summarized in Figures 2 through 5 is that there does not appear to be a significant benefit for use of supercritical steam for electricity production. As shown in these figures, the thermal efficiency for generation of electricity using supercritical steam is only marginally better than that for superheated steam (41.6% vs. 41.0%).

There is a higher risk for development of water leaks into the primary system for production of supercritical steam due to higher pressure supercritical steam condition. In addition to the higher risk for water leaks, the higher pressure would also tend to drive more water ingress should any leaks develop. The marginally-better thermal efficiency potential from use of supercritical steam conditions is not considered adequate to justify the higher risk that supercritical steam poses to the primary system.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The overall conclusions of this limited scope study are as follows:

- A 750°C core outlet coolant temperature can be used to produce superheated steam at attractive conditions (541°C, 17.3 MPa) for co-generation applications (process steam + electricity). This capability is independent of reactor thermal power (applies to full point design power range, 350 MW - 600 MW).
- It is estimated that a core outlet temperature of 750°C can also be used to produce superheated steam at 600°C, 17.3 MPa for reactor powers in the range of 350 MW to 600 MW. The SG transport weight would increase slightly (<20%) over that for the 541°C case; the maximum tube wall temperature would be about the same as that for the 593°C case. Both the weight and tube wall temperature criteria would be satisfied.
- Use of a core outlet coolant temperature of 800°C will most likely require use of higher temperature materials in the steam generator resulting in increased costs for technology development and capital cost.
- Generation of supercritical steam (593°C, 24.2 MPa) is possible using 750°C core outlet coolant temperature for reactor power up to 450 MW, but the overall steam generator weight becomes excessive for a 600-MW reactor.
- There is small incentive to use supercritical steam and the use of supercritical steam poses higher risks for water ingress into the primary system.

4.2 Point Design Recommendations

The point design recommendations are as follows:

- Based on the evaluations performed in this study, all reactor power levels in the range of 350 MW to 600 MW are acceptable. A more detailed evaluation is required for selection of a specific reactor power level in this range and must include consideration of specific potential applications.
- For a process steam/electricity co-generation plant, steam generated by a steam generator in the primary system should be superheated steam at commonly used conditions such as 541°C, 17.3 MPa (1005°F, 2515 psia). However, the steam temperature can be raised to 600°C without undue risk so any steam temperature in the 541°C to 600°C range should be acceptable. Selection of a specific temperature within this range should take actual potential applications into consideration.
- The point design for mixed mean reactor core coolant outlet temperature should be 750°C. Temperatures above 750°C could require more expensive materials in the SG and would likely require additional technology development. A core outlet temperature of 750°C is adequate for generating steam up to 600°C and possibly somewhat higher temperatures. Steam at temperatures up to 600°C is sufficient to satisfy a wide range of process steam applications [MPR 2008].

5 REFERENCES

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APPENDIX A: STEAM GENERATOR PARAMETERS

STEAM GENERATOR - SUPERHEATED STEAM 450 MW - 750°C Helium

Steam Generator Heat Duty	$Q_{mod} = 450\,MW$	$Q_{mod} = 1.54 \times 10^{9}\,\frac{BTU}{hr}$
Helium Inlet Temperature	$TCHe_6 = 750\,°C$	$TFHe_6 = 1382\,°F$
Helium Outlet Temperature	$TCHe_1 = 318\,°C$	$TFHe_1 = 604.4\,°F$
Water Inlet Temperature	$TCH2O_1 = 200\,°C$	$TFH2O_1 = 392\,°F$
Steam Outlet Temperature	$TCH2O_6 = 540.6\,°C$	$TFH2O_6 = 1005\,°F$
Steam Generator Bundle Diameter	$Bundle_{OD} = 4648.2\,mm$	$Bundle_{OD} = 15.25\,ft$
Total Surface Area	$Area_{tot} = 2676.1\,m^2$	$Area_{tot} = 2.88 \times 10^{4}\,ft^2$
Total Vessel Height	$Ves_{height} = 1.58 \times 10^{4}\,mm$	$Ves_{height} = 51.99\,ft$
Shipping Weight	$W_{ship} = 401.6\,tonne$	$W_{ship} = 442.6\,ton$
Wall temp at Superheater outlet	$TCwall_{out_7} = 731.7\,°C$	$TFwall_{out_7} = 1349\,°F$

<u>NOTE:</u> The steam generator tube wall temperatures include correction factors that account for uncertainty in local helium and water temperatures, helium side heat transfer coefficient circumferential variations and local helium velocity peaks.

STEAM GENERATOR - SUPERHEATED STEAM 450 MW 800°C Helium

Steam Generator Heat Duty	$Q_{mod} = 450\,MW$	$Q_{mod} = 1.54 \times 10^9 \frac{BTU}{hr}$
Helium Inlet Temperature	$TCHe_6 = 800\,°C$	$TFHe_6 = 1472\,°F$
Helium Outlet Temperature	$TCHe_1 = 340\,°C$	$TFHe_1 = 644\,°F$
Water Inlet Temperature	$TCH2O_1 = 200\,°C$	$TFH2O_1 = 392\,°F$
Steam Outlet Temperature	$TCH2O_6 = 540.6\,°C$	$TFH2O_6 = 1005\,°F$
Steam Generator Bundle Diameter	$Bundle_{OD} = 4648.2\,mm$	$Bundle_{OD} = 15.25\,ft$
Total Surface Area	$Area_{tot} = 2234.7\,m^2$	$Area_{tot} = 2.41 \times 10^4\,ft^2$
Total Vessel Height	$Ves_{height} = 1.52 \times 10^4\,mm$	$Ves_{height} = 49.81\,ft$
Shipping Weight	$W_{ship} = 375.7\,tonne$	$W_{ship} = 414.2\,ton$
Wall temp at Superheater outlet	$TCwall_{out_7} = 770.8\,°C$	$TFwall_{out_7} = 1419.4\,°F$

NOTE: The steam generator tube wall temperatures include correction factors that account for uncertainty in local helium and water temperatures, helium side heat transfer coefficient circumferential variations and local helium velocity peaks.

STEAM GENERATOR – SUPER-CRITICAL STEAM 450 MW 750°C Helium

Steam Generator Heat Duty	$Q_{mod} = 450\,MW$	$Q_{mod} = 1.54 \times 10^{9} \frac{BTU}{hr}$
Helium Inlet Temperature	$TCHe_6 = 750\,°C$	$TFHe_6 = 1382\,°F$
Helium Outlet Temperature	$TCHe_1 = 318\,°C$	$TFHe_1 = 604.4\,°F$
Water Inlet Temperature	$TC_{w_1} = 200.05\,°C$	$TF_{w_1} = 392.1\,°F$
Steam Outlet Temperature	$TC_{w_6} = 593.3\,°C$	$TF_{w_6} = 1100\,°F$
Steam Generator Bundle Diameter	$Bundle_{OD} = 4648.2\,mm$	$Bundle_{OD} = 15.25\,ft$
Total Surface Area	$Area_{tot} = 4171.31\,m^2$	$Area_{tot} = 4.49 \times 10^4\,ft^2$
Total Vessel Height	$Ves_{height} = 1.9 \times 10^4\,mm$	$Ves_{height} = 62.41\,ft$
Shipping Weight	$W_{ship} = 640.8\,tonne$	$W_{ship} = 706.4\,ton$
Max tube temp at steam outlet	$TCwall_{out_6} = 754.2\,°C$	$TFwall_{out_6} = 1389.6\,°F$

NOTE: The steam generator tube wall temperatures include correction factors that account for uncertainty in local helium and water temperatures, helium side heat transfer coefficient circumferential variations and local helium velocity peaks.

STEAM GENERATOR – SUPER-CRITICAL STEAM 450 MW 800°C Helium

Steam Generator Heat Duty	$Q_{mod} = 450\,MW$	$Q_{mod} = 1.54 \times 10^9 \frac{BTU}{hr}$
Helium Inlet Temperature	$TCHe_6 = 800\,°C$	$TFHe_6 = 1472\,°F$
Helium Outlet Temperature	$TCHe_1 = 340\,°C$	$TFHe_1 = 644\,°F$
Water Inlet Temperature	$TC_{w_1} = 200.02\,°C$	$TF_{w_1} = 392\,°F$
Steam Outlet Temperature	$TC_{w_6} = 593.3\,°C$	$TF_{w_6} = 1100\,°F$
Steam Generator Bundle Diameter	$Bundle_{OD} = 4648.2\,mm$	$Bundle_{OD} = 15.25\,ft$
Total Surface Area	$Area_{tot} = 3379.86\,m^2$	$Area_{tot} = 3.64 \times 10^4\,ft^2$
Total Vessel Height	$Ves_{height} = 1.77 \times 10^4\,mm$	$Ves_{height} = 57.92\,ft$
Shipping Weight	$W_{ship} = 578.3\,tonne$	$W_{ship} = 637.5\,ton$
Max tube temp at steam outlet	$TCwall_{out_6} = 798.2\,°C$	$TFwall_{out_6} = 1468.7\,°F$

NOTE: The steam generator tube wall temperatures include correction factors that account for uncertainty in local helium and water temperatures, helium side heat transfer coefficient circumferential variations and local helium velocity peaks.

STEAM GENERATOR – SUPERHEATED STEAM 600 MW - 750°C Helium

Steam Generator Heat Duty	$Q_{mod} = 610\,MW$	$Q_{mod} = 2.08 \times 10^{9}\,\frac{BTU}{hr}$
Helium Inlet Temperature	$TCHe_6 = 750\,°C$	$TFHe_6 = 1382\,°F$
Helium Outlet Temperature	$TCHe_1 = 318\,°C$	$TFHe_1 = 604.4\,°F$
Water Inlet Temperature	$TCH2O_1 = 200\,°C$	$TFH2O_1 = 392\,°F$
Steam Outlet Temperature	$TCH2O_6 = 540.6\,°C$	$TFH2O_6 = 1005\,°F$
Steam Generator Bundle Diameter	$Bundle_{OD} = 4648.2\,mm$	$Bundle_{OD} = 15.25\,ft$
Total Surface Area	$Area_{tot} = 3193.62\,m^2$	$Area_{tot} = 3.44 \times 10^{4}\,ft^2$
Total Vessel Height	$Ves_{height} = 1.66 \times 10^{4}\,mm$	$Ves_{height} = 54.43\,ft$
Shipping Weight	$W_{ship} = 467.4\,tonne$	$W_{ship} = 515.3\,ton$
Wall temp at Superheater outlet	$TCwall_{out_7} = 735.1\,°C$	$TFwall_{out_7} = 1355.1\,°F$

NOTE: The steam generator tube wall temperatures include correction factors that account for uncertainty in local helium and water temperatures, helium side heat transfer coefficient circumferential variations and local helium velocity peaks.

STEAM GENERATOR – SUPERHEATED STEAM 600 MW - 800°C Helium

Steam Generator Heat Duty	$Q_{mod} = 610\,MW$	$Q_{mod} = 2.08 \times 10^{9}\,\frac{BTU}{hr}$
Helium Inlet Temperature	$TCHe_6 = 800\,°C$	$TFHe_6 = 1472\,°F$
Helium Outlet Temperature	$TCHe_1 = 340\,°C$	$TFHe_1 = 644\,°F$
Water Inlet Temperature	$TCH2O_1 = 200\,°C$	$TFH2O_1 = 392\,°F$
Steam Outlet Temperature	$TCH2O_6 = 540.6\,°C$	$TFH2O_6 = 1005\,°F$
Steam Generator Bundle Diameter	$Bundle_{OD} = 4648.2\,mm$	$Bundle_{OD} = 15.25\,ft$
Total Surface Area	$Area_{tot} = 2664.84\,m^2$	$Area_{tot} = 2.87 \times 10^4\,ft^2$
Total Vessel Height	$Ves_{height} = 1.58 \times 10^4\,mm$	$Ves_{height} = 51.84\,ft$
Shipping Weight	$W_{ship} = 436.6\,tonne$	$W_{ship} = 481.3\,ton$
Wall temp at Superheater outlet	$TCwall_{out_7} = 775.1\,°C$	$TFwall_{out_7} = 1427.1\,°F$

NOTE: The steam generator tube wall temperatures include correction factors that account for uncertainty in local helium and water temperatures, helium side heat transfer coefficient circumferential variations and local helium velocity peaks.

STEAM GENERATOR – SUPER-CRITICAL STEAM 600 MW - 750°C Helium

Exceeds Weight Limit

Steam Generator Heat Duty	$Q_{mod} = 610\,MW$	$Q_{mod} = 2.08 \times 10^{9} \frac{BTU}{hr}$
Helium Inlet Temperature	$TCHe_6 = 750\,°C$	$TFHe_6 = 1382\,°F$
Helium Outlet Temperature	$TCHe_1 = 318\,°C$	$TFHe_1 = 604.4\,°F$
Water Inlet Temperature	$TC_{w_1} = 200.03\,°C$	$TF_{w_1} = 392.1\,°F$
Steam Outlet Temperature	$TC_{w_6} = 593.3\,°C$	$TF_{w_6} = 1100\,°F$
Steam Generator Bundle Diameter	$Bundle_{OD} = 4648.2\,mm$	$Bundle_{OD} = 15.25\,ft$
Total Surface Area	$Area_{tot} = 5126.37\,m^2$	$Area_{tot} = 5.52 \times 10^4\,ft^2$
Total Vessel Height	$Ves_{height} = 2.07 \times 10^4\,mm$	$Ves_{height} = 67.79\,ft$
Shipping Weight	$W_{ship} = 787.9\,tonne$	$W_{ship} = 868.5\,ton$
Max tube temp at steam outlet	$TCwall_{out_6} = 756\,°C$	$TFwall_{out_6} = 1392.8\,°F$

NOTE: The steam generator tube wall temperatures include correction factors that account for uncertainty in local helium and water temperatures, helium side heat transfer coefficient circumferential variations and local helium velocity peaks.

STEAM GENERATOR – SUPER-CRITICAL STEAM 600 MW - 800°C Helium

Exceeds Weight Limit

Steam Generator Heat Duty	$Q_{mod} = 610\,MW$	$Q_{mod} = 2.08 \times 10^{9}\,\frac{BTU}{hr}$
Helium Inlet Temperature	$TCHe_6 = 800\,°C$	$TFHe_6 = 1472\,°F$
Helium Outlet Temperature	$TCHe_1 = 340\,°C$	$TFHe_1 = 644\,°F$
Water Inlet Temperature	$TC_{w_1} = 200.01\,°C$	$TF_{w_1} = 392\,°F$
Steam Outlet Temperature	$TC_{w_6} = 593.3\,°C$	$TF_{w_6} = 1100\,°F$
Steam Generator Bundle Diameter	$Bundle_{OD} = 4648.2\,mm$	$Bundle_{OD} = 15.25\,ft$
Total Surface Area	$Area_{tot} = 4148.76\,m^2$	$Area_{tot} = 4.47 \times 10^4\,ft^2$
Total Vessel Height	$Ves_{height} = 1.9 \times 10^4\,mm$	$Ves_{height} = 62.25\,ft$
Shipping Weight	$W_{ship} = 710.7\,tonne$	$W_{ship} = 783.5\,ton$
Max tube temp at steam outlet	$TCwall_{out_6} = 800.6\,°C$	$TFwall_{out_6} = 1473.1\,°F$

NOTE: The steam generator tube wall temperatures include correction factors that account for uncertainty in local helium and water temperatures, helium side heat transfer coefficient circumferential variations and local helium velocity peaks.

APPENDIX B: POINT DESIGN CRITICAL PARAMETERS

POINT DESIGN PARAMETERS FOR 450MW SUPERHEATED STEAM

1. Gross Thermal Efficiency $\eta_t = 41.03\,\%$
2. High Pressure Turbine Heat Duty $Q_{hp} = 56.38\,MW$ $Q_{hp} = 7.56 \times 10^4\,hp$
3. High Pressure Turbine Steam Flow $W_1 = 115.22\,kg \cdot sec^{-1}$
   $W_1 = 254.01\,lb\,sec^{-1}$
4. High Pressure Turbine Inlet Temp $TTC_1 = 540.6\,°C$ $TTF_1 = 1005\,°F$
5. High Pressure Turbine Inlet Press $P_1 = 17.3\,MPa$ $P_1 = 2509.2\,psi$
6. High Pressure Turbine Outlet Temp $TTC_2 = 253.8\,°C$ $TTF_2 = 488.8\,°F$
7. High Pressure Turbine Outlet Press $P_2 = 2.1\,MPa$ $P_2 = 304.6\,psi$
8. Low Pressure Turbine Heat Duty $Q_{lp} = 128.27\,MW$ $Q_{lp} = 1.72 \times 10^5\,hp$
9. Low Pressure Turbine Steam Flow $W_2 = 115.22\,kg \cdot sec^{-1}$
   $W_2 = 254.01\,lb\,sec^{-1}$
10. Low Pressure Turbine Inlet Temp $TTC_3 = 479\,°C$ $TTF_3 = 894.2\,°F$
11. Low Pressure Turbine Inlet Press $P_3 = 2.1\,MPa$ $P_3 = 304.6\,psi$
12. Low Pressure Turbine Outlet Temp $TTC_4 = 38.4\,°C$ $TTF_4 = 101.1\,°F$
13. Low Pressure Turbine Outlet Press $P_4 = 0.01\,MPa$ $P_4 = 2\,in\_Hg$
14. Reheater Heat Duty $Q_{rh} = 59\,MW$
   $Q_{rh} = 2.01 \times 10^8\,BTU \cdot hr^{-1}$
15. Hot Steam Flow $W_5 = 62.14\,kg \cdot sec^{-1}$
   $W_5 = 136.99\,lb\,sec^{-1}$
16. Hot Steam Inlet Temp $TTC_1 = 540.6\,°C$ $TTF_1 = 1005\,°F$
17. Hot Steam Outlet Temp $TTC_5 = 352.3\,°C$ $TTF_5 = 666.1\,°F$
18. Cold Steam Flow $W_2 = 115.22\,kg \cdot sec^{-1}$
   $W_2 = 254.01\,lb\,sec^{-1}$
19. Cold Steam Inlet Temp $TTC_2 = 253.8\,°C$ $TTF_2 = 488.8\,°F$
20. Cold Steam Outlet Temp $TTC_3 = 479\,°C$ $TTF_3 = 894.2\,°F$

POINT DESIGN PARAMETERS FOR 450MW SUPER-CRITICAL STEAM

1. Gross Thermal Efficiency		$\eta_t = 41.63\%$
2. High Pressure Turbine Heat Duty	$Q_{hp} = 57.05\,MW$	$Q_{hp} = 7.65 \times 10^4\,hp$
3. High Pressure Turbine Steam Flow	$W_1 = 115.35\,kg \cdot sec^{-1}$	$W_1 = 254.31\,lb\,sec^{-1}$
4. High Pressure Turbine Inlet Temp	$TTC_1 = 593.3\,°C$	$TTF_1 = 1100\,°F$
5. High Pressure Turbine Inlet Press	$P_1 = 24.24\,MPa$	$P_1 = 3515.7\,psi$
6. High Pressure Turbine Outlet Temp	$TTC_2 = 301.4\,°C$	$TTF_2 = 574.6\,°F$
7. High Pressure Turbine Outlet Press	$P_2 = 3.5\,MPa$	$P_2 = 507.6\,psi$
8. Low Pressure Turbine Heat Duty	$Q_{lp} = 130.3\,MW$	$Q_{lp} = 1.75 \times 10^5\,hp$
9. Low Pressure Turbine Steam Flow	$W_2 = 115.4\,kg \cdot sec^{-1}$	$W_2 = 254.31\,lb\,sec^{-1}$
10. Low Pressure Turbine Inlet Temp	$TTC_3 = 540\,°C$	$TTF_3 = 1004\,°F$
11. Low Pressure Turbine Inlet Press	$P_3 = 3.43\,MPa$	$P_3 = 497.6\,psi$
12. Low Pressure Turbine Outlet Temp	$TTC_4 = 38.4\,°C$	$TTF_4 = 101.1\,°F$
13. Low Pressure Turbine Outlet Press	$P_4 = 0.01\,MPa$	$P_4 = 2\,in\_Hg$
14. Reheater Heat Duty	$Q_{rh} = 64.43\,MW$	$Q_{rh} = 2.2 \times 10^8\,BTU \cdot hr^{-1}$
15. Hot Steam Flow	$W_5 = 56.78\,kg \cdot sec^{-1}$	$W_5 = 125.17\,lb\,sec^{-1}$
16. Hot Steam Inlet Temp	$TTC_1 = 593.3\,°C$	$TTF_1 = 1100\,°F$
17. Hot Steam Outlet Temp	$TTC_5 = 379.6\,°C$	$TTF_5 = 715.2\,°F$
18. Cold Steam Flow	$W_2 = 115.35\,kg \cdot sec^{-1}$	$W_2 = 254.31\,lb\,sec^{-1}$
19. Cold Steam Inlet Temp	$TTC_2 = 301.4\,°C$	$TTF_2 = 574.6\,°F$
20. Cold Steam Outlet Temp	$TTC_3 = 540\,°C$	$TTF_3 = 1004\,°F$

POINT DESIGN PARAMETERS FOR 600MW SUPERHEATED STEAM

1. Gross Thermal Efficiency	$\eta_t = 41.03\%$	
2. High Pressure Turbine Heat Duty	$Q_{hp} = 75.2\,MW$	$Q_{hp} = 1 \times 10^5\,hp$
3. High Pressure Turbine Steam Flow	$W_1 = 153.6\,kg \cdot sec^{-1}$	
$W_1 = 338.7\,lb\,sec^{-1}$		
4. High Pressure Turbine Inlet Temp	$TTC_1 = 540.6\,°C$	$TTF_1 = 1005\,°F$
5. High Pressure Turbine Inlet Press	$P_1 = 17.3\,MPa$	$P_1 = 2509.2\,psi$
6. High Pressure Turbine Outlet Temp	$TTC_2 = 253.8\,°C$	$TTF_2 = 488.8\,°F$
7. High Pressure Turbine Outlet Press	$P_2 = 2.1\,MPa$	$P_2 = 304.6\,psi$
8. Low Pressure Turbine Heat Duty	$Q_{lp} = 171\,MW$	$Q_{lp} = 2.3 \times 10^5\,hp$
9. Low Pressure Turbine Steam Flow	$W_2 = 153.6\,kg \cdot sec^{-1}$	
$W_2 = 338.7\,lb\,sec^{-1}$		
10. Low Pressure Turbine Inlet Temp	$TTC_3 = 479\,°C$	$TTF_3 = 894.2\,°F$
11. Low Pressure Turbine Inlet Press	$P_3 = 2.1\,MPa$	$P_3 = 304.6\,psi$
12. Low Pressure Turbine Outlet Temp	$TTC_4 = 38.4\,°C$	$TTF_4 = 101.1\,°F$
13. Low Pressure Turbine Outlet Press	$P_4 = 0.007\,MPa$	$P_4 = 2\,in\_Hg$
14. Reheater Heat Duty	$Q_{rh} = 78.7\,MW$	
$Q_{rh} = 2.7 \times 10^8\,BTU \cdot hr^{-1}$		
15. Hot Steam Flow	$W_5 = 82.8\,kg \cdot sec^{-1}$	
$W_5 = 182.7\,lb\,sec^{-1}$		
16. Hot Steam Inlet Temp	$TTC_1 = 540.6\,°C$	$TTF_1 = 1005\,°F$
17. Hot Steam Outlet Temp	$TTC_5 = 352.3\,°C$	$TTF_5 = 666.1\,°F$
18. Cold Steam Flow	$W_2 = 153.6\,kg \cdot sec^{-1}$	
$W_2 = 338.7\,lb\,sec^{-1}$		
19. Cold Steam Inlet Temp	$TTC_2 = 253.8\,°C$	$TTF_2 = 488.8\,°F$
20. Cold Steam Outlet Temp	$TTC_3 = 479\,°C$	$TTF_3 = 894.2\,°F$

POINT DESIGN PARAMETERS FOR 600MW SUPER-CRITICAL STEAM

1. Gross Thermal Efficiency	$\eta_t = 41.63\,\%$	
2. High Pressure Turbine Heat Duty	$Q_{hp} = 76.06\,MW$	$Q_{hp} = 1.02 \times 10^5\,hp$
3. High Pressure Turbine Steam Flow	$W_1 = 153.81\,kg \cdot sec^{-1}$	$W_1 = 339.08\,lb\,sec^{-1}$
4. High Pressure Turbine Inlet Temp	$TTC_1 = 593.3\,°C$	$TTF_1 = 1100\,°F$
5. High Pressure Turbine Inlet Press	$P_1 = 24.24\,MPa$	$P_1 = 3515.7\,psi$
6. High Pressure Turbine Outlet Temp	$TTC_2 = 301.4\,°C$	$TTF_2 = 574.6\,°F$
7. High Pressure Turbine Outlet Press	$P_2 = 3.5\,MPa$	$P_2 = 507.6\,psi$
8. Low Pressure Turbine Heat Duty	$Q_{lp} = 173.74\,MW$	$Q_{lp} = 2.33 \times 10^5\,hp$
9. Low Pressure Turbine Steam Flow	$W_2 = 153.81\,kg \cdot sec^{-1}$	$W_2 = 339.08\,lb\,sec^{-1}$
10. Low Pressure Turbine Inlet Temp	$TTC_3 = 540\,°C$	$TTF_3 = 1004\,°F$
11. Low Pressure Turbine Inlet Press	$P_3 = 3.43\,MPa$	$P_3 = 497.6\,psi$
12. Low Pressure Turbine Outlet Temp	$TTC_4 = 38.4\,°C$	$TTF_4 = 101.1\,°F$
13. Low Pressure Turbine Outlet Press	$P_4 = 0.01\,MPa$	$P_4 = 2\,in\_Hg$
14. Reheater Heat Duty	$Q_{rh} = 85.91\,MW$	$Q_{rh} = 2.93 \times 10^8\,BTU \cdot hr^{-1}$
15. Hot Steam Flow	$W_5 = 75.7\,kg \cdot sec^{-1}$	$W_5 = 166.9\,lb\,sec^{-1}$
16. Hot Steam Inlet Temp	$TTC_1 = 593.3\,°C$	$TTF_1 = 1100\,°F$
17. Hot Steam Outlet Temp	$TTC_5 = 379.6\,°C$	$TTF_5 = 715.2\,°F$
18. Cold Steam Flow	$W_2 = 153.81\,kg \cdot sec^{-1}$	$W_2 = 339.08\,lb\,sec^{-1}$
19. Cold Steam Inlet Temp	$TTC_2 = 301.4\,°C$	$TTF_2 = 574.6\,°F$
20. Cold Steam Outlet Temp	$TTC_3 = 540\,°C$	$TTF_3 = 1004\,°F$

GENERAL ATOMICS
P.O. BOX 85608 SAN DIEGO, CA 92186-5608 (858) 455-3000