Document No. ECS-AF-200589

NGNP Phase B Conceptual Design Studies

WBS PCS.000.S01.

PCS ALTERNATIVES AND SELECTION STUDY

UNRESTRICTED REPORT

October 24, 2008

TOSHIBA Corporation

1. INTRODUCTION

Based on the results of the IHX and HTS alternatives study performed during Phase A of the conceptual design studies, it appears unlikely that it would be practical to use an indirect combined cycle PCS of prototypic size with a tube and shell type IHX because of the very large size of the IHX that would be needed. The more work was performed to evaluate the feasibility of using a printed circuit type compact IHX based on the Heatric design in Phase B.

2. HEAT TRANSPORT SYSTEM (HTS) ALTERNATIVES

The serial and parallel loop configuration considered in the PCS alternatives and selection is shown in Figure 2-1 and Figure 2-2. For instance, the design condition of PCS-side IHX is shown in Table 2-1, representatively.

3. DESIGN DESCRIPTION

3.1 Detail Evaluation of PCHE Module

3.1.1 Evaluation of Methodology to Size PCHE Module

In order to perform more detailed evaluation of methodology to size the PCHE module, the heat transfer calculation is verified using the specifications of the PCHE module designed by Heatric. A couple of equations to predict heat transfer shown below were compared.

- Kay's correlation for fully developed laminar flow
- Zigzag method recommended by General Atomics
- Colburn j-factor used for compact heat exchanger

The result of the zigzag method as shown in Table 3.1.1-5 is almost the same as one of Heatric. Therefore, Toshiba decided to adopt the zigzag method to size the PCHE module for the compact IHX because of the reasonableness, though the Colburn j-factor was used in consideration for conservation in Phase A.

3.1.2 Evaluation of Methodology to Estimate Pressure Drop

The total pressure drop was evaluated by the Weisbach's equation and the zigzag method. The result of the zigzag method as shown in Table 3.1.2-1 is almost the same as one of Heatric. Therefore, Toshiba decided to adopt the zigzag method to estimate the pressure drop PCHE module as well.

3.1.3 Resizing of PCHE Module

The dimensions of the PCHE module for Hot-stage, Cold-stage, PCS-side, and Small IHXs are shown in Table 3.1.3-1. The basic dimensions, that is, number of channels, height of module, and so on, are not changed. The number of modules and the length of module were adjusted not to exceed 40 kPa for the allowable pressure drop of IHX as the tentative target since the pressure drop increased by the zigzag method. The increased length of module is a little and there is no effect on the diameter of IHX. However, the height of IHX goes up due to the increased number of modules. The updated drawing of PCS-side IHX is representatively shown in Figure 3.1.3-3. If the effect of pressure drop is not ignored, the number of module has to be reviewed. Otherwise, it is possible to reduce the height of the IHX if the output of helium circulator is improved.

3.1.4 Effect of 80wt% Nitrogen / 20wt% Helium Mixture on PCHE Module

The effect of using 80wt% Nitrogen / 20wt% Helium for the cold coolant on the size and cost is roughly assessed to assist with the comparison of direct and indirect combined cycle power conversion systems that is performed as part of the PCS alternatives and selection study. The results of the PCHE module sizing of each IHX are shown in Table 3.1.4-2. As for the effect on size of module, 16 modules for the Hot-stage and the Cold-stage are increased compared with the case of only helium for the cold coolant; however the number of module for the PCS-side and the Small does not change. The length of module increased for each IHX. Therefore, not only the weight of PCHE module but also the diameter and height of IHX's pressure vessel are increased. The maximum cost-up is assumed to be 30 M$.

3.2 Preliminary Stress Analysis to Estimate Effect of Thermal Stresses on IHX Lifetime

3.2.1 Analysis Model

The stress analysis of the channel of PCHE module and the stress evaluation were conducted using the design criteria of ASME Code, Sec. III, Subsection NH and [ORNL, 2004]. The stress analysis consists of the structural analysis by pressure load and the thermal stress analysis by thermal load. The objects of analyses are the PCS-side IHX and the Hot-stage IHX. The primary inlet / secondary outlet side of the PCHE module was selected as the evaluation point because of severe condition. The analysis model is depicted in Figure 3.2.1-2. The ABUQUS version 6.5 was used as the analysis software.

[ORNL, 2004] ORNL/TM-2004/308, Simplified Design Criteria for Very High Temperature Applications in Generation IV Reactors, Oak Ridge National Laboratory, December 2004.

3.2.2 Boundary Condition

The pressure conditions of primary channel and secondary channel are 7.0 MPa and 7.1 MPa, respectively. The conditions for thermal stress analysis are 2 cases of the PCS-side IHX and the Hot-stage IHX.

3.2.3 Results and Evaluation

The result of structural analysis is depicted in Figure 3.2.3-1 and the maximum value of Mises stress distribution was 7.0 MPa at the thinnest wall between the primary and secondary channels. The result of primary stress evaluation of the PCS-side at the rated operation as the Level A and B service loadings is shown in Table 3.2.3-1. The primary stress is very low enough to meet the allowable stress value at nearly 810°C and 60-year lifetime by considering the external pressure loaded on the outer surface of PCHE module, which was mistakenly not taken into account in Phase A because the stress was evaluated in only 2-dimensional cross-section inside PCHE module. For the PCS-side IHX, representatively, the result of temperature distribution analysis is depicted in Figure 3.2.3-3 and the maximum temperature was 806°C at the side surface of primary channel. The result of thermal stress analysis is depicted in Figure 3.2.3-4 and the maximum stress was 25 MPa at the plane surface of secondary channel. For the strain limit and creep-fatigue evaluation, the PCHE modules have a prospect to satisfy the design criteria for the requirement of 60-year service lifetime as shown in Table 3.2.3-10 and Table 3.2.3-12, though the operation cycle for evaluation is limited to rated operation and cold shutdown.

3.3 Updated Estimate of Cost for Full-size IHX

The cost of a full-size IHX rose compared with Phase A due to the increased number of PCHE module by the review of the calculation method of the heat transfer and the pressure drop. On the other hand, the cost of the mixture rose further due to the decrease of heat transfer performance. However, the result of this NGNP Phase B conceptual design study differs from one of Phase A and the PCHE modules of each IHX have a prospect to satisfy the requirement of 60-year service lifetime. Therefore, it would be not necessary to exchange the PCHE units during the service lifetime except the environmental effects due to a graphite dust contained into hot coolant as pointed out in Phase A.

4. SUMMARY

The summary of results from this NGNP Phase B conceptual design study on the IHX were shown as follows,

- Through the detailed evaluation of PCHE module, it was indicated that the zigzag method recommended by General Atomics is valid to size the PCHE module and to estimate the pressure drop.
- In terms of flow channels of the PCHE module, the PCHE modules of each type of IHX have a prospect to satisfy the design criteria for the requirement of 60-year service lifetime though the operation cycle for evaluation is limited to rated operation and cold shutdown.
- It would be not necessary to exchange the PCHE units during the service lifetime except the environmental effects due to a graphite dust contained into primary coolant as pointed out in Phase A.
- The estimated weight and cost of a full-size IHX was updated in consideration for the review of the calculation method of heat transfer and pressure drop.
- The effect of 80wt% nitrogen / 20wt% helium mixture for the cost is evaluated and comes to cause the cost rise.

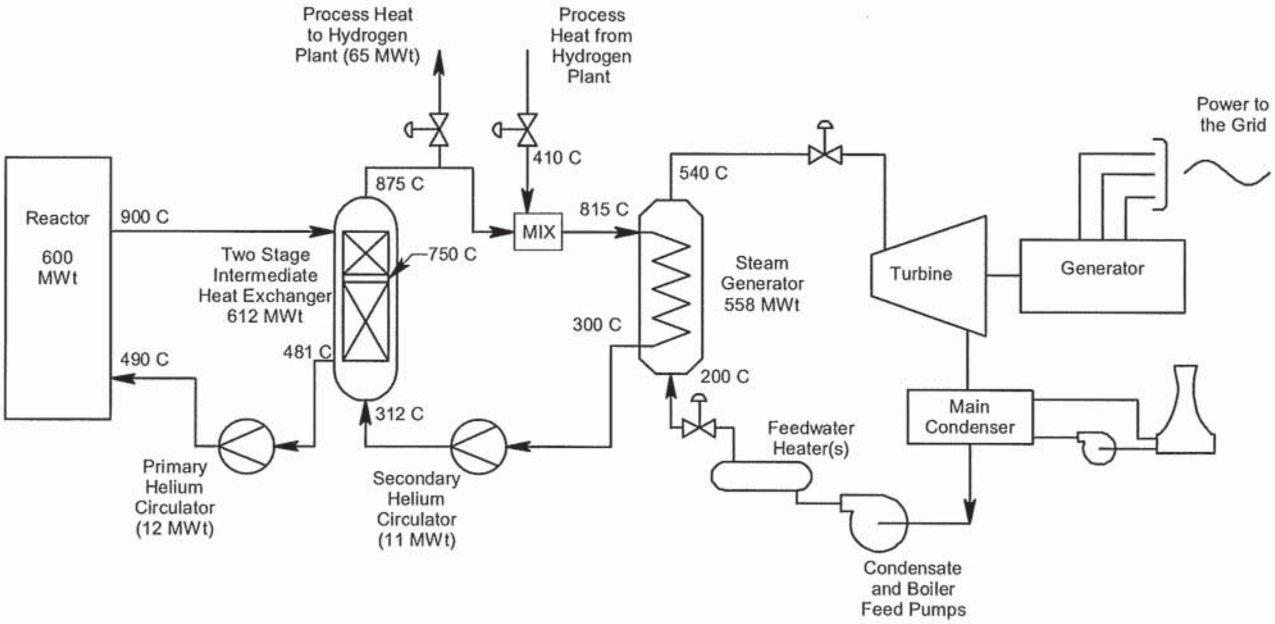


Figure 2-1: NGNP Heat Transport Configuration – Serial Arrangement

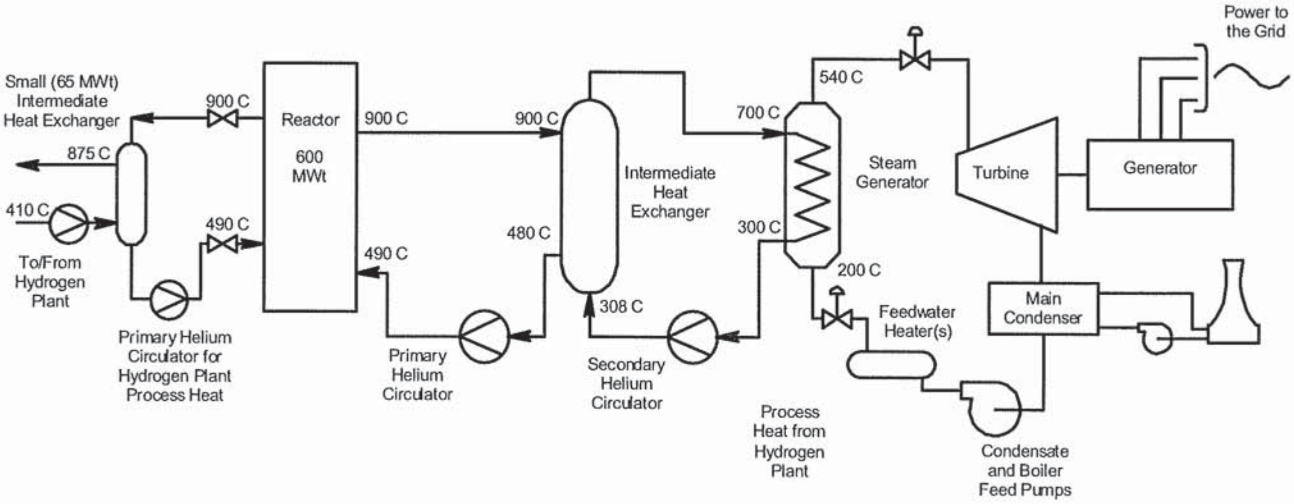


Figure 2-2: NGNP Heat Transport Configuration – Parallel Primary Loop Arrangement

Table 2-1: PCS-side IHX Design Conditions

Parameters	Design Conditions
Heat Load, MW(t)	535
LMTD*, °C	186
Primary Side Fluid	Helium
Primary Side Flow Rate, kg/s	244.96
Primary Side Inlet / Outlet Temperature, °C	900 / 480
Primary Side Inlet / Outlet Pressure, MPa	7.0 / 6.95
Secondary Side Fluid	Helium
Secondary Side Flow Rate, kg/s	262.46
Secondary Side Inlet / Outlet Temperature, °C	308 / 700
Secondary Side Inlet / Outlet Pressure, MPa	7.1 / 7.05
Allowable Pressure Loss**, MPa	0.05

* LMTD = Log-Mean Temperature Difference. ** Tentative condition.

Table 3.1.1-5: Comparison of Results of PCHE Module Sizing (Partially)

Method	Dittus-Boelter and Kay's Correlation	Colburn j-factor	Zigzag Method of GA	Results of Heatric
Heat Transfer Coefficient of Hot Coolant, W/(m^2·K)	924.3	-	1,988	
Heat Transfer Coefficient of Cold Coolant, W/(m^2·K)	924.3	-	1,968	
Heat Transfer Area per Module, m^2	1,432	706	681	680

Table 3.1.2-1: Total Pressure Drop for Evaluation

Flow Channel	Weisbach's Equation kPa	Zigzag Method of GA kPa	Result of Heatric kPa
Primary	12	31	32
Secondary	11	29	31

Table 3.1.3-1: Results of PCHE Module Sizing

Configuration	Serial		Parallel Loop	
IHXs	Hot-stage	Cold-stage	PCS-side	Small
LMTD, °C	46.1	116.8	185.6	43.7
Number of Modules	208 (192)	176 (160)	176 (160)	42 (36)
Number of Channels per Plate	75			
Number of Channels per Each Side	89			
Height of Module, mm	453			
Width of Module, mm	400			
Length of Module, mm	450 (433)	400 (372)	430 (417)	760 (755)
Edge Distance, mm	13			
Layer Thickness, mm	2.4			
Channel Radius, mm	1.5			
Channel Pitch, mm	3.9			
Channel Offset Pitch, mm	12.7			
Channel Offset Height, mm	2.286			
Zigzag Angle, degree	108.5 (108)			
Flow Area per Module, m^2	23.6×10^{-3}			
Heat Transfer Area per Module, m^2	18.5 (17.0)	16.4 (13.2)	13.7 (9.7)	37.6 (39.5)
Effective Heat Transfer Length, mm	359 (331)	319 (256)	266 (188)	730 (767)
Heat Transfer Core Length, mm	291 (268)	259 (207)	216 (152)	593 (620)
Pressure Drop of Primary Side, kPa	48 (32)	46 (32)	35 (31)	27 (16)
Pressure Drop of Secondary Side, kPa	40 (40)	40 (37)	39 (35)	26 (33)

Remark : ( ) is the result using Colburn j-factor in Phase A.

Table 3.1.4-2: Results of PCHE Module Sizing

Configuration	Serial				Parallel Loop			
IHXs	Hot-stage		Cold-stage		PCS-side		Small	
Secondary Coolant	Helium	Mixture	Helium	Mixture	Helium	Mixture	Helium	Mixture
Number of Modules	208	224 (+16)	176	192 (+16)	176	176	42	42
Height of Module, mm	453		453		453		453	
Width of Module, Mm	400		400		400		400	
Length of Module, mm	450	495 (+45)	400	440 (+40)	430	475 (+45)	760	880 (+120)
Increased Weight of PCHE Module, ton		26		22		12		8
Increased Diameter of IHX, mm		90		80		90		240
Increased Height of IHX, mm		906		906		-		-

Note: ( ) is the increased value.

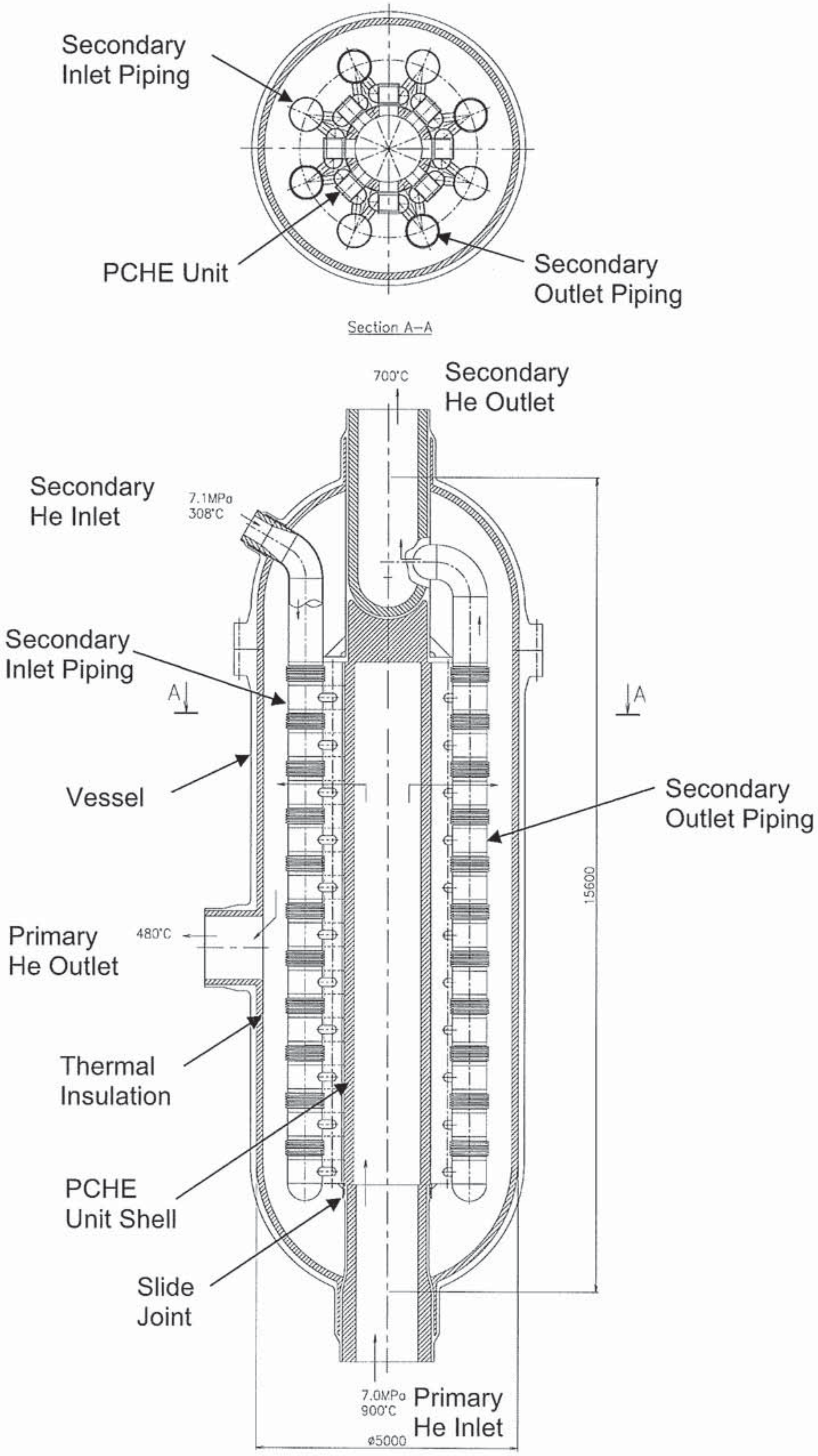


Figure 3.1.3-3: Conceptual Drawing of PCS-side IHX

Table 3.2.3-1: Load Controlled Limits (Pm) of PCS-side (MPa)

Levels A and B Service Limits

Pm

	Cross Section	P01-P02	P03-P04	P05-P06	P07-P08	P09-P10
Pressure Loads	σx	-7.0	-7.1	-7.0	-7.0	-7.1
	σy	-7.0	-7.0	-7.0	-7.0	-7.0
	σz	0.0	0.0	0.0	0.0	0.0
	τxy	0.0	0.1	0.0	0.0	0.0
Pressurel Loads in Axial Direction	σx	0.0	0.0	0.0	0.0	0.0
	σy	0.0	0.0	0.0	0.0	0.0
	σz	-7.0	-7.0	-7.0	-7.0	-7.0
	τxy	0.0	0.0	0.0	0.0	0.0
Combination of Stress Components	σx	-7.0	-7.1	-7.0	-7.0	-7.1
	σy	-7.0	-7.0	-7.0	-7.0	-7.0
	σz	-7.0	-7.0	-7.0	-7.0	-7.0
	τxy	0.0	0.1	0.0	0.0	0.0
Principal Stresses	S1	-7.0	-7.1	-7.0	-7.0	-7.1
	S2	-7.0	-6.9	-7.0	-7.0	-7.0
	S3	-7.0	-7.0	-7.0	-7.0	-7.0
Stress Intensity	Pm	0.1	0.2	0.1	0.1	0.1
Allowable Limits	Smt	15	15	15	15	15

Table 3.2.3-10: Strain Limits of PCS-side (MPa)

Evaluation Points	$(PL+Pb+Q)_{RANGE}^{*}$	3Sm(^)
P01	19	257
P02	29	257
P03	18	257
P04	19	257
P05	18	257
P06	18	257
P07	18	257
P08	18	257
P09	16	257
P10	16	257

*: Maximum Stress Range of Primary plus Secondary Stress Intensity under Level A and B Services

Table 3.2.3-12: Creep-Fatigue Evaluation (Partially)

IHXs	Σ(ni/Ndi)	D	Start-up / Shut-down Cycle n	Design Allowable Cycle Nd	Temp. °C	Service Lifetime hr	Evaluation Point
PCS-side	0.003	1	240	10^5	810	525,600	P02

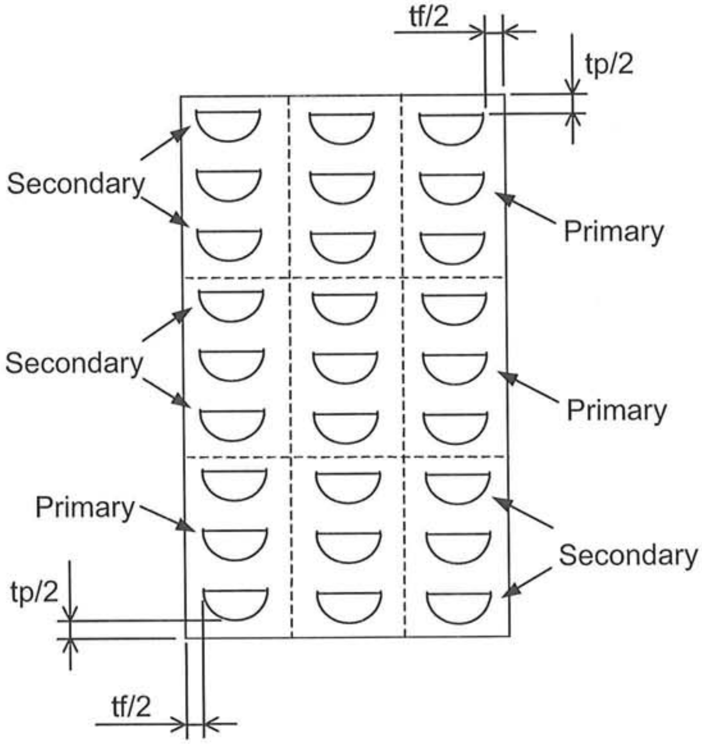
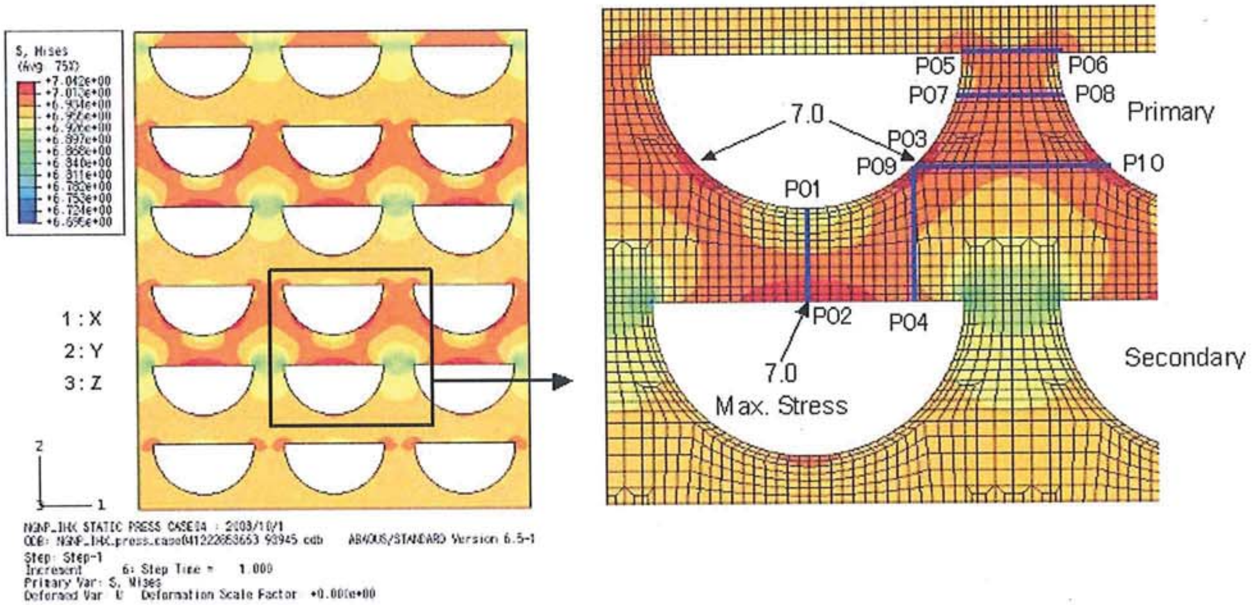


Figure 3.2.1-2: Analysis Model



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Increment      6: Step Time =    1.000
Primary Var: S, Mises
Deformed Var: U   Deformation Scale Factor: +0.000e+00
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Figure 3.2.3-1: Mises Stress Distribution by Pressure Load in PCHE Module (MPa)

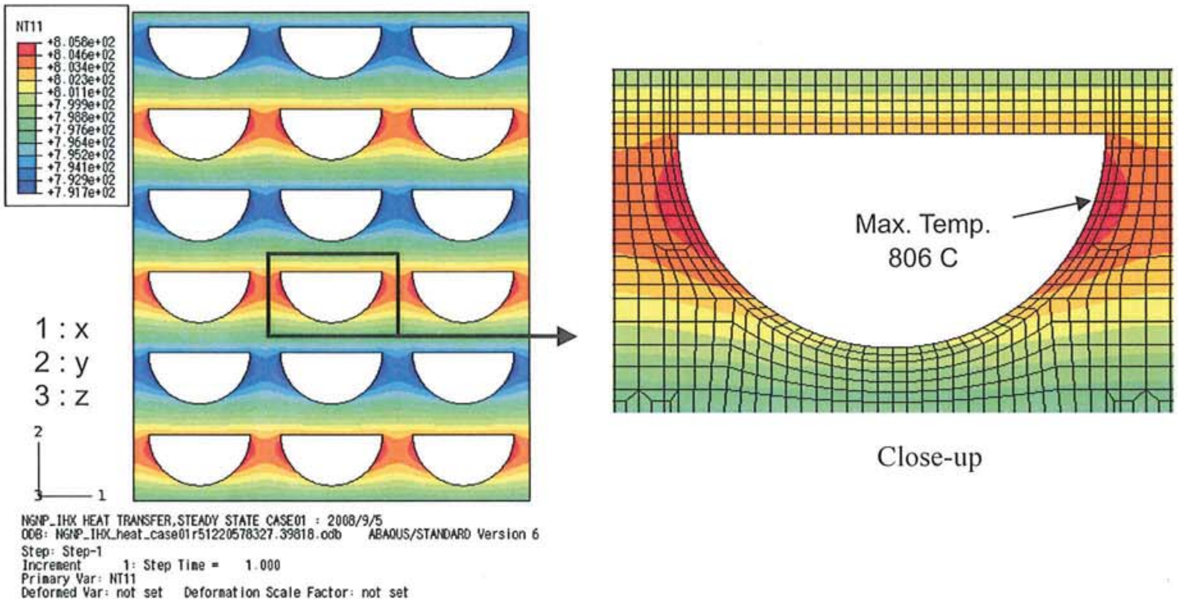

Figure 3.2.3-3: Temperature Distribution in PCS-side PCHE Module (°C)

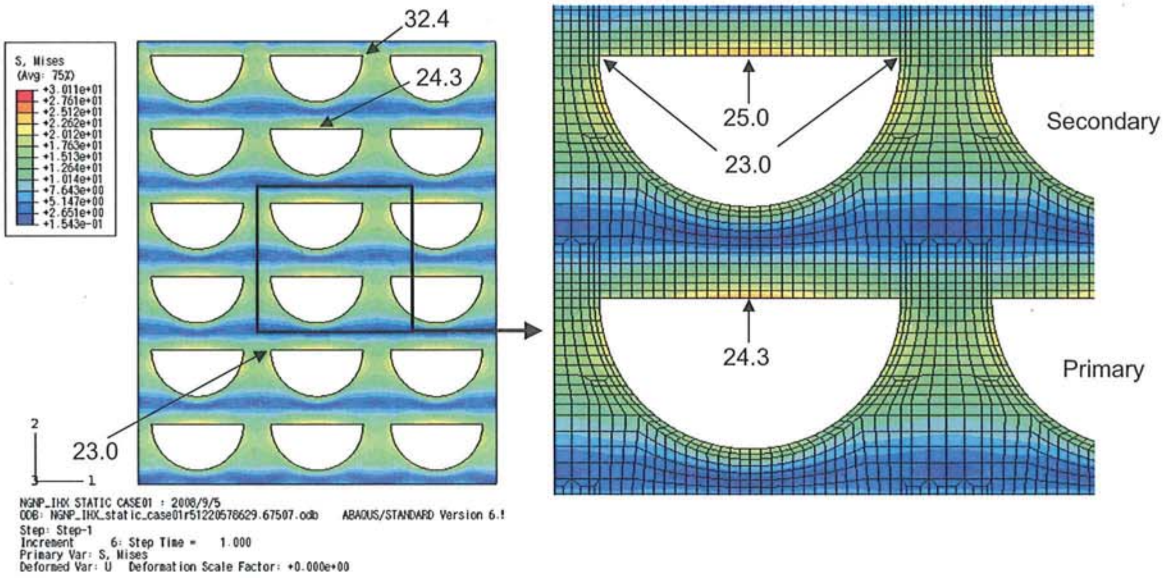

Figure 3.2.3-4: Mises Stress Distribution by Thermal Load in PCS-side PCHE Module (MPa)