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Thermal-Hydraulic Criteria for the APT Tungsten Neutron Source Design

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Abstract

This report presents the thermal-hydraulic design criteria (THDC) developed for the tungsten neutron source (TNS). The THDC are developed for the normal operations, operational transients, and design-basis accidents. The requirements of the safety analyses are incorporated into the design criteria, consistent with the integrated safety management and the safety-by-design philosophy implemented throughout the APT design process.

The phenomenology limiting the thermal-hydraulic design and the confidence level requirements for each limit are discussed. The overall philosophy of the uncertainty analyses and the confidence level requirements also are presented. The phenomenological uncertainty and the geometric uncertainty related to manufacturing tolerances are treated separately. The basis for this separate treatment of uncertainties is discussed. The uncertainty is expressed as a standard deviation obtained by propagation of phenomenological uncertainty (e.g. correlation uncertainty). The phenomenological uncertainty is applied to the nominal geometry and the "worst-case" geometry defined by considering the manufacturing tolerances.

Different sets of criteria are developed for normal operations, operational transients, anticipated accidents, unlikely accidents, extremely unlikely accidents, and accidents during TNS replacement. In general, the philosophy is to use the strictest criteria for the high-frequency events. The criteria is relaxed as the event frequencies become smaller. For normal operations, operational transients, and anticipated events, the design criterion is not to exceed the onset-of-nucleate boiling limits with high confidence. For unlikely events, the main criterion is not to exceed the thermal or flow excursions in the flow channels. Finally, for extremely unlikely events and for events during TNS replacement, the criteria is to keep the Inconel clad temperature below the failure threshold such that source term generation as a result of tungsten vaporization is minimized. Phenomenological limits for these event categories and quantitative confidence level requirements are also discussed.

The THDC must be considered as a guide for the design philosophy and not as a hard limit. When achievable, design margins greater than those required by the THDC must be used. However, if a specific event sequence cannot meet the THDC, expensive design changes are not necessary if the single event sequence results in sufficient margin to safety criteria and does not challenge the plant availability or investment protection considerations.

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Acronyms

APT	Accelerator Production of Tritium
CHF	Critical Heat Flux
DDN	Design Data Needs
DNB	Departure from Nucleate Boiling
EG	Evaluation Guidelines
OBB	Onset of Bulk Boiling
OFI	Onset of Flow Instability
ONB	Onset of Nucleate Boiling
OSV	Onset of Significant Voiding
RHR	Residual Heat Removal
THDC	Thermal-Hydraulic Design Criteria
TNS	Tungsten Neutron Source

Nomenclature

A'	empirical correlation
C	empirical constant
C'	empirical correlation
C_p	specific heat
D	diameter (or hydraulic diameter)
D_{crit}	critical diameter
D_{min}	minimum diameter
f	friction factor
$F_1 - F_4$	empirical functions
G	mass flux
h_{fg}	latent heat of vaporization
L	heated length
p	pressure
q	wall heat flux
q_{CHF}	critical heat-flux
q_{DNB}	heat flux corresponding to departure from nucleate boiling
q_{max}	maximum wall heat-flux for a given channel
q_{ONB}	wall heat-flux at onset-of-nucleate boiling
q_{sat}	heat flux corresponding to onset of bulk boiling
Q	total power deposited in a coolant channel
Q_{CHF}	total power deposited in a coolant channel corresponding to CHF
Re	Reynolds number
T	temperature
T_l	liquid temperature
T_M	clad failure temperature
T_{ONB}	wall temperature at onset-of-nucleate boiling
T_{sat}	saturation temperature

T_w	wall temperature
V	velocity
ΔT_{ONB}	wall superheat at onset-of-nucleate boiling ($T_w - T_{sat}$)
$\Delta T_{sub,i}$	inlet subcooling
μ	dynamic viscosity
ρ	density
σ	standard deviation

Thermal-Hydraulic Criteria for the APT Tungsten Neutron Source Design

1. Introduction

This report presents the thermal-hydraulic design criteria (THDC) used for the APT Tungsten Neutron Source (TNS). The THDC were developed to:

- Properly integrate the safety analyses into the design process to avoid retrofitting safety requirements into a completed design after the fact
- Obtain an up-front agreement among the design engineers, safety analysts, external reviewers, and the regulators on the level of conservatism built into the design of the TNS assemblies
- Guide the identification and prioritization of the design data needs (DDNs)
- Determine a quantitative set of requirements for the experimental uncertainty limits
- Determine the acceptable tolerances in the manufacturing process and guide the post-assembly testing and on-line monitoring requirements

The THDC are not the only design criteria developed for the TNS design. They are implemented in conjunction with the structural design criteria.

Furthermore, the THDC are not a substitute for the safety evaluation guidelines (EGs). In general, if the THDC are met, it is expected the EGs also will be met. However, this assertion must be demonstrated quantitatively for different scenarios.

The THDC are tailored to the conceptual design¹ and its enhancements summarized in Chapter 2. In Chapter 3 discusses the selection of the systems parameters of interest and their limits. The general logic of the confidence level requirements and the types of uncertainties considered are discussed in Chapters 4 and 5, respectively. Chapter 6 outlines the types of events covered by the THDC. A quantitative set of THDC are provided in Chapter 7. Finally, Chapter 8 summarizes and concludes this report.

2. Summary of Enhanced Conceptual Design

The TNS is the primary source of the high-energy particle in the APT target/blanket (T/B) design. The TNS is cooled by heavy water operating at moderate pressures (10-12 bars). Figure 1 provides a schematic description of the primary coolant loops for the TNS. This figure includes only the components important for the thermal-hydraulic discussions and is not intended to be a complete depiction of the cooling systems.

Figure 1. Schematic piping diagram for the TNS heat primary heat removal system and residual heat removal system.

As shown in Figure 1, the primary heat removal loop contains the primary pumps, a pressurizer, and a heat exchanger. The ladder-like geometry shown at the bottom of the figure constitute the TNS assemblies. The coolant is supplied to the TNS assemblies through the headers. The portion of the coolant loop below the headers resides in a cavity vessel maintained at partial vacuum. The residual heat removal (RHR) loop is also attached to the main headers. This loop provides the decay heat removal capability to the TNS when the heat removal capability of the primary loop is lost. Because of the low decay heat immediately after beam shutdown, the flow in the RHR loop is low (~4% of the flow in the primary loop during normal operations). If the decay heat cannot be removed by the RHR loop, the next step in the accident mitigation strategy is to flood the cavity vessel. When the cavity vessel is flooded, the flood level is above the headers.

In the current enhanced conceptual design, there are twelve TNS ladders. These ladders are partitioned among two modules. The front module containing the high-powered ladders will be replaced frequently (~1/yr), whereas the back module will be replaced less frequently. The details of the ladder design are summarized in

Figure 2. As shown, the ladder design changes along the beam length. Ladder 1 corresponds to the ladder exposed to the incident beam first and ladder 12 is the last ladder along the beam's axis.

Because the power densities are higher in the front ladders, these ladders contain more, smaller rungs. The details of the rung geometry for different ladders are summarized in Figure 3.

Ladder Schematic

Ladder	# of Rungs	Rung OD (cm)	Rung Pitch (cm)	Tungsten Volume Fraction
1-4	28	4.343	7.478	58.6%
5-6	22	5.563	9.509	67.9%
7-8	19	6.477	11.001	72.6%
9-13	16	7.696	13.052	77.0%

Figure 2. Details of the ladder design (enhanced conceptual design).

Dimension	Ladders 1-4	Ladders 5-6	Ladders 7-8	Ladders 9-13
Clad Thickness (cm)	0.0127 (5 mil)	0.0127	0.0127	0.0127
Center Hole Dia. (cm)	0.2032 (80 mil)	0.2032	0.2032	0.2032
Tungsten Thickness in Rings (cm)	0.2032 (80 mil)	0.3048 (120 mil)	0.3810 (150 mil)	0.4826 (190 mil)
Ring Thickness (cm)	0.2286 (90 mil)	0.3302 (130 mil)	0.4064 (160 mil)	0.5080 (200 mil)
Flow Gap (cm)	0.1016 (40 mil)	0.1016	0.1016	0.1016

Figure 3. Details of the rung design (enhanced conceptual design).

As shown in Figure 3, each rung contains six concentric tungsten tubes. Hereafter, the concentric tungsten tubes are referred to as rings. The tungsten rings are clad with Inconel on both the inside and the outside surface. Each ring is cooled by two flow channels on either side, which makes the entire rung design a thermally coupled system. The thickness of the rings is kept small [2 mm (80 mils) in ladders 1 through 4] to accommodate the high power densities in the front ladder. To provide the maximum tungsten volume fraction

in each rungs and to enhance the production efficiency, the flow gap is minimized. The nominal flow gap in all the flow annuli is 1 mm.

Figure 4 shows the power densities in the ladders. The decrease in the power density along the beam axis is partially compensated by added tungsten volume in the rungs. The total rung power for the different ladders is shown in Figure 5.

Figure 4. Power densities as a function of ladder number.

Figure 5. Rung power as a function of ladder number.

The current design is at the enhanced conceptual stage. Further refinements on the design details are expected in the future as a result of:

- The preliminary design
- The implementation of the current THDC with detailed uncertainty analyses
- The completion of the accident (transient) analyses

3. Thermal-Hydraulic Parameters of Interest

For an effective thermal-hydraulic design, it must be demonstrated that the deposited power can be effectively removed while keeping the material temperatures within the allowable limits during normal operations, operational transients, and design-basis accidents. The definition of the parameters of interest and their relationship to the limits imposed to meet the design objectives are discussed below.

The deposited power versus the surface temperature relationship is schematically shown in Figure 6. Figure 6 is an idealized illustration of the boiling curve at a single point along the heated surface. The development of the actual boiling curve for forced convective boiling is more complicated than shown in the figure, as the temperature and/or heat flux changes along the axial direction on the heated surface (see Figure 7). Theoretically, it is possible to construct similar boiling curves for different points on the heated surface for a given system. Knowing the relationship between the temperature and the heat flux, either the temperature or the heat flux (or deposited power) can be used to set the design criteria.

The slope in various regions of the boiling curve is important in selecting the controlling parameter. In single-phase convection, the heat-flux is almost a linear function of the temperature difference between the wall and the fluid (Newton's law of cooling). Thus, controlling either the heat flux or the temperature is practical. In the nucleate boiling regime, the surface heat flux exponentially increases with the temperature difference between the wall and the fluid. Small perturbations on the wall temperature result in very large variations in the surface heat flux. Thus, in the nucleate boiling range, typically the heat flux is the controlling parameter for the design.

Two important points on the curve shown in Figure 6 are the Onset of Nucleate Boiling (ONB) and the Departure from Nucleate Boiling (DNB). These points are typically used to set the operating limits. At ONB, nucleate boiling starts at the wall, as illustrated in Figure 7. At this point, the bulk liquid is still highly subcooled and the bubbles grow and collapse while remaining near or attached to the heated wall.

Figure 6. Typical boiling curve.

Figure 7. Schematic description of subcooled flow boiling process.

Further downstream, the liquid near the wall reaches the saturation temperature and bubbles start departing from the wall while staying confined in a boundary layer (bubbly layer) near the wall. This point is typically referred to

Onset of Significant Void (OSV). Figure 7 shows the bulk liquid is still subcooled at this point. OSV is an important point for systems sensitive to hydrodynamic instabilities, such as those containing parallel flow paths. Past the OSV point, the pressure drop increases rapidly with increasing void, and OSV is typically a precursor to instabilities (also known as the Ledinegg instability). The deposited power-to-mass flux ratio at which this instability occurs is also referred to as Onset of Flow Instability (OFI) point. If the system is not sensitive to flow instabilities, the bulk liquid continues to heat-up and saturated boiling may be reached further downstream. Once the bulk fluid reaches saturation, the bubbles are no longer confined in a layer near the wall and they can radially propagate into the core region (as illustrated in Figure 7). This mode of heat transfer is known as the Onset of Bulk Boiling (OBB). Depending upon the system parameter, the low-void heat transfer instability, previously referred to as DNB, may occur anywhere after exceeding the ONB. It is also possible flow regime in saturated boiling may transition into an annular flow, where a thin liquid film exists on the surface and droplet-vapor mixture exists in the core region. Eventually, the thin film on the heated surface dries out. This type of heat transfer instability at high void fractions is referred to as the "dryout."

The APT TNS design contains a number of parallel flow channels and subchannels. A typical engineering solution to mitigate the flow instabilities in this flow configuration is to provide "hard" boundary conditions by designing an inlet orifice with a large pressure drop, which dominates the total pressure drop. However, in the current design, the dominant pressure drop is the frictional pressure drop because of the small hydraulic diameter of the flow channels. Thus, the TNS design is sensitive to flow instability, and it is very unlikely that boiling much beyond OSV may be tolerated. An idealized supply-demand curve for a parallel flow configuration is shown in Figure 8. This figure illustrates that, as void generation starts in the channel, the slope of the pressure drop versus flow rate curve starts changing and eventually reaches a minimum point. Further decrease in the flow rate at this point results in an increase in the pressure drop. For an ideal parallel flow situation, the increase in the pressure drop cannot be accommodated as the flow is diverted to the adjacent parallel channels. This causes a flow excursion, followed by a thermal excursion where the wall temperature quickly increases as a result of reduced heat removal capability by highly voided coolant. This is a classic Ledinegg instability.²

In Figure 8, it is assumed the DNB type of heat transfer instability does not occur before the minimum point in the demand curve (which is referred to as OFI point in the remainder of this report). This is an assumption which must be demonstrated by prototypical experiments. For instance, it is known that for very high flows with high subcooling (resulting in high heat flux removal capability), the heat transfer instability may occur immediately after the ONB. In this report, the term critical heat flux (CHF) refers to thermal excursions and encompasses all the applicable instabilities (DNB, dryout, and OFI). Therefore,

the CHF point sets the limit based on the dominant instability for the APT TNS system.

Figure 8. Schematic description of flow excursion in parallel flow.

Continuing along the boiling curves in Figure 6 and Figure 8, if CHF is exceeded in a system with constant power, the heat transfer mechanism deteriorates rapidly and the heat transfer regime is referred to as the film boiling regime. Transition to film boiling results in elevated surface temperatures because of the high heat transfer resistance of a stable vapor film forming on the heated surface. For typical temperatures reached in film boiling regime, the material temperature limits (strength degradation, melting, enhanced corrosion, etc.) become an issue.

Another important parameter for the THDC is the flow rate. While limiting temperature and surface heat flux provide indirect constraints on the flow rate (via the families of curves shown in Figure 6), there is a need for more direct constraints as a result of pressure drop (structural and pipe sizing limits) and flow regime (turbulent versus laminar) considerations. Finally, the absolute system pressure in various parts of the flow loop needs to be controlled. Besides the structural limits, the pressure determines the saturation temperature, which is important in constructing figures similar to Figure 5 and Figure 6.

Thus, the THDC are based on the following four parameters:

- Surface temperature for the heated elements
- Surface heat flux (or total power deposited to the fluid)
- Flow rate through the coolant channels

- System pressure

The applicable limits on these parameters are discussed in the following subsections.

3.1 Surface Temperature Limits

For the THDC, two phenomenologically different temperature limits are used for normal operations, high-frequency accidents, and low-frequency accidents.

3.1.1 Temperature Limit for Normal Operations and High-Frequency Accidents

For normal operation, operational transients, and anticipated accidents, the design objective is to maintain single-phase operating conditions. Thus, one temperature criterion is:

$$T_w \leq T_{ONB}$$

The following are the bases for limiting the surface temperature (T_w) to less than the ONB temperature:

- Turbulent single phase operations are not sensitive to flow or heat transfer instabilities. Operating in single-phase regime provides a large margin to two-phase instabilities such as OFI and DNB under steady-state operations. Likewise, for transients, the initial conditions provide a comfortable margin to two-phase instabilities.
- During subcooled boiling, bubble formation and collapse result in high frequency (100 -1000 Hz) sonic waves in the system. Such pressure waves are likely to enhance erosion and corrosion of the materials. Considering that the proton beam already sensitizes the surfaces for corrosion, the added corrosive effects must be avoided.

There are a number of theoretical and empirical models available in the literature to predict the ONB. ONB is highly dependent on the surface conditions and the sizes and shapes of nucleation sites available on the heater surface. In general, the surface conditions are not known a priori. Thus, the models typically bound the data using the assumption that cavities of all sizes exist on the surface. When the thermodynamic conditions necessary for the most favorable cavity size to nucleate exist, the nucleate boiling is assumed to initiate. Note that the most favorable cavity size is often much larger than cavity sizes existing in engineering materials. One bounding ONB model is given by Bergles and Rohsenow³ as:

$$\Delta T_{ONB} = 0.556 \left[\frac{q_{ONB}}{1082p^{1.156}} \right]^{0.463} p^{0.234} \quad (1)$$

where p is the local pressure in bar, ΔT_{ONB} is the wall superheat with respect to the saturation temperature at the local pressure in $^{\circ}\text{C}$, and q_{ONB} is the local heat flux in W/m^2 . Figure 9 shows the predicted superheat at ONB for various pressures and surface heat fluxes. The heat flux values shown in Figure 9 are chosen to approximate the peak nominal and decay heat fluxes. The pressure range extends to nominal exit pressure of ~ 10 bar for the TNS channels. As shown in this figure, under nominal operations corresponding to ~ 10 -bar system pressure and $\sim 2\text{-MW}/\text{m}^2$ heat fluxes, approximately 6°C superheat is required for ONB.

However, this model does not account for the dissolved gas effects. The presence of dissolved gas decreases the ONB temperatures because it reduces the steam partial pressure and corresponding saturation temperature. While the magnitude of dissolved gases is not quantified at this time, it is expected the coolant would be nearly saturated with helium and other gases produced radiolytically along the length of the channels. Therefore, even without boiling on the wall, there will be some degassing (void formation) via heating and depressurization as the coolant flows through the channel. Dissolved gases have been shown experimentally to have no noticeable effect on the OFI limit (discussed in the next subsection) for microchannels.^{4,5} The effect of dissolved gases on the ONB was not quantified in these tests.

The main reason for operating under single-phase conditions* is to provide sufficient margin to the two-phase instabilities (OFI). Thus, based on the results of tests reported in References 4 and 5, the presence of dissolved gases has no impact on the margin. Likewise, the presence of dissolved gases typically provides a smooth transition to boiling regime by minimizing or eliminating the sonic wave generation. Therefore, for purposes of THDC development, the effect of dissolved gases on the ONB is of secondary importance.

As an added conservatism, T_{ONB} is replaced by T_{sat} corresponding to channel pressure at the exit of the heated length. Thus, the limit becomes:

$$T_w \leq T_{\text{sat}}$$

* Within the context of the THDC, "single-phase conditions" refer to no boiling on the heated wall, assuming the presence of microbubbles in the channel as a result of dissolved gas content and radiolytic gas generation.

Figure 9. Predicted wall superheat at ONB as a function of pressure.

This formulation provides conservatism with respect to Equation 1, but it neglects the effect of dissolved gases and potential evaporative effects on the wall. There is an experimental program to look at the effect of dissolved gases on the ONB in annuli with small gaps. The consequences of the dissolved gas presence will be quantified using the experimental data and the thermodynamic calculations specific to APT TNS conditions.

3.1.2 Temperature Limit for Low-Frequency Accidents

A higher limit is used for low frequency accident sequences where it is anticipated that, after recovery from the accident, the TNS modules will be replaced. The higher limit is set to the damage temperatures for the Inconel cladding on the tungsten cylinders. Tungsten oxide (especially the tungstic acid formed in steam) is volatile at high temperatures and results in radiological source term if its formation and escape from the cavity is not prevented. As long as Inconel failure from high oxidation, corrosion, or melting does not occur, the formation of the volatile tungsten oxide is prevented. This limit is denoted by T_M . Thus, another temperature criterion applicable to low frequency events is:

$$T_w \leq T_M$$

Based on tests conducted for Inconel oxidation,⁶ the lower bound on the Inconel failure temperature is determined to be $T_M = 1250$ °C. This temperature is less than the Inconel melting temperature and corresponds to the point where accelerated rate of oxidation is observed. In any of the tests conducted, actual failure of the Inconel specimen was not observed until temperatures in excess of 1300 °C were reached. In the analyses, it is assumed no tungsten vaporization and release is possible until the Inconel temperature exceeds 1250 °C. The temperature limit of 1250 °C is applicable

for event sequences where the heat flux or deposited power criteria (CHF) is exceeded. This is discussed in the next subsection.

3.2 Heat Flux Limits

In this report, the local heat flux or the integrated power deposition (into the coolant) are used interchangeably. The type of limiting phenomenon determines the more appropriate parameter. If the phenomenon of interest is the DNB, the local heat flux and the integrated deposited power (which determines the local fluid conditions) are equally as important. However, if dryout or the OFI are the dominant phenomena, the deposited power must be controlled. In the remainder of this report, the local limiting heat flux is referred to as q_{CHF} or the total deposited power limit is referred to as Q_{CHF} . For a system with a uniform heat flux distribution axially and along the heated perimeter, the two limit-parameters can be mathematically related as:

$$Q_{CHF} = q_{CHF} \times L \times P_H$$

where L is the heated length and P_H is the heated perimeter.

For the heat flux limited phenomena, the THDC would be:

$$q_{max} \leq q_{CHF}$$

where q_{max} is the maximum heat flux on either the inner or the outer wall of the annular channel.

For the phenomena where total deposited power is limiting, the general criterion would be:

$$Q \leq Q_{CHF}$$

where Q includes the power supplied from both the inner and outer walls of the channel.

Note that the design objective is to operate in single-phase conditions even during high frequency accidents, as discussed in Chapter 3.1. The addition of the heat flux limit for those events provide added assurance that, even if the temperature limit on the ONB is exceeded (which is a low probability based on the confidence limits discussed later), there is a much lower probability of exceeding the instability limit (CHF).

3.2.1 DNB or Dryout Model

Currently, there are no DNB or dryout correlations directly applicable to the ring bundle geometry used in the APT TNS design. For the design calculations, the Bowring-Macbeth correlation is used.⁷ The parametric range for this correlation is cited as:⁷

Geometry: uniformly heated circular tubes

p: 2 - 190 bars

D: 2 - 45 mm
 L: 0.15 - 3.7 m
 G: 136 - 18,600 kg/m²-s

Within this parametric range, the uncertainty band at 95% confidence level is $\pm 14\%$. However, the applicability of this correlation to the ring-design must be tested using prototypical data. The following are the weaknesses of the Bowring-Macbeth correlation when it is applied to the APT TNS design:

- Its applicability to annuli with small gaps (using hydraulic diameter as the characteristic length) and heated from both sides is suspect.
- The applicability of this correlation under subcooled exit conditions also is questionable.

Nonetheless, as an example of a DNB correlation, Bowring-Macbeth correlation is further discussed. The correlation is given as:⁷

$$q_{DNB} = \frac{A' + \frac{DGC_p \Delta T_{sub,i}}{4}}{C' + L} \quad (2-a)$$

where q_{DNB} is the critical heat flux in W/m², D is the tube diameter in meters, G is the mass flux in kg/m²-s, C_p is the liquid specific heat (J/kg), $\Delta T_{sub,i}$ is the inlet subcooling in °C, and L is the heated length in meters. The parameters A' and C' are given by:

$$A' = 2.317 \left[\frac{D G h_{fg}}{4} \right] \left[\frac{F_1}{1 + 0.0413 F_2 G \sqrt{D}} \right] \quad (2-b)$$

and:

$$C' = 0.077 D G \frac{F_3}{1 + 0.347 F_4 \left(\frac{G}{1356} \right)^{2-0.00725p}} \quad (2-c)$$

where h_{fg} is the heat of vaporization in J/kg, and p is the pressure in bars. The various functions of pressure (F_1 through F_4) are provided in Table 1.

Table 1. Functions F1-F4 in EQS (2-b) and (2-c)

p (bars)	F ₁	F ₂	F ₃	F ₄
1	0.478	1.782	0.400	0.0004
5	0.478	1.019	0.400	0.0053
10	0.478	0.662	0.400	0.0166
15	0.478	0.514	0.400	0.0324

3.2.2 OFI Model

In the absence of any data, the OSV model provided by Saha and Zuber⁸ may be used as a predictor for the OFI in parallel channels. The Saha-Zuber model is developed over a wide range of parameters and the error band is reported as $\pm 25\%$. However, the data base does not include flow in annuli with small gaps (~ 1 mm). The model may be summarized as:

$$q_{OSV} = \begin{cases} 455 \frac{k(T_{sat} - T_l)}{D} & \text{for } \frac{GDC_p}{k} \leq 70,000 \\ 0.0065 GC_p (T_{sat} - T_l) & \text{for } \frac{GDC_p}{k} > 70,000 \end{cases} \quad (3)$$

where k is the thermal conductivity of the liquid and T_l is the bulk liquid temperature.

Recently, microchannel OFI data applicable to conditions of rod-bundle TNS design were obtained at the Georgia Institute of Technology (GIT).⁴ The data show the Saha-Zuber correlation can be used as a predictor of the OFI within the parametric range of interest. However, a more accurate correlation of the data was given as:⁴

$$q_{OFI} = 0.9 q_{sat} \quad (4)$$

where q_{sat} corresponds to the deposited power required to reach bulk saturation at the channel exit. For this simple correlation, the error band with 95% confidence level is reported to be $\pm 6.9\%$.⁴ A test program has been initiated to repeat these experiments using an annular flow channel with a 1-mm gap.

Figure 10 shows the mass flux versus heat flux conditions corresponding to DNB and OFI using Equations (2) and (4), respectively. In generating this figure, it is assumed the diameter in Equation (2) may be replaced by the hydraulic diameter (2 mm) of an annulus with a 1 mm flow gap. Other conditions representative of the current TNS design are listed in the figure. As shown in Figure 10, within the mass flux range of interest, the predicted OFI and DNB magnitudes are comparable.

Figure 10. Heat flux and mass flux corresponding to OFI and DNB.

3.3 Flow Rate Limits

Figure 11 shows a typical friction factor versus Reynolds number plot for a given surface roughness. As shown, the slope is steep in the laminar range compared to the turbulent range. Also, in the transition regime, the curve shows a non-monotonic behavior (this behavior is mostly valid for circular tubes). In a highly parallel flow, these factors enhance flow maldistribution as a result of small variations in the geometry of the flow paths. Consequently, it is advantageous to stay away from these regimes and operate under fully turbulent conditions. For normal operations, a limit is placed on the Reynolds number to keep the flow turbulent in all the channels. The lower limit on the laminar-to-turbulent transition Reynolds number for annular channels range is between 2100 and 2500, depending upon the radii ratio.⁹ To provide sufficient margin away from the transition regimes, a Reynolds number limit of 6000 is chosen. Furthermore, rung-to-rung flow distribution becomes more uniform as the pressure drop across the rungs increases. Increasing the pressure drop across may be achieved by going to highly turbulent flows. There is also considerable degradation of heat transfer in the laminar and transitions regimes as compared to the turbulent flow. In conclusion, maximizing the flow rate through the rungs is the objective in the THDC. In doing so, the pressure drop and total pressure constraints imposed by the structural limits and material erosion limits must be considered.

Figure 11. Typical friction factor correlation for a circular tube.

3.4 Pressure

The need for pressure drop requirements is discussed in the previous section. In terms of absolute pressure, one important parameter is to maintain as high a saturation temperature as possible at the exit of the heated elements. Increasing the saturation temperature increases the margin to ONB. Likewise, as the flow goes through the rest of the loop outside the TNS and through the pumps, it is important to maintain a coolant temperature much less than the local saturation temperature to avoid pump cavitation. As a second-order impact on the THDC, the coolant pressure also affects the transport properties, which in turn, affect the heat removal effectiveness. In conclusion, for the THDC, maximizing the system pressure without jeopardizing the structural integrity is the objective.

4. Confidence Level Requirements

As discussed above, the primary limits are set on the surface temperature and the surface heat flux. In the hierarchy of strictness, the most stringent criterion is the ONB, followed by the CHF. The least stringent criterion is the material damage temperature (T_M). For high frequency events, not exceeding the ONB is the primary criterion and not exceeding the CHF is the back-up criterion. For low frequency events, exceeding the CHF is acceptable as long as the temperatures remain less than the damage temperature (T_M). CHF criterion is the primary criterion for medium frequency events $10^{-2}/\text{yr}$ to $10^{-4}/\text{yr}$. For high and medium frequency events, it is expected the TNS will be re-used after recovery from the accident. This logic is graphically illustrated in Figure 12,

which shows \ the confidence level required to meet a given criterion decreases with decreasing event frequency.

Figure 12. Graphical illustration of the confidence level requirements.

Regardless of the event frequency, for the events requiring TNS replacement, the criterion for the low-frequency events are used.

Table 2 shows the number of standard deviations (hereafter abbreviated as σ or std dev.) from the mean corresponding to a given one-sided confidence level assuming a Gaussian distribution. As shown, one can achieve 99.9% confidence level at 3- σ from the mean. Typically, a 3- σ margin is adequate to declare high confidence that models and correlation (phenomenological) uncertainties are bounded. The type of uncertainties important for the TNS design are discussed next.

Table 2. Number of Standard Deviations Versus One-sided Confidence Limits for Gaussian Distribution

# of Standard Deviations	0.5	1.0	1.5	2.0	2.5	3.0	3.5
Confidence Limit (%)	69.15	84.13	93.32	97.73	99.38	99.87	99.98

5. Types of Uncertainties

In quantifying the uncertainty in the APT TNS performance, the following types of uncertainty must be considered:

- Phenomenological uncertainty (models and correlations)
- Geometric uncertainty (manufacturing tolerances)
- Uncertainties in coolant and TNS material properties

- Uncertainty in weather related parameters (coolant inlet temperature, atmospheric pressure)

The uncertainties in the material and coolant properties are typically small and are expected to have negligible contribution to the overall variance, with the exception of those that have high uncertainty (e.g. surface emissivity). This type of uncertainty is not discussed further.

If the coolant inlet temperature is allowed to vary with the ultimate sink temperature (ambient temperature), it is truly a random variable which goes through diurnal and seasonal variations. This behavior is not included in the uncertainty analyses and a bounding value is used. Another weather related uncertainty is the atmospheric pressure. Pressure variations are typically small and they are not considered further in the uncertainty analysis.

Two major types of uncertainty important in the TNS design are the geometric and phenomenological uncertainty. In general, there is a fundamental difference between the phenomenological and geometric uncertainties. The application of phenomenological uncertainty typically results in an intrinsic confidence level (independent of the number of times the uncertainty is applied). On the other hand, the confidence level associated with the use of geometric uncertainty (manufacturing tolerances) is an extrinsic magnitude that depends on the number of sampling. These issues are discussed in detail in the following subsections; it is important to understand the fundamental difference between the geometric and phenomenological uncertainties before such uncertainties are applied in the THDC implementation.

5.1 Phenomenological Uncertainty

The phenomenological uncertainty refers to the uncertainty in the models and correlations, and include experimental data uncertainty and measurement uncertainty during the assembly process and during operations. A comprehensive list of the phenomenological uncertainties includes:

- Friction factor correlations used in design calculations
- Form loss correlations used in design calculations
- Pre-assembly and post-assembly hydraulic characterization data
- Heat transfer coefficient correlations used in design calculations
- ONB correlation used in limits methodology
- CHF correlation used in limits methodology
- Clad damage characterization data used in limits methodology
- On line pressure, flow rate, and temperature measurements during operations in relation to limits

The phenomenological uncertainty is the uncertainty associated with applying a physical principle into a specific set of conditions. In most cases, the physical principle is expressed in the form of an empirical correlation developed using prototypical data that inherently contains some scatter. If the correlation is theoretically based, the uncertainty stems from the simplifying assumptions made on the boundary conditions, initial conditions, and/or the dominant terms of the governing conservation equations.

The example discussed here refers to a set of laminar flow friction factor data and its correlation. Figure 13 illustrates a hypothetical set of data with a theoretically based correlation, where the correlation coefficient C can be evaluated using statistical fit to the data. Also shown in Figure 13 is an error band drawn around the correlation which refers to the 95% confidence limit in quantifying the correlation coefficient C . The correlation is given as:

$$f = C/Re$$

where $Re = \rho V D/\mu$, ρ is the fluid density, V is the average fluid velocity, D is the channel hydraulic diameter, and μ is the fluid viscosity. This correlation is developed using the physical principles and scaling laws. In a perfect set of experiments, where the experimental conditions perfectly match the assumptions corresponding to the derivation of Equation (5) and where the instruments provide perfect readings, a unique value of C is obtained. However, the experiments are not perfect and the scatter illustrated in Figure 13 arises. For instance, the following result in data scattering in a narrow band:

- Small amounts of impurities in the test fluid
- Small instrument errors even after a careful calibration
- Small variations in the thermodynamic state variable affecting the properties
- Small tolerances on the test section geometry

Figure 13. Hypothetical friction factor data and correlation.

When the correlation is developed over a wide enough database, typically a 95% confidence interval is sufficient to validate the applicability of the model. The exact value of C for a given Reynolds number is not known. However, based on this type of assessment, one would conclude the exact value is within the quantified uncertainty. In this hypothetical example, two out of twenty data points are outside the quantified uncertainty band. However, this does not imply that the model is invalid 10% of the time it is used. The data points outside the uncertainty band simply imply that in these two tests, the actual experimental conditions were considerably different than the measured or calculated conditions. For instance, larger instrument errors or larger than average geometric tolerances may cause this discrepancy.

As an example, it is assumed 100 identical flow channels are used in the design. It is also assumed the Reynolds number for each one of these channels can be quantified accurately. The use of the above correlation with the 95% confidence interval does not imply the friction factor in five out of 100 channels will be outside the uncertainty band. In this specific example, if the model fails to predict the behavior of one channel, it is highly likely it will fail to predict the behavior of all the other identical channels. The failure to predict the behavior is not a result of a random occurrence (note that all the channels are identical). The failure to predict implies something more fundamental, i.e. the physical model used in developing the correlation does not apply to the design conditions. This type of uncertainty is associated with the confidence in the knowledge of the physical phenomenon. Therefore, it is important to treat the knowledge uncertainty (referred to as the phenomenological uncertainty) from the geometric uncertainty, which is truly a random variable, especially for the uncertainty associated with manufacturing tolerances.

The phenomenological uncertainty is a measure of the confidence in matching the actual conditions with the experimental conditions, or the mathematical

relationship developed based on the experimental conditions. As such, the phenomenological uncertainty is an intrinsic uncertainty that does not depend on the number of flow channels. Regardless of the number of times the correlation is used, a confidence level corresponding to 2-std dev. is typically adequate to bound this type of uncertainty, given that one starts with a set of prototypical experiments and/or modeling assumptions. In critical applications which require added confidence, typically, a 3- σ band provides a conservative bound.

Note that the phenomenological uncertainty typically contains the geometric uncertainty to a degree. For the example discussed above, the geometric tolerances in the experimental set-up already contribute to the total variance in the friction factor data. However, the data are typically obtained from carefully controlled tests for which the tolerances are small. Furthermore, it is difficult to quantify the relative contribution of the tolerances to the total variance. For the purposes of this report, it is assumed the phenomenological variance is totally independent of the geometric variance. This is slightly conservative, as it results in double accounting of the geometric effects.

5.2 Geometric Uncertainty

There are two types of geometric uncertainties to consider:

- Changes in geometry as a result of the phenomenology (thermal expansion, swelling, corrosion/erosion)
- Manufacturing tolerances

The first type can be phenomenologically modeled. Thus, any uncertainty associated with the geometric distortion as a result of thermal expansion or swelling must be included in the phenomenological uncertainty discussed above.

The second type, manufacturing tolerances, must be explicitly accounted for in the design. The need for explicit modeling stems from the extrinsic nature of this uncertainty that may exhibit itself as a truly random variable. Going back to the friction factor example, one can look at the changes in hydraulic diameter as a function of manufacturing tolerances. For this example, the probability density function of the hydraulic diameter is assumed to be uniform between $D_{\min}$ and $D_{\max}$, as shown in Figure 14. The minimum allowable hydraulic diameter based on friction factor considerations is denoted by D_{crit} in Figure 14. For a given channel, the probability of being less than the limiting diameter is 1%. However, within the range of this example, if there are 100 channels with the same statistics on the manufacturing tolerance, it is expected the diameter in one out of 100 channels will be less than the limit. However, if the aspiration is not to be less than the limit with 99% confidence in *any* of the 100 channels, the tolerance statistics must provide 99.99 confidence that $D > D_{\text{crit}}$. As the number of channels are increased, the confidence limit requirement

approaches one. At the limit, the statistical requirement becomes $D_{crit} = D_{min}$. For this example, D_{min} may be referred to the "worst-case" channel on a deterministic basis. Thus, if one can tolerate the worst-case channel, then the design adequacy is accomplished for any channel. Unfortunately, for the TNS design, the "worst-case" geometry cannot be quantified by a single geometric dimension. The following tolerances must be considered in defining the worst-case geometry:

- Concentric tube thicknesses (tungsten tube and cladding thicknesses)
- Eccentricity in the tubes
- Eccentricity in the nesting of the tubes (placement on the support plate)
- Bowing of the tubes
- Support plate fixture dimensions
- Gap between tungsten ring and Inconel clad

Figure 14. Hypothetical probability density function for tube diameter.

5.3 Overall Uncertainty Methodology

The proposed approach to quantify the uncertainty in the THDC implementation is to separate the phenomenological uncertainty and the geometric uncertainty. The main reasons for this separation are:

- The intrinsic aspect of the phenomenological confidence level versus the extrinsic feature of the geometric confidence level computations
- The large number of channels existing in the TNS design

The overall uncertainty methodology is outlined below:

1. For the phenomenological uncertainty, an overall standard deviation is computed using linear (or non-linear when necessary) propagation of errors. The bounding value is assumed to be 3σ away from the mean.
2. The phenomenological aspects of the geometric uncertainty (thermal expansion, swelling, erosion/corrosion) are combined with the phenomenological uncertainty.
3. The manufacturing tolerances are dealt with on a 'worst-case' geometry basis. For a large number of parallel flow channels, two options are being considered for the definition of the worst-case geometry:
 - Define a worst-case channel by algebraic stack-up of the tolerance limits on various dimensions in a single channel.
 - Consider the adjacent channel in conjunction with the stack-up of the tolerances.
4. Some of the phenomenological uncertainty in the data used already has effects of geometric tolerances, especially if the data are collected using a number of different flow channels with the same nominal geometry. However, to be conservative, the tolerancing effects on the phenomenological uncertainty is ignored.

6. Event Categories Covered by the THDC

Confidence level as a continuous function of the event frequency (as sketched in Figure 12) is neither necessary nor adequate. In many cases, the point estimates of the event frequencies are not available. Even when such estimates are available, there is considerable uncertainty associated with such frequency estimates. Thus, the THDC are as step-functions for ranges of event categories.

The THDC are developed for the following five categories, including normal operations and postulated transients:

Normal Operations and Operational Transients

This category includes the normal steady-state operations of the TNS assemblies. Also included are planned transients such as plant start-up, shut-down, TNS module replacement, scheduled maintenance, etc.

Anticipated Events

This category includes upset conditions with frequencies greater than $10^{-2}/\text{yr}$. Note that events falling within this category refer to upset conditions with high frequency and should not be confused with planned transients falling within the Operational Transients category.

Unlikely Events

This category includes accident sequences with frequencies ranging from $10^{-4}/\text{yr}$ to $10^{-2}/\text{yr}$. It is expected that all design-basis accidents (DBA) will have frequencies $\geq 10^{-4}/\text{yr}$ (including natural phenomena and external events).

Extremely Unlikely Events

This category includes accident sequences with frequencies ranging from $10^{-6}/\text{yr}$ to $10^{-4}/\text{yr}$. Some of the events caused by external initiators or initiated by natural phenomena in this frequency range may be beyond design-basis accidents (BDBA). The THDC do not apply to BDBA, however, a few design-basis events caused by internal initiators may fall within this frequency range. The THDC apply to these events.

Events Associated with TNS Replacement

Besides the event frequency, another important consideration is the potential for replacing the TNS assemblies after recovery from a given event. If the intent is to continue production with the same TNS assembly after the event, strict THDC are used to ensure temperatures during the event do not reach or exceed values resulting in long-term deterioration of the TNS materials. This strategy is applied for the high-frequency events to minimize the need for TNS replacement. However, if the event is such that the TNS will be replaced regardless of the accident consequences, the objective of the THDC are to prevent immediate material damage leading to radiological source term production until replacement. It is expected that most events requiring cavity flood as the mitigation would result in TNS replacement regardless of the final outcome of the accident. In general, these are low-frequency events. One exception to this general logic are events occurring during planned TNS replacement. The high-energy module of the TNS is expected to be replaced frequently ($\sim 1/\text{yr}$). Events such as loss of forced cooling to TNS during replacement are expected to be in the anticipated or unlikely range. However, despite the high frequency, it is not necessary to apply strict THDC for such an event because the TNS will be out-of-service after the event, regardless of the event consequences.

The frequency ranges used in categorizing the events refer to the sequence frequencies. Thus, the preventive and mitigative systems and components are credited in the sequence frequencies. However, the safety classification of

such preventive and mitigative schemes are beyond the scope of the THDC. The classification must be determined by comparing the results of the hazard analyses with the EGs.

As a final note on the event categories, the different limits for different event frequency categories must be used as a guide and not a hard limit. If the analyses show the THDC is not met for a given event, the following are the recommended steps consistent with the integrated safety management:

- Design changes to meet the limit must be considered.
- If design changes are not feasible, the justification for the exception must be documented.
- The frequency numbers must not be targeted for more refined analyses in order to meet the limit, unless an additional mitigation strategy (engineering fix) is introduced to lower the event frequency.

Similarly, it is prudent to include extra design margin for events with frequencies approaching the upper bound in each of the categories. For example, for an anticipated event with frequency of nearly once a year, it is prudent to design to normal operation limit rather than the anticipated event limit.

7. Thermal-Hydraulic Design Criteria

The details of the limits in various event categories are discussed in the following subsections. Because the phenomenological and geometric uncertainty are treated separately, the discussion below is divided into two sections. The THDC for the nominal geometry is discussed in Chapter 7.1 and the THDC for the "worst-case" geometry is discussed in Chapter 7.2. Before discussing the bases for the chosen magnitudes, the design limits on the surface temperature and heat flux are summarized in Figure 15 and Figure 16. At this time, two notes are warranted with respect to these figures:

- The transition from unlikely to extremely unlikely temperature limits are not as smooth as visually implied in Figure 14. For the extremely unlikely DBA, the limit is the damage temperature of Inconel, which is ~ 1200 °C, whereas the limit for the unlikely events is the ONB, which is ~ 200 °C. The basis for such a large change in the temperature limit philosophy for these events is discussed in Chapter 7.1.4.
- Figure 16 implies that 3σ for the heat flux ratio is less than 0.5. It is assumed this can be achieved by prototypical testing on the heat flux limit. If the uncertainty analyses show this assumption cannot be satisfied, either the tolerances must be tightened by more careful testing and design practice, or the THDC logic must be revisited. The importance of the 0.5 limit is discussed in detail in the following subsections.

Figure 15. THDC for the surface temperature.

Figure 16. THDC for the heat flux.

7.1 THDC For Nominal Geometry

In the nominal geometry, the dimensions discussed in Chapter 2 are used. No uncertainty as a result of the manufacturing tolerances is included in the uncertainty analysis. The standard deviations referred to in the following discussion are obtained by propagating the phenomenological uncertainty only.

7.1.1 Normal Operations and Operational Transients

The primary criterion for normal operations and the operational transients is the ONB. The temperature limit is set to $T_w < T_{sat}$ with a 3- σ margin. In the unlikely event that boiling is initiated in a channel, the back up criterion is $q < q_{CHF}/2$ also with a 3- σ margin. There are two reasons this factor of 2 is used in this limit.

- The factor of 2 provides added confidence that the limits will not be exceeded.
- In the design, the heated elements are concentric cylinders with coolant channels on either side, as shown in Figure 3. The heat transfer from one side of the heater may be limited as a result of:
 - flow blockage in one of the coolant channels
 - one side of the heater reaches or exceeds CHF instability (as a result of geometric uncertainty)
 - increased heat transfer resistance on one side (larger gap between the Inconel clad and the tungsten tube)

In the unlikely case of this phenomenon occurring on the heaters on both sides of the coolant channel, the power deposited into this coolant channel may be twice the nominal design value. Thus, with this criteria, CHF is not exceeded even if the heat from two adjacent heaters is completely deposited into a single coolant channel. Furthermore, if CHF is exceeded in a coolant channel for other reasons (e.g. flow blockage), the adjacent channels remain coolable and the CHF phenomenon does not propagate through the entire set of concentric tubes.

For normal operations, the channel Reynolds number limit is set to ≥ 6000 . Obviously, this limit does not apply to operational flow transients. In general, it is practical to apply the temperature and heat flux criteria in terms of flow rate. Thus, the maximum flow rate that meets all three criteria are chosen:

- No wall nucleation at 3- σ margin.
- Maximum heat flux is less than $q_{CHF}/2$ with 3- σ margin.

- Reynolds number is higher than 6000. This is a best-estimate Reynolds number value for nominal geometry because margin is already built into the 6000 limit.

The limits on the pressure are set based on the following considerations:

- To provide sufficiently high T_{sat} to meet the temperature and heat flux criteria listed above
- To meet the structural criteria
- To satisfy the loop design requirements (e.g. no pump cavitation)

7.1.2 Anticipated Events

For anticipated events, the requirements are similar to the operational transients, however, a lower uncertainty margin is required. The temperature limit is set to $T_w < T_{\text{sat}}$ with a 2- σ margin. In the unlikely event that boiling is initiated in a channel, the back up criterion is $q < q_{\text{CHF}}/2$, also with a 2- σ margin. No Reynolds number criteria apply to these events. Thus, the flow rate criterion is the maximum needed to meet the wall temperature and heat flux criteria.

7.1.3 Unlikely Events

For plant availability considerations, the criteria for unlikely events are also set more conservatively than the safety criteria. The objective is to avoid material damage requiring replacement of the TNS after recovering from the event. The temperature limit is set to $T_w < T_{\text{sat}}$ with a 1- σ margin. In the unlikely event that boiling is initiated in a channel, the back up criterion is $q < q_{\text{CHF}}/2$ on a best-estimate basis. Note that the factor of 2 for the heat flux criterion is maintained. This provides more than 3- σ margin to CHF. Combining the probability of the conditions requiring the factor of 2 with the low frequency of these events, it was determined that the additional design margin was not warranted. No Reynolds number criteria apply to these events. Thus, the flow rate criterion is the maximum needed to meet the wall temperature and heat flux criteria.

7.1.4 Extremely Unlikely Events

For extremely unlikely design-basis events, the limit is the Inconel failure temperature that must be met at a 3 std dev. margin. It is expected that after such an event, the TNS modules will be replaced. Thus, the main concern is to limit the tungsten vaporization and the potential for a source term.

7.1.5 Events During TNS Replacement

For events during TNS replacement, the limit is the Inconel failure temperature that must be met at a 3 std dev. margin. The event frequency is irrelevant for these events. The limits apply to the TNS module being replaced. Thus, even for high frequency events, because the TNS module is being replaced, the main concern is to limit the tungsten vaporization.

7.2 THDC for the Worst-Case Geometry

As discussed previously, in defining the worst-case geometry, the following manufacturing tolerances must be considered:

- Concentric tube thicknesses (tungsten tube and cladding thicknesses)
- Eccentricity in the tubes
- Eccentricity in the nesting of the tubes (placement on the support plate)
- Bowing of the tubes
- Support plate fixture dimensions
- Uneven gap between tungsten ring and Inconel clad on either side

With the exception of the last bullet, the effect of the other parameters is the reduction of the flow and increase in deposited power in the worst case channel. These tolerances must be considered in the definition of the worst-case geometry. At this time, it is assumed a highly reliable method for cladding the rings will be developed, eliminating the need to consider the last bullet. However, if such a highly reliable method cannot be developed, the impact of the uneven gap conditions must be evaluated.

An algebraic stack-up of all tolerances for an annulus in a set of nested thermally-coupled annuli may not necessarily be the worst-case. Furthermore, the number of total flow channels makes the definition of a worst-case channel geometry almost impossible, given the degree of freedom introduced by the number of considered tolerances.

To define the worst-case geometry and limit the degree of freedom in the definition, the following post-manufacturing and post assembly testing are required:

- Hydraulic characterization of each rung after assembly. The hydraulic characterization involves measuring the flow rate for a given pressure drop to satisfy the corresponding specification for each rung. The testing provides the total flow and the corresponding pressure drop in each rung. For the parallel subchannels, the pressure drop is constant. Thus, only the flow distribution within a rung with an invariant total flow must be considered in defining the worst channel.

- A precise weight measurement of each ring and each rung (after assembly).
- Geometric characterization of each ring and each rung after assembly.

Even with these restrictions, the definition of the worst-case channel in a thermally coupled set of seven flow channels separated by six heated elements is not trivial. Using the post-manufacturing and post-assembly data as the constraints, a Monte-Carlo sampling approach is recommended to define the worst case channel within a rung. In defining the worst-case geometry, the one-sided 99% confidence limit on the power-to-flow ratio during normal operating conditions must be used. After defining the worst-case geometry, the following limits must be applied for different event categories.

7.2.1 Normal Operations and Operational Transients

The primary criterion for normal operations and the operations transients is the ONB. The temperature limit is set to $T_w < T_{sat}$ with a $1-\sigma$ margin. Note that the margin is reduced to $1-\sigma$ as compared to $3-\sigma$ margin needed for the nominal geometry.

In the unlikely event that boiling is initiated in a channel, the back up criterion is $q < q_{CHF}$ also with a $3-\sigma$ margin. Note that the factor of 2 required for the nominal geometry is dropped because of the following:

- The likelihood of the actual existence of the worst-case channel is very small already. This likelihood combined with the 3 std deviation margin to CHF is believed to provide adequate margin for operations.
- If the worst-case channel exceeds CHF, the propagation is prevented as long as the adjacent channels meet the nominal channel requirements. The likelihood of having three worst-cases channels adjacent to each other is extremely small, given the constraints imposed on the post-assembly testing.

There is no Reynolds number limit for the worst-case geometry. In general, it is practical to apply the temperature and heat flux criteria in terms of flow rate. Thus, the maximum flow rate meeting the two criteria are chosen:

- No wall nucleation at $1-\sigma$ margin
- Maximum heat flux is less than q_{CHF} with $3-\sigma$ margin

7.2.2 Anticipated Events

For the worst-case geometry, the limits on the anticipated events are identical to the limits for operational transients discussed previously.

7.2.3 Unlikely Events

The temperature limit is set to $T_w < T_{sat}$ using best-estimate phenomenological modeling. However, if boiling is initiated in the worst-case channel, the back up criterion is $q < q_{CHF}$ with a 2- σ margin. Again, the lowering of the confidence level is justified because of the low frequency of the events, combined with the small likelihood of a worst-case channel presence. The flow rate criterion is the maximum needed to meet the wall temperature and heat flux criteria.

7.2.4 Extremely Unlikely Events

For these design-basis events, the limit is the Inconel failure temperature that must be met with a 1- σ margin. Again, the main concern is to limit the tungsten vaporization. Since exceeding the limit will result in the vaporization of tungsten in one ring (worst-case ring) only, the consequences are acceptable. Thus, a 1- σ margin is adequate. One important note is that the worst-case geometry for this consideration may be different than the worst-case geometry for the previous cases, where power-to-flow ratio is minimized. Flow is irrelevant for the failure limit because it is assumed all forced cooling is lost.

7.2.5 Events During TNS Replacement

For these design-basis events, the limit is the Inconel failure temperature that must be met at a 3- σ margin. The event frequency is irrelevant for these events. Because the event frequency may be high, a 1- σ limit is used to minimize the potential of a source term generation. The limits apply to the TNS module being replaced. Thus, even for high frequency events, because the TNS module is being replaced, the main concern is to limit the tungsten vaporization.

8. Summary and Conclusions

In this report, the bases for the THDC are discussed. Based on the presented logic, a set of THDC for different event categories were developed. The THDC include the limiting phenomenology and the confidence level required to meet the limits. The phenomenological uncertainty determines the standard deviation in the limits calculations. The uncertainty resulting from manufacturing tolerances is treated separately and less restrictive confidence level requirements are imposed for the worst-case geometry resulting from manufacturing tolerances.

The definition of the worst-case geometry requires a number of post-manufacturing and post-assembly data are collected and evaluated. The worst-case geometry is defined using a 1% probability limit, including the effect

of worst-case adjacent channel configurations. The resulting THDC are summarized in Table 3.

Table 3. Summary of THDC

Event Category	T_w	q
Normal Operations (NO)* and Operational Transients (OT) *NO also must meet $Re \geq 6000$	<u>Nominal Geom.</u> $T_w \leq T_{ONB} (@ 3\sigma)$ <u>Worst-Case Geom.</u> $T_w \leq T_{ONB} (@ 1\sigma)$	<u>Nominal Geom.</u> $q \leq q_{CHF/2} (@ 3\sigma)$ <u>Worst-Case Geom.</u> $q \leq q_{CHF} (@ 3\sigma)$
Anticipated Events frequency $\leq 10^{-2}/yr$	<u>Nominal Geom.</u> $T_w \leq T_{ONB} (@ 2\sigma)$ <u>Worst-Case Geom.</u> $T_w \leq T_{ONB} (@ 1\sigma)$	<u>Nominal Geom.</u> $q \leq q_{CHF/2} (@ 2\sigma)$ <u>Worst-Case Geom.</u> $q \leq q_{CHF} (@ 3\sigma)$
Unlikely Events $10^{-2}/yr < \text{frequency} \leq 10^{-4}/yr$	<u>Nominal Geom.</u> $T_w \leq T_{ONB} (@ 1\sigma)$ <u>Worst-Case Geom.</u> $T_w \leq T_{ONB} (BE)$	<u>Nominal Geom.</u> $q \leq q_{CHF/2} (BE)$ <u>Worst-Case Geom.</u> $q \leq q_{CHF} (@ 2\sigma)$
Extremely Unlikely Events $10^{-4}/yr < \text{frequency} \leq 10^{-6}/yr$	<u>Nominal Geom.</u> $T_w \leq T_M (@ 3\sigma)$ <u>Worst-Case Geom.</u> $T_w \leq T_M (@ 1\sigma)$	N/A
TNS Replacement Events (Independent of frequency)	<u>Nominal Geom.</u> $T_w \leq T_M (@ 3\sigma)$ <u>Worst-Case Geom.</u> $T_w \leq T_M (@ 3\sigma)$	N/A

Note the following additional considerations in the implementation of the THDC:

- THDC are not a substitute for the safety consequence limits and one must meet the safety consequence limits independent of the design criteria considerations.
- The THDC must be implemented in parallel to structural design criteria. If the structural design criteria are not met, the THDC are meaningless because certain assumptions are made in the THDC implementation in terms of maintaining a fixed geometry.

- The THDC must be considered as a guide for the design philosophy and not as a hard limit. When achievable, design margins greater than those required by the THDC must be used. On the other hand, if a specific event sequence cannot meet the THDC, expensive design changes are not necessary if the single event sequence results in sufficient margin to safety criteria, and it does not challenge the plant availability or investment protection philosophies.
- Judgment must be used in comparing the transient results to the THDC. For instance, if the design criterion is not to exceed the ONB, the main objective is to reach a single-phase quasi-steady condition after the transients. If the ONB limit is exceeded briefly during a transient, the consequences of this must be carefully considered. If the event recovers from two-phase conditions rapidly and this prompt recovery is documented with a convincing analysis, the objectives of the THDC are considered met.

9. References

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