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Calandria Vessel Integrity under Severe Accident Loads

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ABSTRACT

This paper discusses the integrity of the calandria vessel of a CANDU reactor under severe accident loads. The potential failure modes of the vessel are identified. They include thermal creep failure, overpressure failure and mechanical overload failure. Thermal creep failure of the vessel can occur if film boiling occurs over a significant area at the bottom of calandria vessel, thereby causing the vessel wall to heat up. Overpressure failure can occur if large, sustained rapid steam generation associated with relocated core debris into the moderator fluid occurs and the generated steam cannot be adequately relieved through relief ducts. Overload failure would occur if the mass of relocated core debris is sufficient to produce stresses in the vessel wall that exceed ultimate tensile stress. The limits associated with these failure modes are evaluated and used to generate representative likelihoods of calandria vessel heat loads..

INTRODUCTION

Severe accidents in CANDU involve a number of broadly common stages in which heat transfer degradation occurs first in the reactor fuel and then progresses to the fuel channels (pressure tubes and calandria tubes). For the fuel channel components to experience significant degraded heat transfer the passive heavy water moderator has to be depleted to expose the outer calandria tubes to steam cooling conditions. This can occur in events in which either the moderator system heat sink is lost leading to moderator boil off [1], or a rupture path occurs which allows either partial or full draining of the moderator fluid out of the calandria vessel. There are two large volumes of water (the moderator and shield water) that surround the reactor core and act as in-situ passive heat sinks in severe accidents. This has significant impacts on severe accident management. These unique passive features of operating CANDU reactor designs result in severe accidents that are expected to progress with ample opportunity for operator actions to stabilize the plant and mitigate the consequences. They also ensure that large CANDU reactors are inherently tolerant of a prolonged loss of engineered heat sinks at decay power levels.

The calandria vessel is a key component that can mitigate the progression of severe accidents to ones that involve ex-vessel relocation of solid and molten core debris. By assuring the integrity of this vessel and the in-vessel retention of core debris the progression of events to molten core–concrete interaction (MCCI) can be precluded. In order to demonstrate this core retention capability it is essential that all potential failure modes of the vessel be identified and evaluated. This is the focus of this paper.

CANDU SEVERE ACCIDENT PROGRESSION

During the progression of severe accidents in a CANDU reactor it is possible that the moderator fluid inventory in the calandria vessel will become gradually depleted either due to boil-off as heat is transferred from hot deformed fuel channels or due to leakage out of a ruptured low elevation flow path connecting to the vessel. Without actions to reestablish heat removal in fuel channels or to establish makeup of liquid to the vessel, the fuel channels will gradually become uncovered, starting with the highest elevation channels in the core. Once uncovered the temperature of the fuel and fuel channels will escalate causing thermal creep strain failure of the channel due to overheating. Once failed, channels will relocate downward and become suspended on intact channels at lower elevations. This process is referred to as core disassembly.

As core disassembly proceeds, the failed channels are initially supported by the intact channels that are still covered and being cooled by the moderator liquid. However, once uncovered, the next row of channels will also be subject to overheating and creep strain failure. Eventually, the load imposed on intact channels by the accumulated core debris can cause rapid shear failure of channels due to mechanical overload and the core will relocate to the bottom of the vessel.

The calandria vessel is surrounded by a separate water system that provides radiation shielding. This water provides a means of cooling the wall of the calandria vessel by nucleate pool boiling heat transfer, thereby halting the progression of core degradation and damage. In order to provide stable mitigation of core damage progression and to prevent relocation of core debris out of the calandria vessel, it is necessary that calandria vessel integrity be maintained. Maintaining the integrity of the calandria vessel is a key factor that limits the relocation of molten core material into the containment and possible initiation of MCCI which can lead to significant challenges to containment integrity. Therefore, a systematic assessment of the potential failure modes of this vessel is necessary to support severe accident mitigation in CANDU reactors.

CALANDRIA VESSEL FAILURE MODES

Under severe accident loads, mechanical and thermal loadings will challenge the calandria vessel integrity. Vessel failures above the level of core debris are not a concern unless they activate phenomena that can cause subsequent vessel failure below the level of the core debris. The potential failure modes of the vessel include thermal creep failure, overpressure failure and mechanical overload failure. The location of vessel failure is of critical concern and it has to occur at a location below the level of core debris in the vessel in order that core debris can relocate. Thermal creep failure of the vessel can occur if film boiling occurs over a significant area at the bottom of calandria vessel, thereby causing the vessel wall to heat up [2],[3],[4]. Overpressure failure can occur if large, sustained rapid steam generation associated with relocated core debris into the moderator fluid occurs and the generated steam cannot be adequately relieved through relief ducts. Overload failure would occur if the mass of relocated core debris is sufficient to produce stresses in the vessel wall that exceed ultimate tensile stress. The limits associated with these failure modes are evaluated and representative likelihoods of calandria vessel heat loads are derived.

MECHANICAL LOADING OF THE CALANDRIA ASSEMBLY

The first group of failure mechanisms considered is those involving either static or dynamic mechanical loading of the vessel wall.

Static Mechanical Loadings

The static mechanical loading mechanisms are considered below.

Dead Weight Load

Dead weight load on the vessel is initially (prior to core disassembly) due to the weight of the heavy water contained in the vessel. This dead weight load is compensated partially by the buoyancy force acting on the outside of the calandria vessel due to the static pressure of the shielding water surrounding the vessel. Depending upon the reactor design the shielding water is contained within either a concrete shield vault (Pickering B and CANDU-6 designs) or a steel shield tank (Bruce and Darlington designs) that contain the calandria vessel. For the different reactor designs the mass of heavy water moderator in the calandria vessel (200 to 260 Mg) is approximately 1.5 times the total weight of the fuel and fuel channels (135 to 170Mg). Therefore the dead weight load on the calandria vessel after core disassembly is actually lower than the initial, normal dead weight load due to the moderator fluid. Therefore, the dead weight load is not a significant challenge to the calandria vessel integrity as long as the vessel wall temperature does not increase to a level at which creep strain can occur.

Sustained Overpressure

The vessel can be subjected to a sustained static overpressure in the event that a channel failure occurs during the accident progression. This can lead to discharge of two-phase coolant into the vessel that transiently increases the internal pressure to approximately 138 kPa(g), at which pressure calandria relief duct rupture disks burst to provide overpressure protection. The sustained overpressure will be less than 138 kPa(g) after the rupture disks burst, however the overpressure is conservatively evaluated at a sustained value of 138 kPa(g). Since this pressure is within the design envelope and the steam temperature at saturation during the steam discharge over-pressure is limited to within the ASME Level C limits. Therefore, static overpressure is not a challenge to the calandria vessel integrity.

Local Stress Discontinuities

The stresses in the calandria vessel wall due to static mechanical loading are small, as discussed above. Therefore, the local stress at discontinuities, such as nozzle attachments to the vessel, while greater than the stresses in the bulk material, are also small and do not represent a challenge to vessel integrity. Furthermore, the large majority of nozzles are at upper elevations of the vessel and it is only those few nozzles at the bottom of the vessel that are of relevance to in-vessel retention.

Dynamic Mechanical Loadings

The dynamic loading of the calandria vessel is associated almost exclusively with events in which one or more fuel channels fail leading to two-phase coolant discharge into the vessel. In some instances hot fuel debris in the fuel channels may also be ejected to cause local vapor generation from debris heat rejection.

Transient Pressurization

As discussed above calandria vessel rupture disks are designed to burst at a typical overpressure of 138 kPa(g). The calandria relief ducts, in association with the rupture disks are designed to limit overpressure in the vessel to less than ASME Level C limits. Since the design can accommodate a fuel channel failure this does not present a challenge to vessel integrity. A significant number of fuel channels would have to fail in rapid succession, as might be the case in the very improbable scenario of a failure to shutdown following a positive reactivity insertion [5]. The CANDU design incorporates two physically separate, equally capable and independent shutdown systems. These highly redundant systems, together with design provisions to reduce the probability of common mode failure make this event a very low risk contributor.

Another mechanism for rapid transient pressurization involves the collapse of a hot disassembling core into a pool of moderator fluid. In CANDU the core collapse process occurs while the core debris is solid and hence vapor generation is limited to heat transfer at solid hot surfaces. These steam surges result in a transient pressure loading of the calandria vessel that are limited by the fact that the rupture disks in the four 0.609 m (24") diameter calandria relief ducts will have burst. This provides a large discharge area of 1.17 m^2 for steam flow. At a vessel over pressure of 138 kPa(g) the pure steam flow rate out of the four relief ducts is approximately 1260 kg/s which represents a power of 2330 MW. This is of the same order as 100% full thermal power of CANDU reactors and therefore a transient overpressure of this magnitude is unlikely, even though this magnitude of overpressure is within design limits. In addition, the steam surges will occur sporadically and involve only a portion of the core which has overheated during the core disassembly process, reflecting the slow and discrete nature of fuel channel collapse as the moderator boils off. Because the vessel over-pressure will be limited, steam surges do not pose a significant challenge to calandria vessel integrity.

Impulsive Loading

There are two main sources of impulsive loading of the calandria assembly. They are core collapse and supersonic pressure waves generated immediately after a fuel channel rupture. In the latter case there may be a limited amount of molten fuel material ejected at the time of fuel channel failure. It is not possible to accumulate large amounts of molten fuel in a channel at high pressure and not have the channel fail. The response of the calandria vessel wall to this impulse loading can be described by the equation of motion for the radial displacement *u(t)* of a thin-walled cylinder subjected to an impulse pressure *f(t)* which is given by:

$$\frac{d^2u(t)}{dt^2} + \omega_{shell}^2 u(t) = \frac{f(t)}{\rho\tau_m}, \tag{1}$$

where ρ and τ_m are the calandria shell material density and thickness, respectively. The natural frequency of vibration of the thin-walled calandria shell is given by

$$\omega_{shell}^2 \equiv \frac{E}{\rho R_{CV}^2}, \tag{2}$$

where E is the modulus of elasticity and R_{CV} is the radius of the calandria vessel. For small width impulses with specific impulse equal to $I = f_0 \Delta t$ the maximum strain of the shell is given by:

$$\varepsilon_{\max} \le \frac{I}{R_{CV}\,\rho\tau_m\omega_{shell}} \tag{3}$$

Using values for the geometry and material of CANDU calandria vessels in Eq. (3) and (4), a total specific impulse of greater than 1.2 MPa-s is required for local strain failure of the vessel (10% local plastic strain). This level of impulse loading is only associated with a very large number of channels (approximately 20) failing simultaneously. This number of channel failures is not possible for severe accident sequences other than highly improbable loss of shutdown events. Therefore, impulse loading is not a significant challenge to vessel integrity.

THERMAL LOADING OF THE CALANDRIA ASSEMBLY

These are loads that can directly compromise the integrity of the calandria vessel if the vessel wall attains elevated temperatures at which thermal creep strain can occur at prevailing load levels. In particular, thermal loading is independent of mechanical load. The failure mechanisms are characterized by material phase transformations that result in load bearing capability of the structure.

Wall Melt-through

The last channels to fail are those at the bottom periphery of the core. These channels are low power channels and will be cool at time of core collapse due to the fact that upper channels that have failed are supported by lower cooled channels. The weight of the accumulated core debris causes mechanical failure of the lower channels due to either shear or pull-out of rolled joints at the ends of the channel. These cool lower channels will subsequently heat up following dryout of the debris bed. They will also heat up at a slower rate due to their low decay heat power levels. Therefore, there will always be a solid debris layer separating the calandria vessel wall and the hotter internal material in the debris bed. Furthermore, as the fuel in the bottom layer of channels heats up the tubes and fuel will deform by creep strain due to the weight of upper debris on the channel segments, thereby forming a compressed conductive layer that protects the calandria vessel wall from any molten corium pool that forms inside the debris bed. Any melt relocating downward will be restricted by the narrow gaps between these lower channels and will freeze on the cooler surfaces. Therefore, melt through of the vessel wall is a physically unreasonable failure mechanism provided that CHF does not occur on the outer bottom surface of the vessel. A very conservative lower bound from the literature is 0.3 MW/m^2 [2],[3],[4].

Thermally-induced Stresses

The thermal loading of the calandria vessel is described by a heat flux $q_i''(\theta,t)$ on the inner surface of the calandria shell. It describes the heat load from the debris and is assumed to be a function of azimuthal angle. The dynamic temperature distribution through the calandria shell is given by the transient conduction equation in which axial conduction is neglected because the temperature gradient is low in this direction.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k_{ss}\, r\,\frac{\partial T(r,\theta,t)}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \theta}\left(k_{ss}\frac{\partial T(r,\theta,t)}{\partial \theta}\right)=\rho C_P^{ss}\frac{\partial T(r,\theta,t)}{\partial t}\,, \tag{4}$$

where $T(r,\theta,t)$ is the temperature of the calandria shell and k_{ss} is the thermal conductivity of the stainless steel Calandria Vessel. The calandria shell temperature is subject to the boundary conditions at the inner (r_i) and outer (r_o) radii of the shell

$$-k_{ss}\left.\frac{\partial T(r,\theta,t)}{\partial r}\right|_{r=r_i}=q_i''(\theta,t) \tag{5}$$

$$k_{ss}\left.\frac{\partial T(r,\theta,t)}{\partial r}\right|_{r=r_0}+h_{sw}\left[T(r=r_0,\theta,t)-T_\infty\right]=0 \tag{6}$$

and is also subject to the periodicity boundary condition $T(r,\theta,t)=T(r,\theta+2\pi,t)$. Here h_{sw} is the heat transfer coefficient to the shield water. However, given the relatively slow transient variation in heat flux and the relatively thin wall (3 cm) of the vessel, the thermal profile of the calandria shell is well characterized by the steady sate solution (i.e. dynamic heat conduction can be ignored).

Radial Thermal Gradients

The calandria shell temperature profile along the radial direction is approximately linear. The variation of the thermal conductivity k_{ss} with temperature is weak. Therefore, corrections to the calandria shell thermal profile due to the temperature dependence of k_{ss} are negligible. The temperature profile along the radial direction is then given by

$$T_{shell}(r)=T_\infty+\frac{q_i''(\theta,t)r_i}{k_{ss}}\left[\ln(r_0)-\frac{k_{ss}}{h_{sw}r_0}\right]-\frac{q_i''(\theta,t)r_i}{k_{ss}}\ln(r)\,, \tag{7}$$

where $T_{i,o}$ correspond to the inner and outer calandria shell surface temperatures, respectively, and r_i is the radial coordinate of the inner calandria surface. The thermal stresses in the calandria shell due to the radial variation of shell temperature are compressive at the inner wall surface and tensile at the outer surface. The hoop and axial stresses are given by

$$\begin{aligned}
&\mathit{Compressive}\\
&\sigma_\theta=\sigma_z=-\frac{E\alpha\Delta T}{2(1-\mu)}\left(1+\frac{m}{3}\right)\\
&\mathit{Tensile}\\
&\sigma_\theta=\sigma_z=\frac{E\alpha\Delta T}{2(1-\mu)}\left(1-\frac{m}{3}\right)\\
&(1+m)=\frac{r_i+\tau_m}{r_i}=1+\frac{\tau_m}{r_i}
\end{aligned} \tag{8}$$

Where, μ is the Poisson ratio, α is the coefficient of linear expansion, r_i is the vessel inner radius and τ_m is wall thickness of the vessel.

Azimuthal Thermal Gradients

The variation of thermal stress in the calandria shell due to the azimuthal variation of shell temperature is largely negligible given that the azimuthal temperature gradients are small. However, at the intersection between the upper debris bed surface and the calandria shell, there will be a non-negligible change in the azimuthal temperature variation due to the change in heat flux at this interface (e.g. below the upper surface the heat flux is governed by conduction through the debris crust, while above the upper surface the heat flux is governed by radiative heat transfer between the hot upper surface and the calandria shell above the debris bed) In particular, at this interface over $\Delta\theta \sim \tau_m / R_{CV}$, there will be a very localized temperature difference at the inner surface of the vessel wall on the order of ~100K., as shown in Figure 1

LONG-TERM RETENTION OF CORE DEBRIS

Core Debris Geometry

Prior to formation of a volumetrically heated molten pool within the debris the heat transfer is conduction limited through the solid layers in contact with the vessel wall. Most of the heat generated goes into heating up the core debris. Once a molten pool of core debris forms within the debris bed convection heat ransfer provides an effective means of dissipating significant amounts of decay heat through the upward facing surface of the debris bed. For a semi-circular cavity, the average heat flux dissipated through the downward facing surface of the debris bed is given by the correlation due to Mayinger et. al. [6]

$$\bar{q}''_d = 0.54 Ra^{0.18} \left(\frac{h_{DB}}{R_{CV}} \right)^{0.26} \frac{\Delta T}{k_c}, \tag{9}$$

where $\Delta T \equiv T - T_{mp}$ is the melt superheat giving the temperature T of the melt above the melting point T_{mp} of the corium. The average downward heat flux depends upon the geometric correction factor $\left(h_{DB} / R_{CV}\right)^{0.26}$, which is significant for CANDU geometries since h_{DB}, the height of the debris bed, is significantly less than the calandria vessel radius. The heat flux through the upward facing surface of the debris bed to the calandria shell surface above the debris bed is given by the correlation ([6] and [7])

$$q''_u = 0.36 Ra^{0.23} \frac{\Delta T}{k_c} \tag{10}$$

The internal Rayleigh number for the molten pool is

$$Ra = \frac{g\beta Q_v h_{DB}^5}{k_c \nu \alpha}. \tag{11}$$

Here, g is the acceleration due to gravity, β is the bulk modulus, k is the thermal conductivity of the molten corium, ν is the kinematic viscosity, α is the thermal diffusivity, and Q_v is the volumetric heat generation rate. The thermal conductivity of the corium k_c is not purely the molecular conductivity k_0 as internal radiation introduces temperature-dependent corrections to the molecular conductivity. Based upon Epstein et. al. [8], the thermal conductivity k_c with internal radiation corrections (on the order of 0.3%) is given by the expression

$$k_c(T) = k_0 \left\{ 1 + \frac{0.46}{N} \left[\left(1 + \frac{T}{T_{mp}} \right) \left(1 + \frac{T^2}{T_{mp}^2} \right) \right]^{0.82} \right\}, \tag{12}$$

where T is the temperature of the melt, T_{mp} is the melting temperature of the corium and the conduction-radiation parameter is given by $N = k_0 \kappa / 4n^2 \sigma_B T_{mp}^3$. The conduction-radiation parameter depends upon the molecular conductivity k_0, the absorption coefficient κ , the Stefan-Boltzmann constant σ_B and the refractive index n.

The average downward heat flux represents the average heat being dissipated through the downward-facing surface of the calandria vessel. Due to the non-zero radius of curvature of the bottom of the calandria vessel, the heat flux at any point along the calandria shell in direct contact with the debris bed will be a function of azimuthal angle. The downward heat flux is therefore dependent upon the azimuthal angle

$$q''_d(\theta) = \bar{q}''_d \cdot f(\theta)\,, \tag{13}$$

where $f(\theta)$ expresses the azimuthal variation of the downward heat flux determined from experiments in semi-circular cavities [9]. It should be noted that previous work on this azimuthal variation focused upon a semi-circular cavity with a convecting pool of maximum height equal to the radius of the cavity. These experimental results are extrapolated to represent the downward heat flux from the debris bed in the CANDU calandria vessel in the following manner. The functional form $f(\theta)$ is assumed to be directly given based upon experiments [4]. It is then normalized so that

$$\bar{q}''_d = \int_0^{\theta_{DB}} d\theta\, q''_d(\theta)\,, \tag{14}$$

where $\bar{q}''_d$ is given by Eq. (5) and θ_{DB} is the angle between the calandria vessel vertical midpoint and the intersection of the upper debris surface with the calandria shell.

The radiative heat transfer to the calandria vessel surface above the debris bed is given in terms of the fraction of radiation incident at each point of the calandria shell from the upward-facing debris bed. Approximating the calandria vessel as a surface of infinite extent in the axial direction, this is expressed as

$$q''_{uCV} = -\frac{q''_u}{2}\int_{S_u} dS_u \frac{(\hat{n}_u \cdot \vec{r})(\hat{n}_{CV} \cdot \vec{r})}{r^3}\,, \tag{15}$$

where the surface integral is over the upper debris bed surface and $\vec{r}$ is the vector between the points on the upper debris surface and the calandria surface above the debris bed.

The sharp change in heat transfer across the upper debris bed surface leads to very localized radial and azumuthal ttemperature gradients at the inner vessel surface in the region of the debris bed interface, as shown in Figure 1.

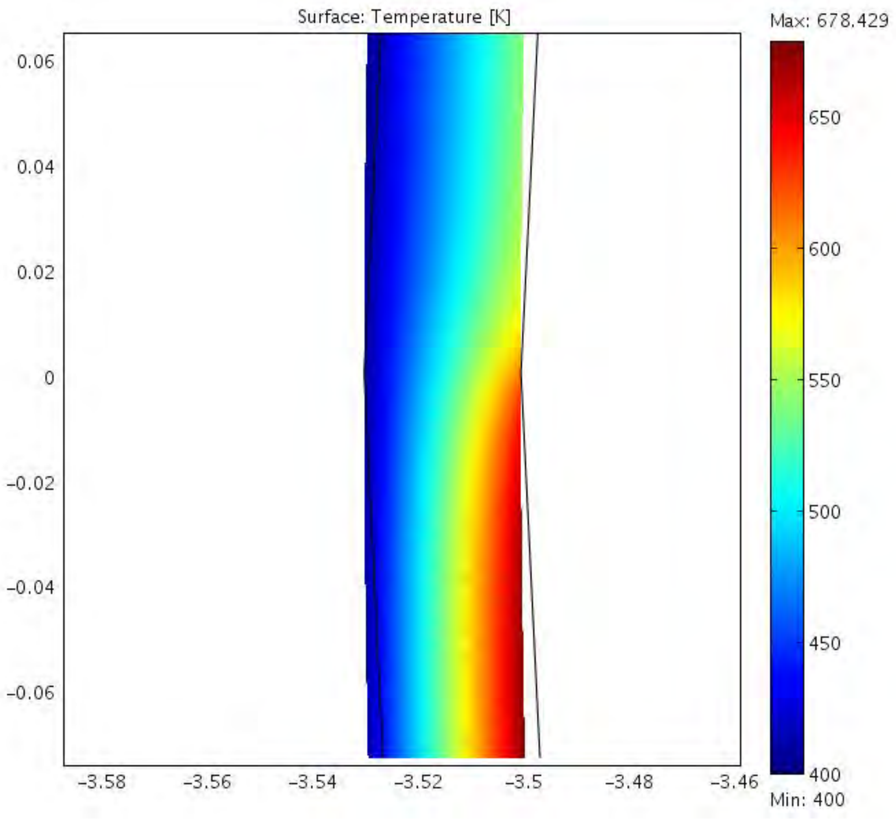

Figure 1: Temperature Profile across the Interface of the Upper Debris Bed Surface

(x-axis is radial distance and y-axis is the position above (+ve) or below (-ve) the surface of the debris bed)

It is important to note that the temperature gradient shown in Figure 1 is very localized to the inner surface in the region of the interface and that the temperature in the outer part of the vessel wall does not vary significantly. This indicates that there is not a large variation in the tensile thermal hoop stresses in the outer surface, whereas as the compressive stresses at the inner surface can experience very localized variations. However, it is the tensile stresses that are important with regard to vessel integrity and they are less than half of the yield stress for the stainless steel vessel material. (max te4nsile stress at the interface is 125 MPa).

Failure Likelihood as a Function of Core Debris Parameters

The likelihood function of decay heat level is shown in Figure 2 and represents the decay heat level at the time that the molten pool form in the debris bed. It is strongly peaked about approximately 1% full power. It rapidly decays for decay heat levels above 1% full power, reflecting the low likelihood of severe accidents in CANDU progressing to complete core disassembly early in the accident. A much slower decay occurs for decay heat levels less than 1% full power. This reflects the dominance of accidents which have late core disassembly for CANDUs and the fact that the decay heat level decreases slowly at longer times. The effect of these decay heat power variations upon the average downward heat flux is given in Figure 3. The downward heat is sufficiently lower than the lower bound CHF of 0.3 MW/m^2 that there is no reasonable likelihood of exceeding a CHF on the outer surface of the calandria vessel during CANDU severe accidents.

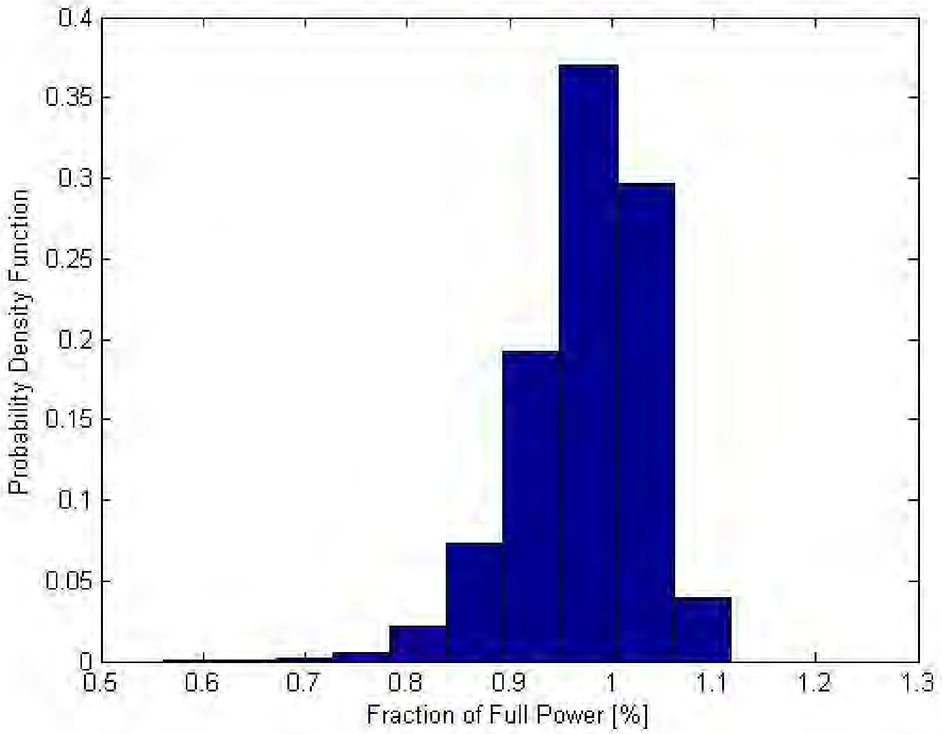

Figure 2: Likelihood Function for Decay Heat Level

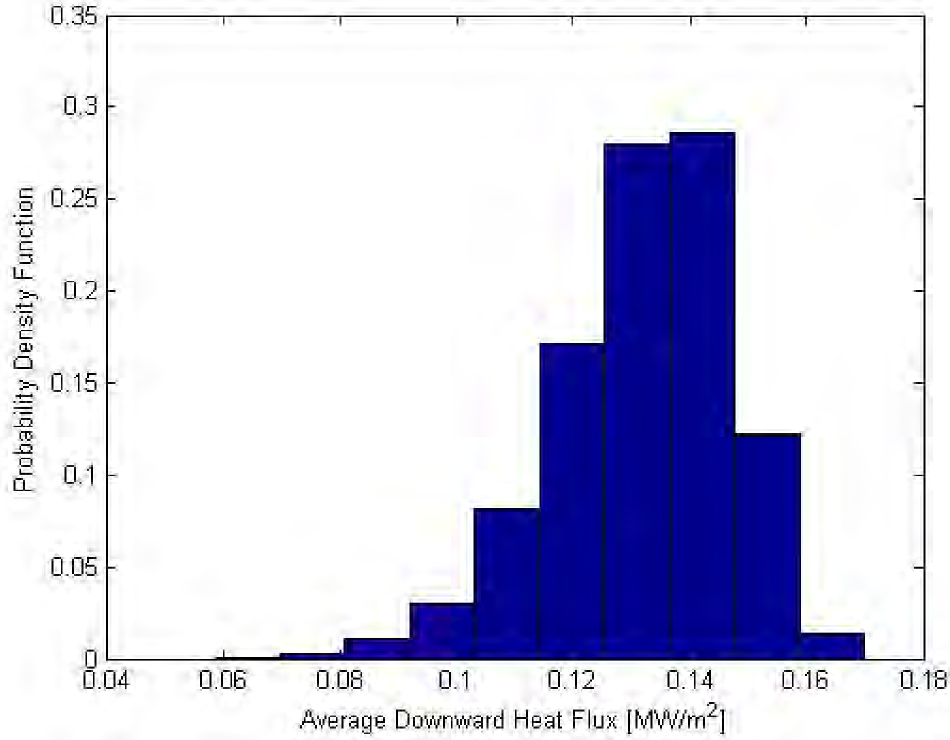

Figure 3: Likelihood Distribution of Average Downward Heat Flux

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REFERENCES

1. J.T. Rogers, "*A Study of the Failure of the Moderator Cooling System in a Severe Accident Sequence in a CANDU Reactor*", Proc. 5th Int. Meeting on Thermal Nuclear Reactor Safety, Karlsruhe, Sept. 1984.
2. R.E.Henry and H. Fauske, "*External Cooling of a Reactor Vessel under Severe Accident Conditions*", Nucl. Eng. Des., **139**, 31, 1993.
3. F.B. Cheung and K.H. Haddad, "*A Hydrodynamic Critical Heat Flux Model for Saturated Pool Boiling on a Downward Facing Curved Heating Surfac*e", Int.J. Heat Mass Transfer, **40**, 6, pp 1291-1302, 1997.
4. T.G. Theofanous, et.al., " *In-vessel Coolability and Retention of a Core Melt*", Nuc. Eng. Des., **169**, 1-48, 1997.
5. J.C. Luxat and B.W. Spencer, "*Insights to the Phenomenology and Energetics of Reactivity Initiated Accidents*", Proc. ENS/ANS Conf. on Thermal Reactor Safety, Avignon, France, October, 1988.
6. Mayinger,F, Jahn, M, Reineke, H.H. and Steinbrenner, U., "*Examination of Thermalhydraulic Processes and Heat Transfer in a Core Melt*", Federal Ministry for Research and Technology Final Report BMFT RS48/1, 1975.
7. Kymalainen, O. et al, "*Heat Flux Distribution From a Volumetrically Heated Pool with High Rayleigh Number*", Nuclear Engineering and Design, **149**, pp 401-408, 1994.
8. Epstein, M, Cheung, F.B., Chawla, T.C., and Hauser, G.M., "*Effective Thermal Condusctivity for Combined Radiation and Free Convection in an Optically Thick Heated Fluid Layer*", Jour. of Heat Transfer, **103**, pp 114-120, 1981.
9. Jahn, M and Reineke, H.H., "*Free Convection Heat Transfer with Internal Heat Sources*", Proc. 5th Int. Heat Transfer Conf., Tokyo, 1974.