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SENSITIVITY STUDIES OF HEATER ROD DESIGN FOR TRANSIENT CRITICAL HEAT FLUX EXPERIMENTS IN TREAT

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SENSITIVITY STUDIES OF HEATER ROD DESIGN FOR TRANSIENT CRITICAL HEAT FLUX EXPERIMENTS IN TREAT

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ABSTRACT

An important area of reactor safety is the cladding-to-coolant heat transfer under fast transient conditions. These conditions can occur during events such as a reactivity-initiated accident (RIA). In this paper we present the work performed under a laboratory directed research and development (LDRD) project, headed by Idaho National Laboratory (INL). The goal was to develop a test matrix to inform on the design of a borated steel heater rod that will induce critical heat flux (CHF) within an experimental capsule filled with water, using the TREAT facility, when submitted to a power pulse. The energy deposition in the rod and occurrence of CHF were identified as the most important key Figures of Merit (FoMs) used in the design process. Energy deposition was varied by using different pulse characteristics and various boron concentrations in the rod. A power coupling factor (PCF) was determined for each boron concentration.

A sensitivity study determined the lowest limiting PCF needed to induce CHF in water with different degrees of subcooling while keeping pressure constant. Boron concentrations between 0.1-1.54 wt.% were considered. Additionally, the value of CHF is also known to increase during a rapid transient. A CHF multiplier sensitivity study focused on an example case concluded that CHF is no longer exceeded when the value is between 2.6- and 2.9-times higher. Lastly, a self-shielding study was performed to determine whether a borated tube could be used in place of a solid borated rod. The study determined that the inner 1mm of the rod can essentially be excluded or instrumented without heat generation penalties.

KEYWORDS
CHF- Critical Heat Flux
PCF- Power Coupling Factor
DNB-Departure from Nucleate Boiling

1. INTRODUCTION

The nuclear industry generates large amounts of base load electricity while at the same time keeping a stellar safety record. One type of postulated design basis accident occurs when there is a sudden and unexpected insertion of reactivity resulting in a subsequent increase in reactor power and the temperature of the reactor components. This type of event is called a reactivity-initiated accident (RIA). In a pressurized water reactor (PWR), the most limiting RIA event occurs during the accidental ejection of a control rod cluster, due to a failure in the reactor control mechanism [1].

Inherent feedback mechanisms, such as that resulting from the Doppler broadening of U-238, mitigate the rapid rise in reactivity during an RIA. Nevertheless, the fuel and cladding elements of the core will experience a rapid temperature increase that could induce a boiling crisis in a reactor system. In PWRs, this boiling crisis occurs when the onset of nucleate boiling (DNB) is observed. DNB occurs when the density of bubbles surrounding the cladding is considerable enough that a vapor film develops between the cladding and coolant heat transfer interface (bubble crowding) [2]. Because of the much lower heat transfer efficiency of the formed vapor film, this results in the insulation of the fuel and cladding components of the core impacted by this event. The generation of bubbles around the surface of the cladding is dependent on two parameters; the bulk temperature of the coolant as well as the heat flux coming out of the cladding into the surrounding coolant [2].

Critical heat flux (CHF) is indicative of when the onset of DNB event occurs in a PWR system. CHF is characterized by the sudden drop in the heat transfer coefficient at the cladding-to-coolant boundary, causing a rapid increase in cladding temperature. Post-CHF behavior is characterized by a low heat flux film boiling phase during which elevated temperatures and embrittlement of the cladding can occur [1]. As the fuel pellets expand with increasing temperature, cladding embrittlement can lead to cladding failure and the subsequent release of highly radioactive fission products into the coolant.

Experimental data and visual observations have shown that under rapid power transient conditions, such as during an RIA event, the mechanisms leading up to a DNB crisis around a fuel rod in a PWR differ than what is observed during steady state heating [3]. In fact, during rapid irradiation conditions, more random nucleation sites have been observed to form around the experimental cladding surface, leading to improved heat transfer between the cladding and coolant (see Figure 1) [4]. As a result, the boiling crisis event will occur at higher CHF values under these circumstances and the cladding temperature increase would temporarily level, before rising after the onset of DNB event occurs. This also means that a higher rod energy deposition would be needed to induce CHF under these fast-transient conditions. Likewise, a lower energy deposition would induce CHF in the cladding-to-coolant interface, around a rod that is being heated under steady conditions; assuming same thermal and surface material properties in both cases.

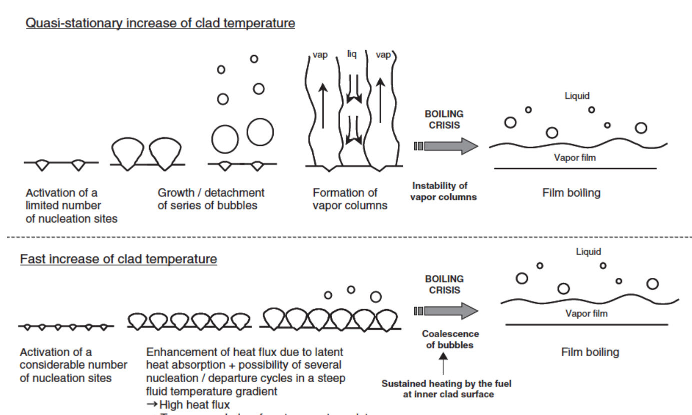

Figure 1. DNB Mechanism Comparison Between Steady State vs. Fast Transient Heating Conditions [4].

The heat transfer between fuel cladding and coolant under rapid transients is not well understood due to a lack of experimental data under these conditions. This has led to major uncertainties between computer models used to predict important parameters such as maximum cladding temperature and CHF values. For example, the comparison of RIA fuel codes, found in the reference 4 benchmark, showed major discrepancies in the cladding temperature behavior as a function of time. Additionally, this means that each of the different codes used, predicted the occurrence and the value of the CHF differently [5]. The difference in cladding temperature was indicated to be a result of heat transfer conditions, mainly under the film boiling phase, due to the different assumptions made in the CHF correlations of these RIA fuel codes [5].

Historically, CHF correlations have been a function of hydrodynamic parameters such as mass flux, pressure and equilibrium quality. Recent studies have suggested that bubble formation mechanisms are also impacted by surface characteristics such as topography, roughness and wettability. These have been shown to have significant effects on CHF predictions [6]. Pool boiling CHF was observed to increase with surface roughness in one experiment [7]. The results from another experiment showed that with increasing surface wettability, the heat flux through the heat surface improves [8]. In addition to this, CHF values have been experimentally shown to be higher during rapid transients [4]. The additional impacts of these parameters are expected to be a major cause for the uncertainties in predicting CHF and maximum cladding temperature in the event of an RIA.

Conservative limitations govern the design and safety margins in light water reactors (LWRs) due to this lack of understanding of heat transfer under fast irradiation conditions. Better prediction of these important parameters will provide enhanced best-estimate fuel safety criteria intended to prevent a boiling crisis. This will enable the operation of current and future LWRs at higher powers, resulting in improvements to their fuel cycle performances.

The work present in this paper has been performed under a laboratory directed research and development (LDRD) project, headed by Idaho National Laboratory (INL). The modeling goal is to develop a test matrix to inform on the design of a heater rod that will be subjected to in-pile pool boiling transient irradiation testing using the Transient Reactor Test (TREAT) facility. TREAT is a thermal spectrum graphite reactor that is capable of reproducing power pulses, with energy depositions similar to that found in the event of an LWR RIA. The heater rod is made up of borated type-316 stainless steel (SS-316) material, that generates heat through the (n, α) capture reaction. The overall experimental objective of the project will be to develop a rodlet that will be inserted into the TREAT facility, using the minimal activation retrievable capsule holder (MARCH) irradiation vehicle and the Static Environment Rodlet Transient Test Apparatus (SERTTA) experimental vehicle both developed at INL [9,10]. The SERTTA vehicle will be filled with pressurized water coolant. The rodlet design will seek to induce CHF, when subjected to a power pulse, in the coolant surrounding it. The impacts of several hydrodynamic and surface parameters, as well as several design basis characteristics, shown in Figure 2, will be investigated using this experimental rodlet in TREAT.

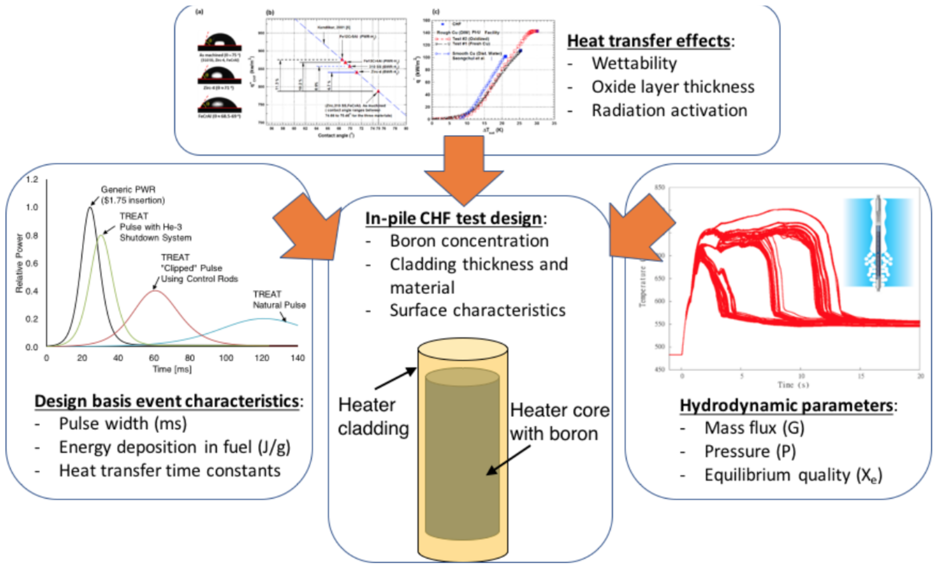

Figure 2. Scope of Experimental In-Pile Testing and Modeling Matrix Illustrating all Key CHF Impacting Parameters Identified for this LDRD.

The modeling approach of this project focused on creating prototypic PWR system conditions and material characteristics. In order to inform on the rodlet design, several key Figures of Merit (FoMs) and their level of importance were considered. The FoMs selected were the energy deposition in the borated rodlet, peak outer cladding temperature, occurrence of CHF, and the heat transfer time constant between the rodlet and the coolant.

The energy deposition in the rod and the occurrence of CHF were identified as the FoMs with the highest priority in the study. The study seeks to induce CHF in the water surrounding the experimental heater rodlet and characterize the point when CHF occurs so that new or modifications to current CHF correlations can be developed for fast transient conditions. Additionally, manifestation of CHF is dependent on all the other key FoMs identified as well as the hydrodynamic properties of the coolant. The rod energy deposition and deposition rate are also of high priority, because of their direct impacts on the occurrence of CHF, as well as its effects on the maximum cladding temperature.

Variations in the energy deposition in the rodlet will be achieved by utilizing different TREAT pulse characteristics and potentially various concentrations of natural boron in the experimental steel rodlet. Thorough a neutronics study, a power coupling factor (PCF) was calculated for each boron concentration case in the rod. This PCF serves as a ratio of how much power was expected to be generated in the rod per power generated in the TREAT facility as a result of a power pulse. A study was conducted to determine what PCF is needed to induce CHF in water with different degrees of subcooling. The ranges of boron concentration considered in the study were bound between 0.1-1.54 wt.%. Additionally, the pool boiling CHF value is expected to increase by as much as 10 times during a rapid transient, when compared to a steady state transient in subcooled water [4]. Therefore, a secondary task of this study was to determine what CHF value multiplier is needed to inhibit the occurrence of CHF for a chosen subcooling case.

The heat transfer time constant determines the change in fuel, cladding and coolant temperature over time. It also directly impacts the occurrence of CHF because of its effects on the cladding temperature as a function of time. The heat transfer time constant is a function of the thermal properties of the fuel and the surface thermal resistance of the coolant. Additionally, it is inversely proportional to the volumetric heat capacity and radius of the rod. In the case of the borated steel rodlet, due to the higher order of magnitude of the thermal conductivity value in steel compared to oxide-based commercial PWR fuel, the volume conductivity would not be accurately represented. Further, the heat transfer coefficient to the coolant in pool boiling conditions found in the SERTTA capsule, is much different than the flow boiling regime found in PWR cores. For these reasons, the heat transfer time constant is of low priority for this study.

The final task of this study consisted of investigating the self-shielding effects of the borated rodlet. This was done to determine whether a borated tube in place of the suggested solid rod could be used, with similar heat generation results. Several advantages can be implemented with the use of a borated tube, in place of a solid borated rod. These advantages will be described later in this paper.

2. RESULTS

2.1 Power Coupling Factors Study

The purpose of this study was to determine the heat generation response of the borated steel rod placed in TREAT, using the MARCH-SERTTA irradiation vehicle system, for varying concentrations of natural boron. In order to achieve this, a neutronics analysis was conducted using the Serpent Monte Carlo reactor physics code initially developed at the VTT Technical Research Centre of Finland [11]. Advantage was taken of an available Serpent model of TREAT provided by INL [12].

Although the model used the SETH capsule, its material components are similar from a neutronics point of view to the SERTTA capsule [9]. For the analysis, the components in the model were all kept the same with the exception of the placement of a borated SS-316 rodlet, instead of the Urania rodlet, and the addition of SS-316 cladding material in the model (Figure 3). The borated rodlet has a radius of 0.475cm, typical of a PWR fuel rod, and a height of 10.16 cm. The neutronics analysis included boron concentrations between 0.1-1.54 wt.% natural boron.

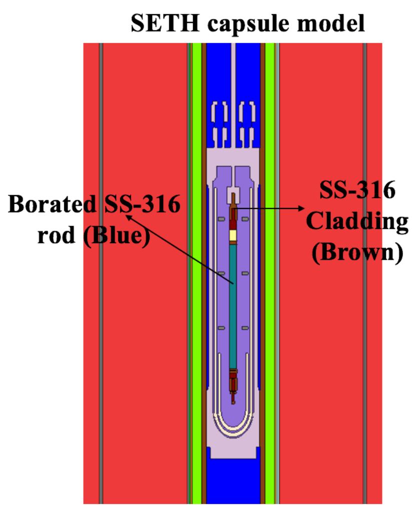

Figure 3. Illustration of the Borated Steel Rod Placed in SETH Capsule.

For each concentration case the heat generated in the rod was determined using Serpent. Following, rough arithmetic calculations were performed to verify that both heat generation results were within the same order of magnitude. The arithmetic calculations were slightly higher than the Serpent results. This was most likely due to the arithmetic calculations not taking self-shielding effects and peak thermal flux spectral shifts into account.

The heat generation calculations in Serpent were outputted in units of Watts. Using the known material density of the rod, the calculated volume and the steady state reactor power of 1000 W in the Serpent model, a PCF was calculated for several boron concentrations, shown in Table I. Interpolation of PCFs values between these known cases, was performed by using a polynomial fit.

Table I. PCF Calculations for Several Natural Boron Concentration Cases.

Natural Boron Concentration (Wt.%)	Heat Generated in Rod (W)	Reactor Power (W)	Power Factor (W/g – MW)
0.10	8.39E-04	1000	0.020
0.19	1.45E-03	1000	0.035
0.49	2.95E-03	1000	0.070
1.00	4.02E-03	1000	0.096
1.54	4.79E-03	1000	0.115

In actuality, the PCF using the water-filled SERTTA capsule could be higher than those determined from the SETH model. This is because the latter is a dry capsule and there would be less neutron moderation around the outside of the heater rodlet, relative to the SERTTA capsule, as a result. The advantage of these power factors is that the heat generated in the rod can be scaled to different reactor power outputs or weight samples of the rodlet. These power factors were used to provide a framework for the concurrent thermal hydraulics analysis following this study.

2.2 Power Factors Sensitivity Study

A power factor sensitivity study was conducted to determine what PCF coupling factor is needed to induce the CHF phenomenon in water coolant with different degrees of subcooling. This sensitivity study was conducted by coupling the thermal-hydraulics Reactor Excursion and Leak Analysis Program (RELAP5-3D), with the Risk Analysis Virtual Environment (RAVEN) code [13,14]. The RELAP5-3D code was initially developed from an initial task of modeling common LWR accidents, to its current multidimensional capabilities that allow it to model a full range of reactor components and transient situations [13]. RAVEN has the capability to act as a controller of the RELAP5-3D input parameters and identify the most important parameters impacting reactor safety [15].

The sensitivity study was started with the construction of a borated rodlet model submerged in water, within the SERTTA capsule, using the RELAP5-3D code. The model, shown in Figure 4, consists of several vertical hydrodynamic components. A pipe component was used to represent the pool of water surrounding the experimental rodlet. The pipe was 10.16 cm long and had a flow area of 10.93 square cm. This was equal to the volume of coolant surrounding the rod in the SERTTA capsule, as provided by INL. A heat structure (HT), with 80 mesh volumes, was used to represent the borated heater rod. The HT had an outer radius of 4.75 mm, similar to the outer cladding radius of a PWR fuel rod, and was attached throughout the entire length of the pipe component. The material used in the HT was stainless steel. Power cards were used to model the transient power pulses that the rodlet would experience inside the TREAT facility. Additionally, a power factor option in the code was used to represent different boron concentrations in the rod. These factors were taken from the PCFs calculated in the neutronics study.

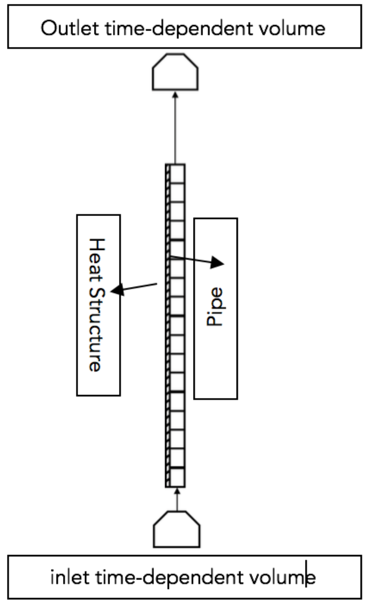

Figure 4. Schematic of the RELAP5-3D Model.

The flow in the model was set to zero to simulate pool boiling conditions in the rod capsule. Further, the coolant pressure was kept at 500 psi for all cases. The approach of the sensitivity study was to vary the PCFs for each of the subcooling cases studied, assuming a fixed power transient with a total energy deposition of 920 MJ in the TREAT core. The degrees of subcooling explored were 40°, 30°, 20°, 10° and 0°C.

In order to determine when CHF was exceeded for a subcooling case, characteristics of predicted post-CHF behavior were used. These are better described in the work by Bessiron [3]. After CHF is exceeded, there is a transition boiling phase and subsequent establishment of a film boiling phase, throughout which the heat transfer between the cladding and coolant significantly drops [3]. The maximum cladding temperature is determined by the heat flux during the film boiling phase [3]. The higher the energy deposition, the longer the total duration of the film boiling phase, and therefore the higher the cladding temperature reached. Lastly, a rewetting heat flux peak is observed. The purpose of this rewetting peak is to terminate the established film boiling phase [3]. Thus, improving the cladding-to-coolant heat flux and subsequently, lowering the temperature of the cladding down to the saturated temperature of the coolant.

The methodology for the sensitivity study was conducted as follows. An initial broad sweep of PCF was performed for each subcooling case. These PCFs represented boron concentrations between 0.1-1.54 wt.% in the steel rod. Then, a more defined sweep was conducted to better pinpoint when the occurrence of CHF was first observed. The 20°C subcooling case was chosen to demonstrate the process. The broad sweep of this subcooling case is shown in Figure 5. The first occurrence of CHF was determined by the first rewetting peak manifestation. All other cases with higher energy depositions than this case, induced CHF along with a longer film boiling phase as expected in predicted post-CHF behavior.

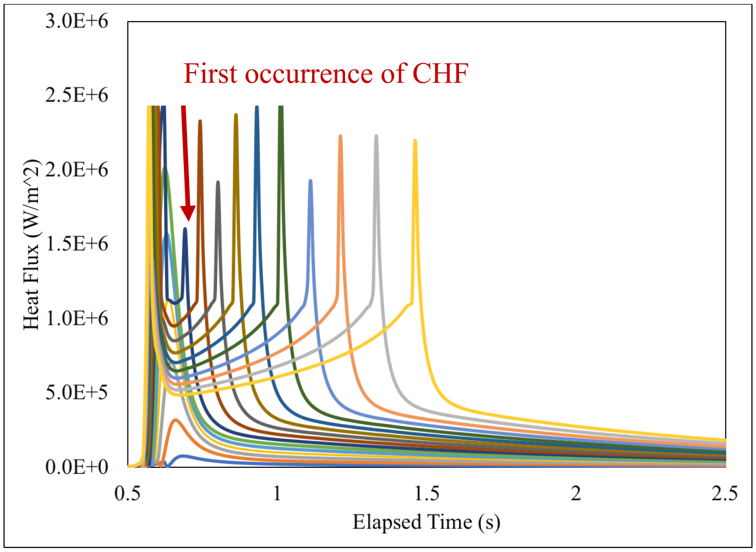

Figure 5. PCF Sensitivity Study Broad Sweep for the 20°C Subcooling Case.

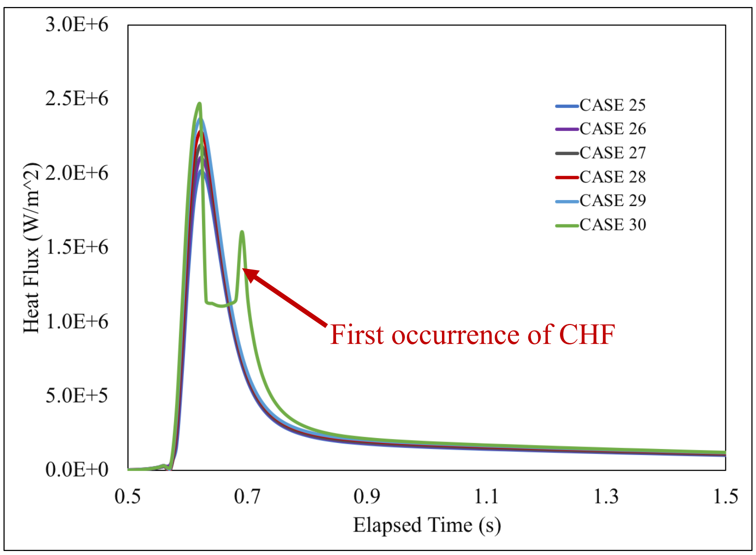

Figure 6. PCF Sensitivity Study Defined Sweep for the 20°C Subcooling Case.

The more defined sweep, shown in Figure 6 above, indicated that CHF was exceeded with a PCF higher than 0.0562 W/g-MW for the 20°C subcooling case. This corresponded to a natural boron concentration of 0.35 wt.%. The cladding temperature behavior, shown in Figure 7, further supports the occurrence of CHF. In the boron concentration case with observed CHF, the cladding temperature is seen to increase higher than the other cases, due to the insulating effect of the film boiling phase after DNB. Then the temperature of the cladding decreases down to the saturated temperature of the coolant after the occurrence of the rewetting peak. This is important, because cladding damage can occur during this larger, and longer lasting, rise in cladding temperature.

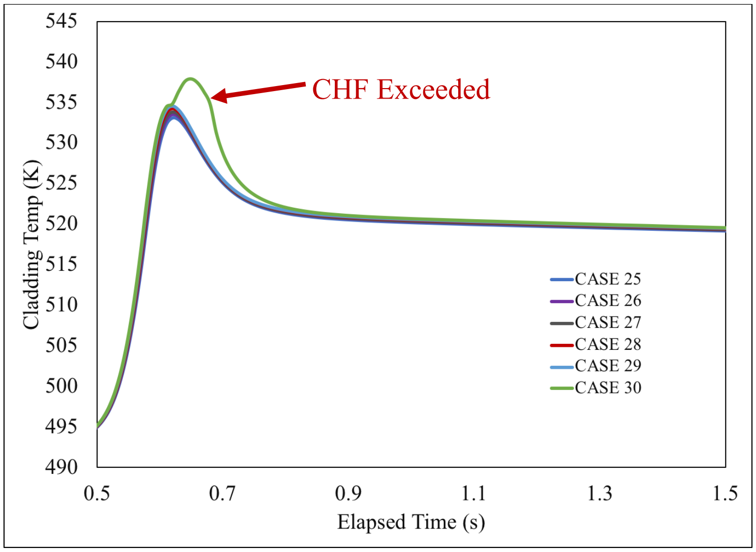

Figure 7. Cladding Temperatures for 20°C Subcooling Case Defined Sweep.

The results of the sensitivity study for the different subcooling cases are shown in Table II. In addition, a mesh study was conducted to determine whether the number of HT mesh volumes had an impact on the PCF outcomes. The results from this sensitivity study conducted with the 80-mesh model HT, were compared to those from a 5-mesh point model with the results shown in Table II.

Table II. Results for the PCF Sensitivity Study for the Subcooling Cases.

Coolant Subcooling (°C)	PCF- 80 mesh (W/g-MW)	Nat-B Wt.%	PCF- 5 mesh (W/g-MW)	Nat-B Wt.%
40	0.073	0.53	0.080	0.63
30	0.064	0.43	0.071	0.51
20	0.056	0.35	0.064	0.43
10	0.052	0.31	0.056	0.35
0	0.047	0.27	0.047	0.27

2.3 CHF Multiplier Sensitivity Study

A CHF multiplier sensitivity study was conducted by coupling the RELAP5-3D and RAVEN codes. The purpose of this study was to determine what value multiplier of the outputted CHF, under specified conditions, would inhibit the occurrence of CHF around the rodlet. Experimental NSSR pool boiling experiments have shown that during fast energy deposition rates, such as that experienced during an RIA, higher heat fluxes can be achieved due to a higher density of nucleation sites on the rodlet cladding surface. This results in pool boiling CHF values that are about 10 times higher than those found during steady state heating [4].

The RELAP5-3D model used was the same described in the PCFs study above. Improvements to this model were made by conducting axial and radial mesh point sensitivity studies. Two power pulses with energy depositions of 920 MJ and 1407 MJ were used. RELAP5-3D has a CHF multiplier parametric feature which was set to 5.0 to inhibit the occurrence of CHF [13]. For both power pulses, the studies concluded that a minimum of 15 radial mesh points is needed to accurately predict the maximum heat flux and cladding temperatures. The number of axial nodes, was determined to have no significant impact on these parameters.

The CHF study was then performed using this improved model. Over 550 CHF multiplier cases were conducted using different combinations of the power pulse energy deposition, degree of coolant subcooling and rodlet boron concentration. PCFs pertaining to an experimental rodlet with boron concentrations of 1.5 and 2.0 wt.% were used. These PCFs were 0.114 and 0.131 W/g –MW respectively for these two boron concentrations. The investigated degrees of subcooling were 40°, 30°, 20°, 10° and 0°C. Further, power pulse with total energy depositions of 920 and 1407 MJ were used. Using RAVEN, the RELAP5-3D CHF multiplier parameter was varied between a default value of 1.0 and increased up to 3.0 times the normal CHF value.

A case was chosen to demonstrate the approach of the CHF multiplier sensitivity study. The chosen case had a rodlet boron concentration of 2.0 wt.%, a power pulse energy deposition of 1407 MJ, and a coolant subcooling of 30 °C. Figure 8 shows, for this case, that CHF is no longer exceeded between a multiplier value that is 1.9- and 2.0-times higher. This was determined using characteristics of predicted post-CHF behavior, specifically the presence of a rewetting heat flux peak [3]. This was further supported by the cladding temperature behavior shown in Figure 9. In the cases with a CHF multiplier higher than 2.0, the substantial rise in cladding temperature as a result of the film boiling phase is no longer observed. The results of the CHF multiplier study are shown in Tables III and IV below.

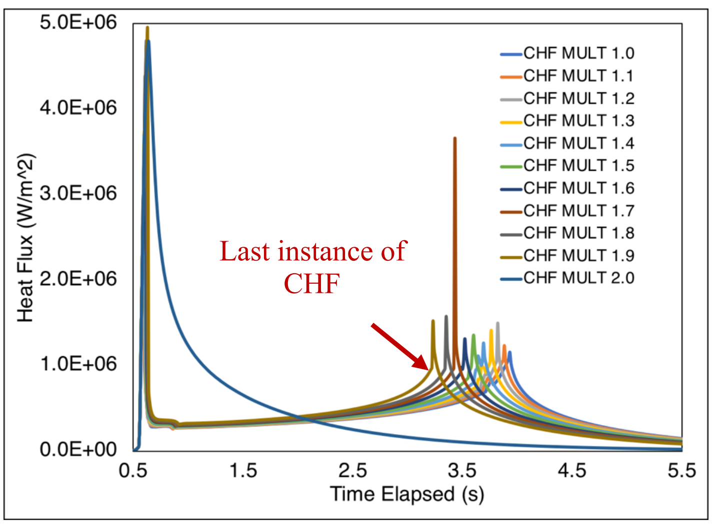

Figure 8. Heat Flux Behavior of the CHF Multiplier Cases Studied.

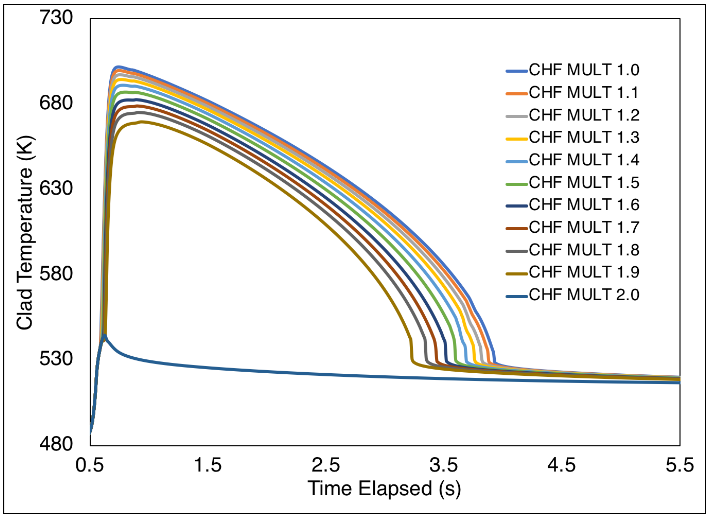

Figure 9. Cladding Temperature for the CHF Multiplier Cases Studied.

Table III. CHF multipliers for the Rodlet with 1.5 wt.% Natural Boron Concentration.

Subcooling Case (°C)	920 MJ Power Pulse	1407 MJ Power Pulse
40	No CHF	1.5
30	No CHF	1.6
20	1.0	1.7
10	1.1	1.9
0	1.3	2.2
Total Rod Energy deposition:	**4361 J**	**6670 J**

Table IV. CHF multipliers for the Rodlet with 2.0 wt.% Natural Boron Concentration.

Subcooling Case (°C)	920 MJ Power Pulse	1407 MJ Power Pulse
40	1.0	1.8
30	1.1	1.9
20	1.2	2.1
10	1.4	2.2
0	1.5	2.6
Total Rod Energy deposition:	**5014 J**	**7669 J**

2.4 SELF-SHIELDING STUDY

The last task of the work performed in this paper, consisted of a neutronics investigation into the self-shielding effects of the borated heater rod, to determine where most of the power is expected to be generated. Self-shielding is a result of the majority of the neutrons being absorbed around the outer rim of the rodlet. Appropriately, the inner regions of the rodlet will experience considerably lower neutron flux levels and a resulting shielding effect is observed [16]. This will subsequently lead to an increase in the ^{10}B (n, α) capture reaction rate as you radially move away from the center of the rod.

The objective of this study was to determine what borated tube thickness can be used to obtain similar heat generations as that from a solid borated rod The Serpent neutronics code was used to investigate the self-shielding effects of the rodlet. The radius of the rodlet was split into 10 cylinders with equal radial intervals. Heat detectors, a feature of Serpent, were used to measure the power generated in each cylinder [11].

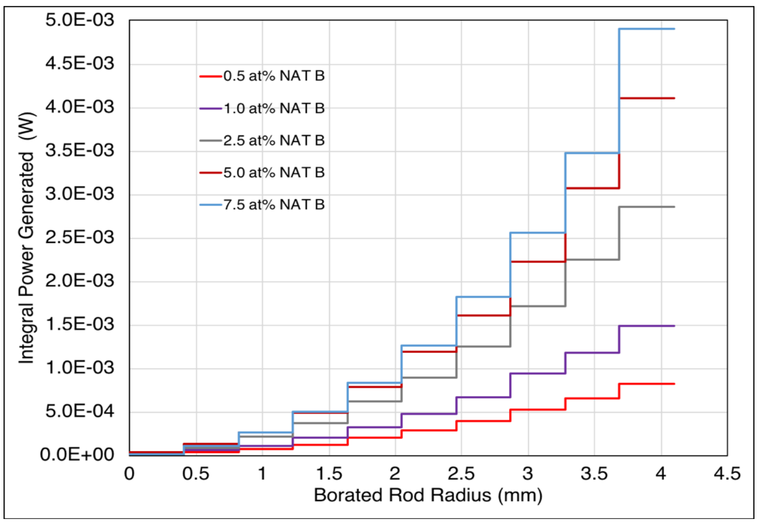

Figure 10. Integral Power Generated vs. Rod Radius.

The results of the self-shielding study are shown in Figure 10. Less than 5-7% of the total power generated in the rod was observed to occur in the inner 1mm of the borated rod for all of the cases studied. Additionally, the self-shielding effects were enhanced with increasing boron concentration. This is expected, because the B-10 atoms are more densely packed within the same rod volume. The main takeaway of this study, is that a 3 mm thick borated tube will yield similar heat generations than a solid borated rod with a 4.1 mm outer radius. Several advantages of using a tube instead of a solid rod include the placement of thermal couples (TC) and optical probes inside, to observe temperature changes indicating the occurrence of CHF during the experimental phase of this LDRD.

3. CONCLUSIONS AND FUTURE WORK

The work presented in this paper provides an idea on the limits of a preliminary test matrix for the development of an experimental borated steel rodlet for in-pile transient CHF testing using the TREAT facility. As expected, a higher PCF will be needed to induced CHF in coolant water with increasing degrees of subcooling. A CHF inducing PCF was determined for each degree of subcooling. In reality, these may not be accurate because of the higher CHF value expected during an RIA. Therefore, a CHF multiplier value was conducted that indicated that a boron content higher than 1.5 wt.% might be needed. Lastly, the self-shielding study concluded that the inner 1mm of the rod can be excluded without heat generation penalties.

Future work will look to expand the initial parameter space, to improve the design test matrix that will inform on the development of the experimental rodlet. PCF factors corresponding to up to 2 wt.% natural boron content will be included. Additionally, transient pulses with energy depositions greater than 920 MJ will be investigated for different degrees of subcooling. The effects of the coolant pressure on the manifestation of the CHF will also be studied. The goal of this future study will be to find cases that could potentially induce CHF, assuming a magnitude multiplier of about ten times as observed in previous experimental transient pool boiling work.

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