The Development of Trip Coverage Maps for the McMaster Nuclear Reactor

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Abstract

PARET/ANL is a coupled point-kinetic and thermalhydraulic code with reactivity feedback modeling capability. A conservative PARET/ANL model of the McMaster Nuclear Reactor (MNR) has been developed by considering the characteristics and operating limits of the MNR core. A conservative modeling approach assesses MNR safety system coverage in the context of reactivity initiated accidents (RIAs) previously studied in the Safety Analysis Report. The PARET/ANL modeling provides power and temperature vs. time results from which trip coverage maps have been generated for each accident category. Modeling limitations are discussed in the context of both MNR operating and safety limits.

1. Introduction

Trip coverage maps report the conditions under which a particular safety system is capable of arresting a reactor transient before specific reactor thermal limits are reached. As a result, trip maps are useful for evaluating safety envelopes, setting reactor operating limits and for regulatory review.

In support of MNR's current operating license, the Safety Analysis Report (SAR) evaluates the reactor shutdown systems' capabilities [1]. This trip map development uses the same accident scenarios considered in the SAR and adds additional safety system understanding to the body of MNR safety analysis work.

Trip coverage maps are developed by simulating reactor transients with an appropriate software tool. A large number of simulations are required to parametrically determine where the safety system's boundaries of capabilities lie. These boundaries indicate reactor conditions where a specific engineered safety system is predicted to be capable of arresting a power transient and where it may be ineffective at doing so. Superimposed individual coverage maps of each reactor shutdown system create cumulative maps which clearly indicate the number of safety systems credited with covering specific accident scenarios; cumulative coverage maps may also highlight reactor conditions lacking safety system coverage in the prevention of specific thermal limits.

2. The McMaster Nuclear Reactor

MNR is an open-pool materials testing reactor (MTR type) used for academic research and various commercial activities, such as the production of radioisotopes. MNR currently operates at 3 MW on a 16 hr/day, 5 day/week schedule and is licensed to operate at 5 MW.

2.1 Fuel assemblies

Figure 1 shows the MTR-type plate fuel assemblies used in MNR. In 2007 MNR completed a conversion from HEU (93% enriched) to LEU (20% enriched) fuel as a participant in the Reduced Enrichment for Research and Test Reactor (RERTR) program. Standard fuel assemblies contain sixteen fuelled plates and control assemblies contain nine. Each fuel plate is fabricated by sandwiching the 0.51 mm thick U_3Si_2-Al fuel meat between 0.38 mm thick aluminium cladding and is separated by a 3 mm wide coolant channel.

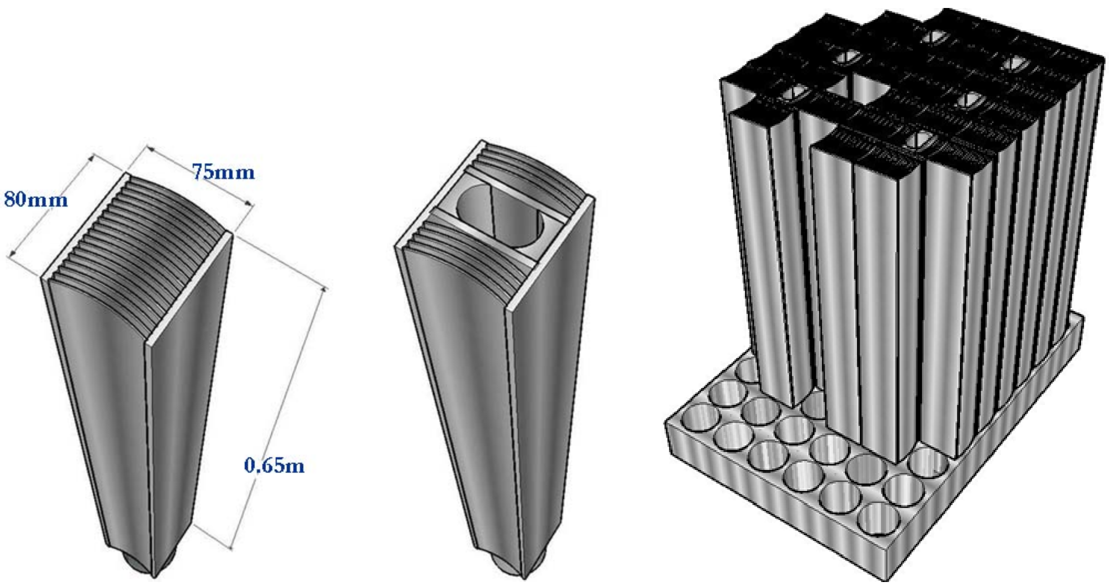

Figure 1 (L) Standard fuel assembly (C) Control fuel assembly (R) Stylized core, composed of standard fuel assemblies and six control fuel assemblies where control rods are inserted.

2.2 The MNR core

The core is arranged with fuel assemblies on a 9x6 grid plate as shown in Figure 1. Reactor power is controlled via five gang-operated shim/safety absorber rods (Ag-In-Cd) and one stainless steel regulating rod, all housed within control fuel assemblies. The rods are motor driven and connected to the rod drives by electromagnets. Typically there are approximately 30 standard fuel assemblies in addition to the six control fuel assemblies in the core. Exit burnups of 50% and 35% ^{235}U depletion are targets for the standard and control fuel assemblies respectively.

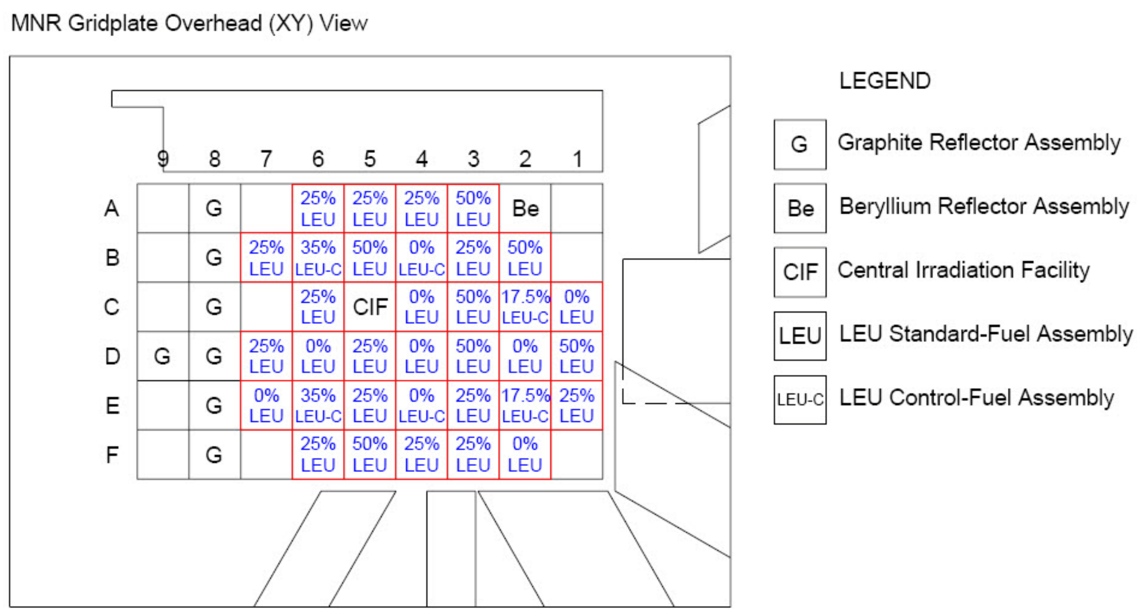

Figure 2 Reference Core arrangement developed for MNR safety analysis showing the burnup (in percent) of each fuel assembly [2]. All fuel assemblies initially 20% ^{235}U.

A representative core configuration, the MNR LEU Reference Core (RC), is utilized for the work presented herein [2]. The RC is a bounding configuration of the core used in safety analysis and conservatively represents the MNR power density distribution. The MNR LEU RC configuration is shown in Figure 2.

Cooling of the core during high power (>0.1 MW) operation is achieved by top-down forced convection. Pool water is forced down through the coolant channels between fuel plates, into a common plenum beneath the grid plate and then through the bottom of the reactor pool. During low power operation (<0.1 MW) cooling is achieved through upward buoyancy induced natural convection. Minimum total core flows are specified in the Operating Limits and Conditions document and correspond to specific reactor operating power ranges [3]. Table 1 shows the modelled channel flux rates used for trip map development. These assumed mass fluxes are conservative and are consistent with the minimum flows specified in the Safe Operating Envelope [4,5].

Power Range	1 W → 100 kW	100 kW → 2 MW	2.01 MW → 3 MW	3.01 MW → 4 MW	4.01 MW → 5 MW
Minimum Total Core Flow	Natural Convection	900 USgpm	1200 USgpm	1600 USgpm	1900 USgpm
Model Channel Flow	-	262 kg/m^{2}s	342 kg/m^{2}s	449 kg/m^{2}s	532 kg/m^{2}s

Table 1 Conservative model channel flow rates within each power range used for trip map development during reactor transient simulations.

2.3 MNR engineered safety systems

The MNR safety/control instrumentation channels use ion chambers and amplifiers to generate a signal. Each channel can initiate either a rod reverse, where the shim/safety rods are driven into the core at a speed of 0.113 cm/s, or a scram, where the shim/safety rods drop into the core in a measured time of 0.5 s [2]. The channels are referred to by their set point and associated trip response, for example the 125% high flux (HF) scram, and are listed in Table 2:

System	Function	Detector(s)	Control	Alarm(s)
Start-up Channel (SUC)	Monitor core during shutdown, approach to critical and low power	Fission chamber	No	Period: < 30 s reverse
Logarithmic Neutron (Log N) Channel	Monitor neutron flux at all powers; indicate reactor period.	Compensated ion chamber	No	Period (<4 s scram, <10 s reverse, <30 s inhibition); Reverse at 110% nominal power
Linear (Lin N) Channel	Regulate reactor power according to set point	Compensated ion chamber	Yes	LSE reverse
Safety Channel	Monitor at intermediate and high power; supply current for absorber magnets	Two (2) uncompensated ion chambers	No	Scram at 125% nominal power

Table 2 MNR instrumentation and alarm responses [1].

3. The PARET/ANL code

PARET/ANL is a coupled point-kinetics and thermalhydraulics code which contains a light-water properties library in the pressure and temperature ranges typical of MTR-type reactors [6,9]. The code contains a heat transfer model, continuous reactivity feedback and employs various empirical convective heat transfer correlations. PARET/ANL simulations have been compared to SPERT-I experimental transients and found to agree quite well [6]. PARET/ANL is maintained by Argonne National Laboratory as part of the RERTR Program and is considered an industry standard tool for research reactor analysis.

4. Accident scenarios considered

The SAR trip evaluation considers four reactivity initiated accident (RIA) sub-categories: (i) withdrawal of the regulating rod from low and high power, (ii) movement of an in-core irradiation sample, (iii) withdrawal of the shim/safety rods from high power and (iv) fuel handling accidents. Each event category can be modelled in PARET/ANL by resolving their characteristics into a range of equivalent reactivity insertion rates.

5. Results

For each particular accident category, an appropriate magnitude of reactivity insertion was specified in the PARET/ANL MNR model and the resulting power transient was calculated. The simulated transient progressed until a thermal limit was reached in the core's hottest single fuel channel, or until the simulated safety instrument successfully arrested the transient. The onset of either bulk boiling, film boiling or 450 ^{o}C clad surface temperatures were used as the thermal limits. In all the analyzed cases, bulk saturated boiling occurs before film boiling while maintaining a large margin to the clad surface temperature limit. Consideration of the more severe thermal limit was undertaken to assess the results within the context of MNR accident analysis.

5.1 Self limiting transient

Figure 3 shows an example of a PARET/ANL MNR transient simulation initiated by the rapid manual withdrawal of an in-core irradiation sample while preventing all instrumentation channels from arresting the accident progression. The transient shown in Figure 3 assumes reactor power is steady at 1.24 MW when the 2 mk sample is manually withdrawn in 0.1 s, resulting in a reactivity insertion rate of 20 mk/s. A power step within the first 0.1 s is followed by a slow power progression until off-setting coolant density and fuel temperature reactivity changes hold reactor power at 3.67 MW. The fuel centreline temperature of the hottest fuel plate at 3.67 MW is predicted to be a benign 137 ^{o}C; bulk saturation temperatures are not reached in any region of the core.

The transient shown in Figure 3 is self limiting, however, instrument channels are capable of arresting the transient. If instrument channel actions were credited in the analysis, at transient time 0.025 s the +7% LSE reverse and the 110% HF reverse would each initiate a reverse, at 0.03 s the <10 s period would signal a reverse, at 0.032 s the <3.8 s period would initiate a scram, and at 0.9 s both 125% HF scram channels would initiate a scram.

5.2 PARET/ANL limitations

Analysis of a reactivity transient initiated by the postulated loss of regulating rod control which inserts up to 5.25 mk was performed and the results are presented in Figure 4. As before, no safety system actions initiated by instrument channels were credited in the simulation.

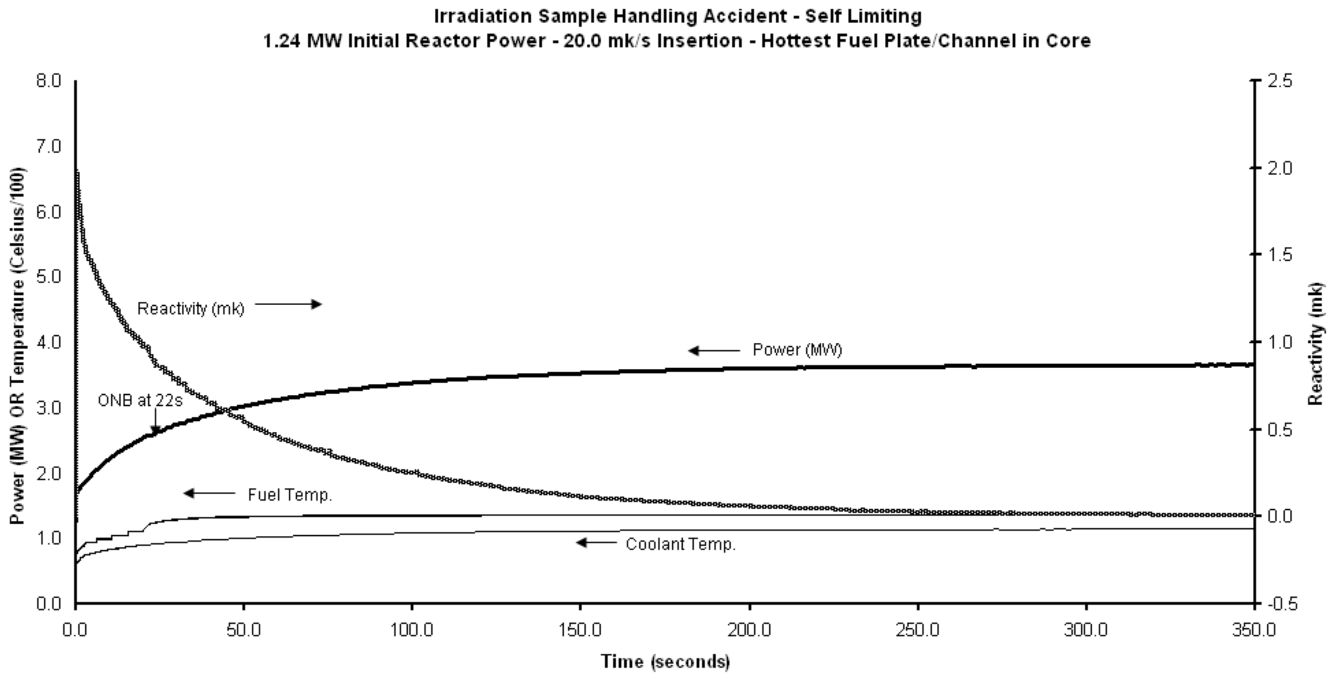

Figure 3 A PARET/ANL power transient simulation of MNR initiated by the withdrawal of an in-core sample with no safety system credited. Coolant channel flow remains at a constant 262 kg/m^2s throughout.

As the Figure 4 transient shows, MNR is not predicted to generate enough negative feedback to prevent the onset of bulk coolant boiling in the single hottest coolant channel when 5.25 mk is inserted at a rate of 0.01 mk/s from an initial power of 0.1 MW.

The simulation shown in Figure 4 demonstrates the limitation of PARET/ANL to simulate transients into late accident stages. The generation of significant coolant void in a coolant channel creates asymptotic values in the incompressible PARET/ANL hydraulic model - in reality coolant voiding would induce a large negative reactivity insertion. The PARET/ANL simulation crashes at 340 s (where the plot ends) and is the reason why bulk boiling (the onset of significant void) needed to be used as a thermal limit in this trip map development. In the Figure 4 transient bulk boiling occurs in the outlet of the hottest coolant channel at 329.3 s and 3.73 MW when the hottest centerline fuel temperature is 137 ^{o}C and the hottest clad surface temperature is 135.8 ^{o}C.

Onset of nucleate boiling (ONB) first appears on the hottest clad section at 258.5 *s* when reactor power is 2.53 MW. The effect of feedback on the net reactivity is apparent once reactor power reaches levels which raise fuel, clad and coolant temperatures. The net reactivity decreases after approximately 160 s due to the coolant and fuel temperature feedback effects. An extensive amount of boiling creates a large negative feedback.

The PARET/ANL code predicts the Figure 4 transient would be arrested by the 7% LSE reverse, the 110% HF reverse, both 125% HF scrams and the manual scram on alarm. In the case of a manually triggered scram, the operator can be credited with shutting down the reactor within 300 s of an audible alarm [1]. At a transient duration of 21 s the 7% LSE is the first instrument to alarm and thus at 321 s a manual scram can be credited since bulk boiling is not reached in the single hottest coolant channel until 329.3 s. These results indicate that there are multiple safety system actions which, if credited, would provide protection.

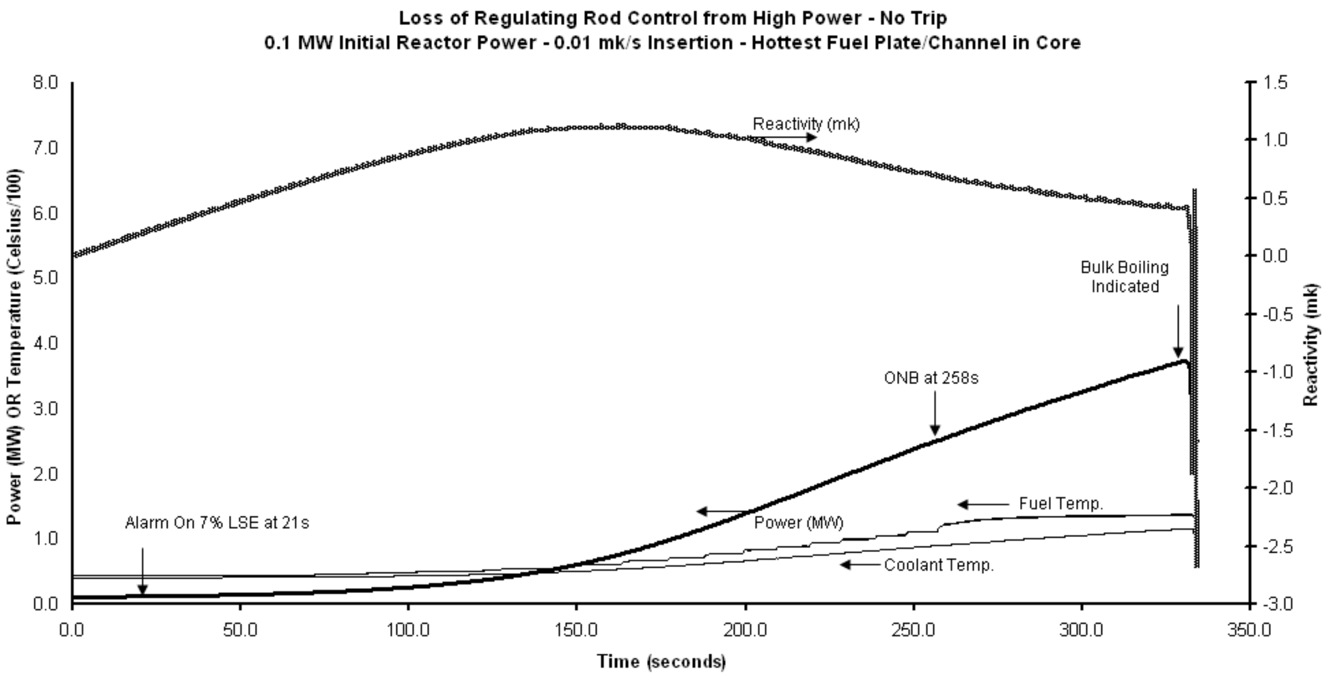

Figure 4 A PARET/ANL power transient simulation of MNR initiated by the loss of control of the regulating rod with no safety system actions credited. Coolant channel flow remains at a constant 262 kg/m^2s throughout.

5.3 Cumulative trip coverage maps

In the same manner the transients detailed in Figures 3 and 4 have been compared to the instrument channel set points, this has been done for each instrument within each of the three accident categories. The result is four cumulative trip coverage maps shown in Figures 5 through 8 and two fuel handling accident plots shown in Figures 9 and 10.

The cumulative maps number each instrument channel 1 thru 8 as they are in the SAR trip evaluation [7]. The coverage map developed for high power loss of regulation rod control, shown in Figure 5, is divided at 0.18 mk/s to indicate the largest expected reactivity insertion rate associated with the loss of regulating control accident. During a loss of regulation rod event, given that the reactivity worth profile of MNR rods are known and the rod drive speed is a constant 1.13 cm/s, the expected reactivity insertion rate during such a postulated accident is 0.01-0.18 mk/s. Within this reactivity insertion rate range, the PARET/ANL modelling predicts MNR to be actively prevented from reaching bulk boiling in the single hottest coolant channel by at least four separate instruments.

The cumulative map for the withdrawal of the shim/safety rods from low power shows that under some circumstances bulk boiling will be induced prior to a trip. The controlled manipulation of the shim/safety rods frequently occurs under manual control therefore the 7% LSE reverse cannot be credited. Trip set points for the 110% HF reverse and both 125% HF scram channels are set according to the reactor's normal high operating power; a transient initiated in a low power naturally-convection-cooled state will not be arrested by these channels until power has surpassed the point where bulk boiling has occurred. As well, the rate of reactivity insertion is not sufficient for rate trips or reverses to be fully capable. These situations combine to allow only the <3.8s

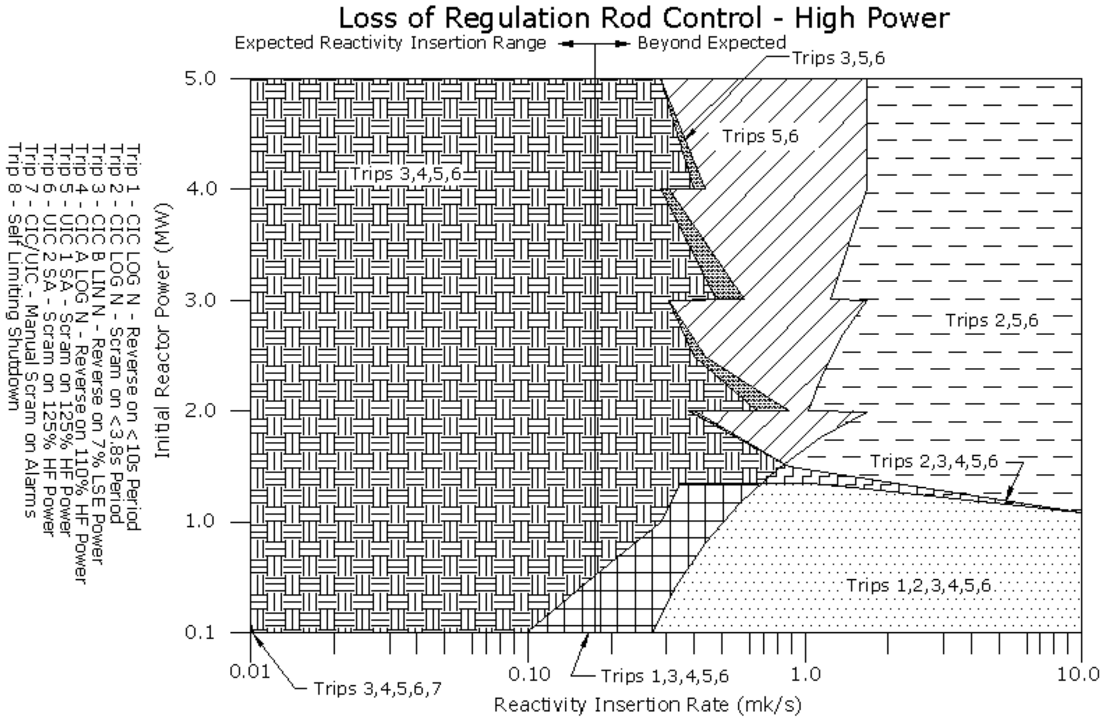

Figure 5 The cumulative trip coverage map for the loss of regulation rod control accident from high (>0.1 MW) power. For interest, this map extends the reactivity insertion rates beyond what the withdrawal of the regulating rod is capable of inserting.

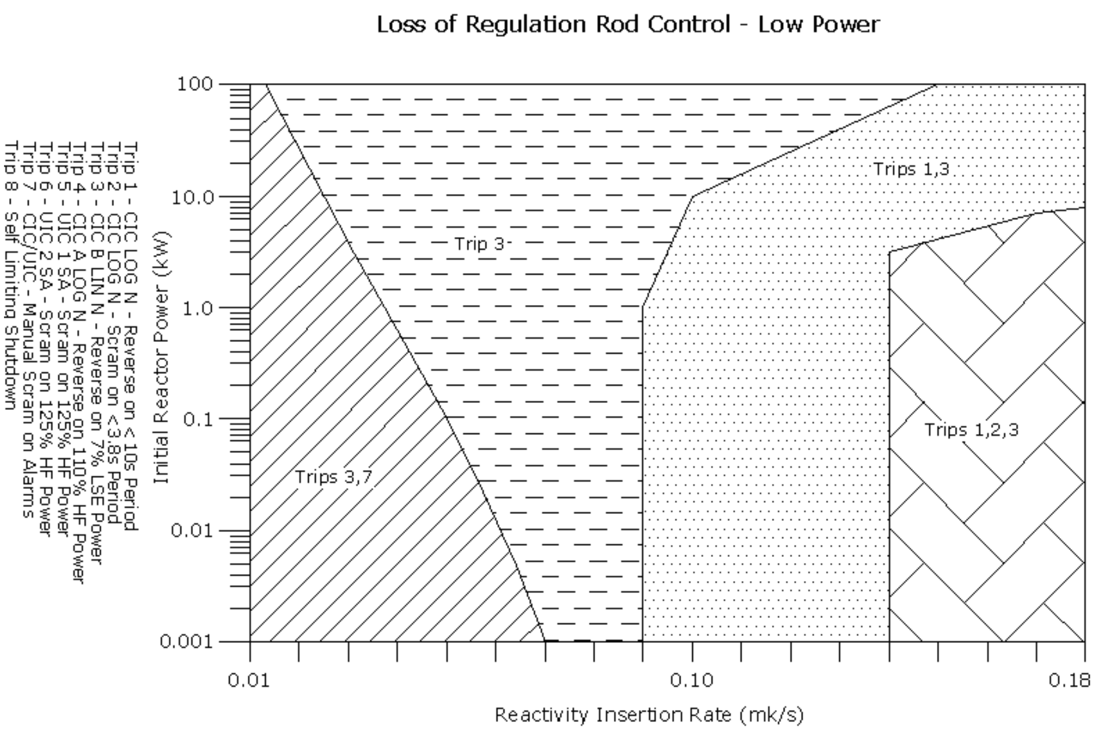

Figure 6 The cumulative trip coverage map for the loss of regulation rod control accident from low (<0.1 MW) power.

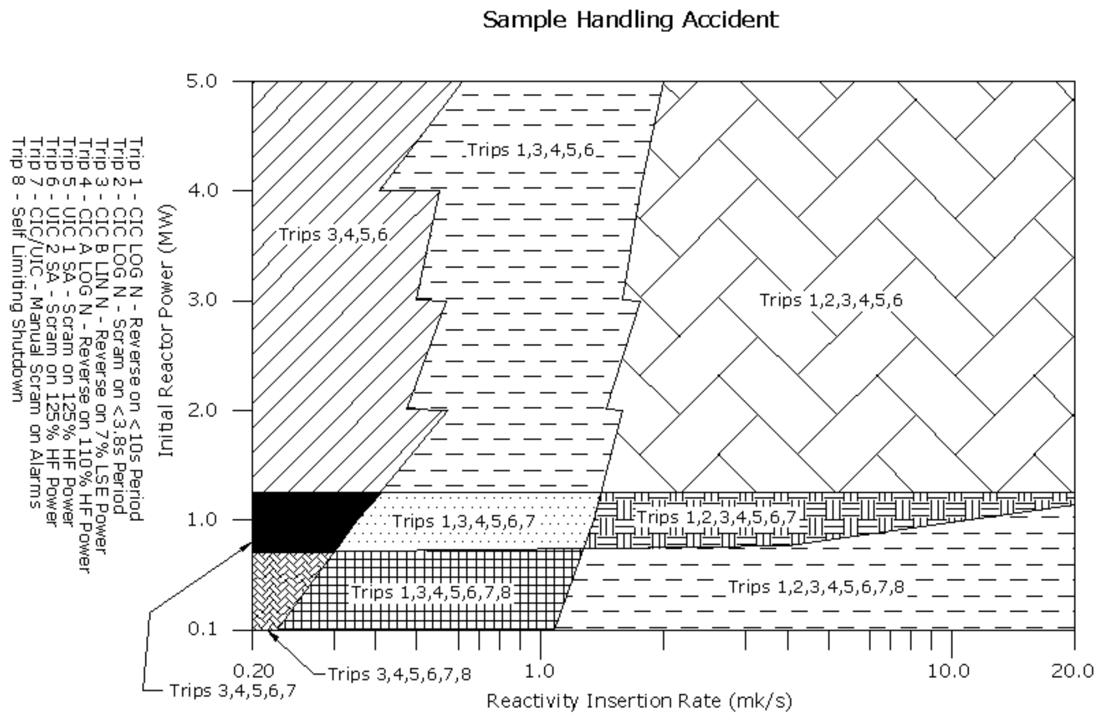

Figure 7 The cumulative trip coverage map for the withdrawal of an in-core irradiation sample accident from high (>0.1 MW) power.

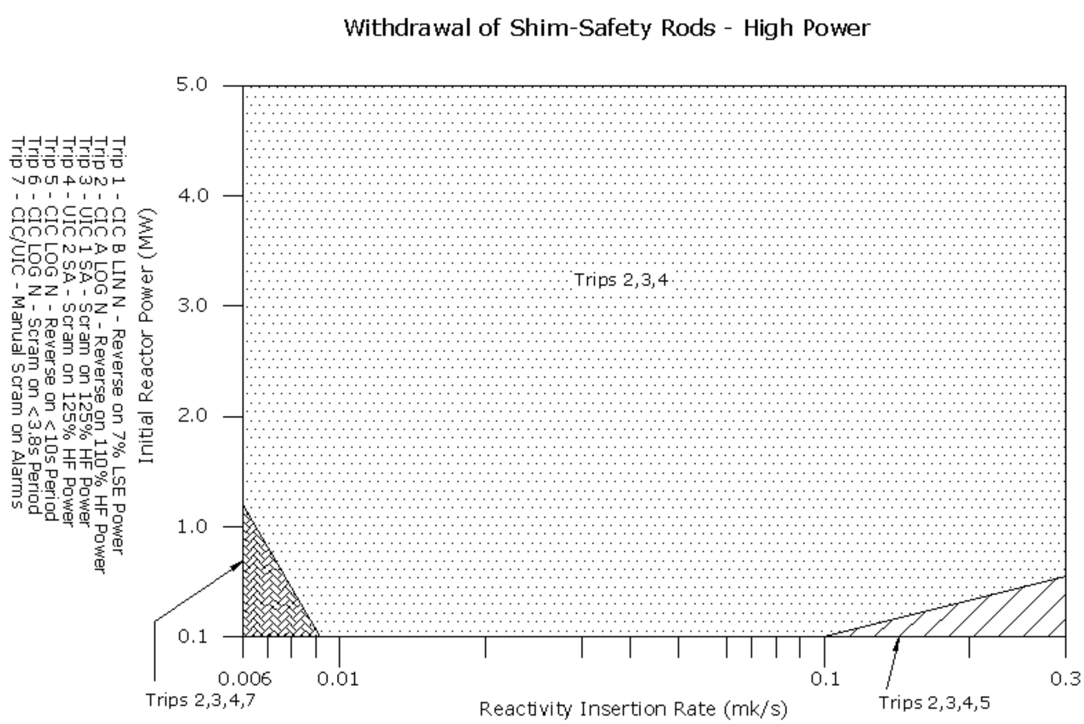

Figure 8 The cumulative trip coverage map for the loss of shim/safety rod control accident from high (>0.1 MW) power.

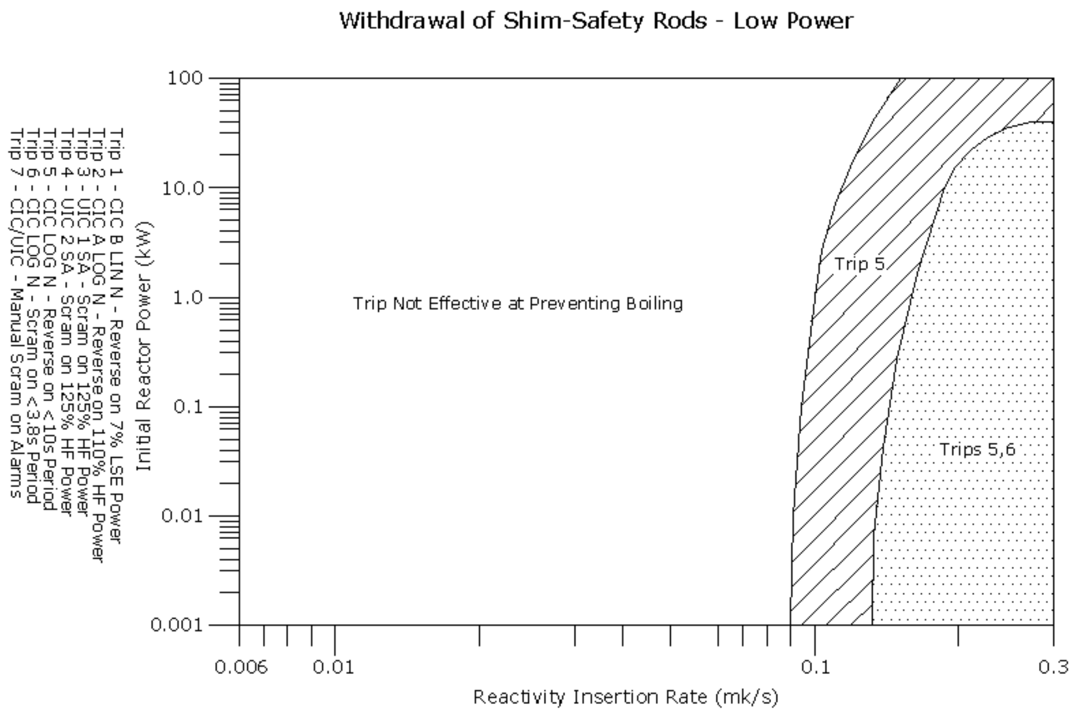

Figure 9 The cumulative trip coverage map for the loss of shim/safety rod control accident from low (<0.1 MW) power.

period scram and <10s period reverse to be partially capable of preventing bulk boiling in such a situation. The total withdrawal of all five shim/safety rods has the potential to insert a very large amount of reactivity, approximately 55 mk. As a result the ability of the system to self-limit such a transient does depend upon boiling/void reactivity feedback and consequently post-boiling characteristics require consideration. This aspect was considered outside the scope of the study.

Figure 5 and 7 display abrupt sawtooth-like changes in the coverage boundary near 2.0, 3.0 and 4.0 MW. These result from the assumed changes in the administrative minimum allowable flow rates.

All cumulative trip coverage maps demonstrate instrument trips which monitor reactor period are generally effective only at higher reactivity insertion rates. Lower reactivity insertion rates simply do not result in short reactor periods within the range required to trigger such a rate scram. Comparatively, high power reverses and manual scrams are more effective at preventing transients driven by slow reactivity insertion rates and as is demonstrated in Figure 10, scrams triggered by high power set points are capable of arresting both slow and fast transients.

Postulated fuel handling accidents occur when the reactor is in a shutdown state (modelled as a critical core with extremely low power since PARET/ANL cannot simulate a subcritical assembly) under manual operation. This accident scenario adds large amounts of reactivity in a short amount of time (*e.g.* 12.3 mk in 2.0 s), therefore the <10 *s* period and 110% HF reverses are not capable of arresting such a fast moving transient. Additionally, when MNR is operated manually the +7% LSE reverse channel is not available, and cannot be credited. However, the PARET/ANL model predicts both 125% HF scram channels and the <3.8 s period scram are effective at arresting such a transient before any thermal limit is reached, as shown in Figure 10 and 11.

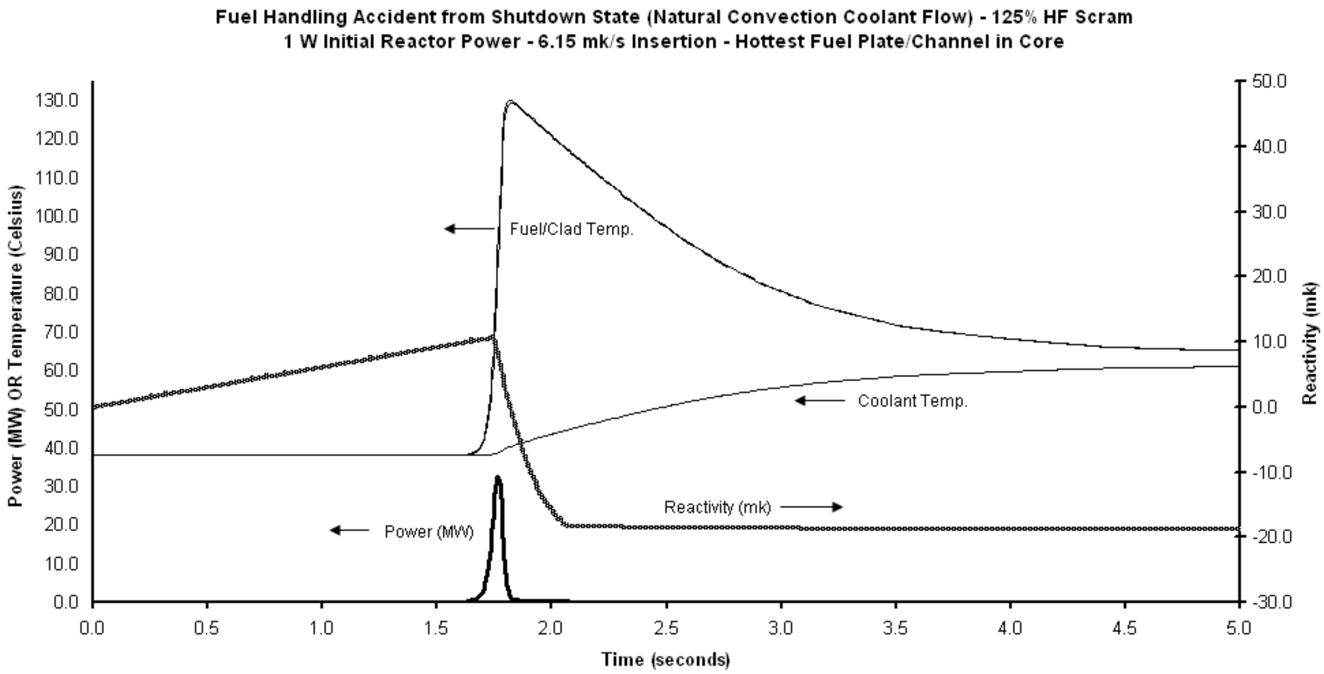

Figure 10 A PARET/ANL ANL power transient simulation of MNR initiated by dropping a fresh fuel assembly into a vacant central core location. Natural convection coolant channel flow.

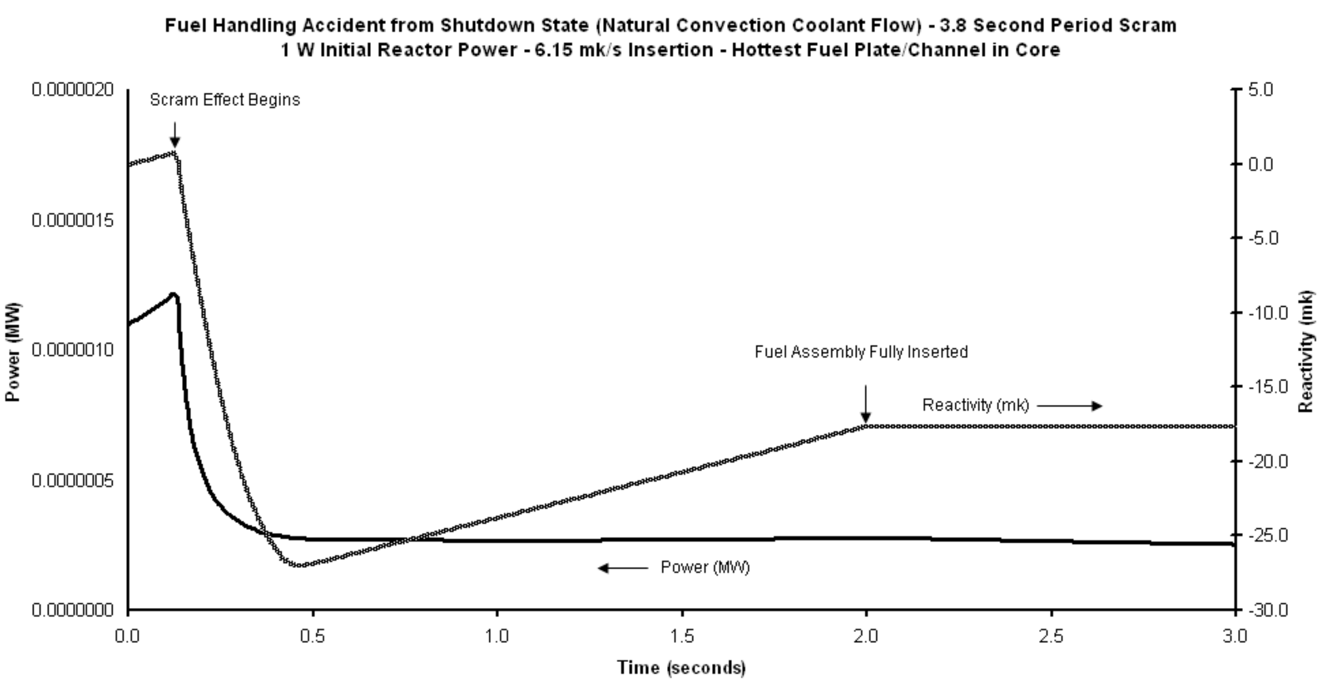

Figure 11 A PARET/ANL ANL power transient simulation of MNR initiated by dropping a fresh fuel assembly into a vacant central core location. Natural convection coolant channel flow.

The scram set point for both 125% HF channels in Figure 10 is set at 6.875 MW; the transient quickly reaches this set point in 1.72 s. Reactor power peaks at 33.4 MW at 1.77 s before the insertion of the shim/safety rods lower reactor power. At the moment of peak reactor power the maximum fuel temperature is 90.8 ^{o}C and from 1.77 s onwards the reactor power drops but fuel temperature continues to rise until 1.82 s when fuel temperature reaches a peak of 130.0 ^{o}C. The average reactor period between 0 and 1.77 s is 0.1 s. Although reactor power reaches levels much higher than licensed operating power the fuel and clad temperatures are still well below thermal safety limits; the short duration of time spent at high powers in this transient is not predicted to release enough energy to significantly heat the fuel, clad or coolant.

In a less dramatic transient shown in Figure 11, the <3.8 s scram instrument channel arrests the fuel handling accident transient before power grows to a significant value. Fuel, clad and coolant temperature (which are not plotted in Figure 11) all remain at the pool temperature of 38 ^{o}C. The dropped fuel assembly continues to add reactivity after the scram until 2.0 s; however, the depth of the scram shutdown is enough to keep the reactor deeply subcritical.

6. Findings and recommendations

6.1 Findings

The MNR SOE document, which defines the administrative minimum flow for MNR operation according to reactor power, uses analysis methods which aim to avoid bulk saturated boiling during normal operation [4]. The PARET/ANL simulation analysis supports this existing work in that these recommended minimum flow rates used in the PARET/ANL model of MNR at corresponding steady state reactor powers do not induce saturated bulk boiling.

Every reactivity initiated accident will eventually trigger overpower trip set points if the transient is not first self limited by reactivity feedback. However, overpower instruments which initiate a reverse are not effective in the case of fast reactor transients which generate temperatures beyond thermal limits before the shim/safety rod bank can be driven into the core. Rate trips are useful in that a fast moving transient can be detected as soon as it begins, before large amounts of energy are deposited into the core. Scrams initiated by overpower trips are effective at preventing fast and slow transients. When considering MNR power transients, slow moving transients may not trigger a rate trip instrument. Therefore, the MNR design appropriately employs a mix of overpower trips and rate trips which, as demonstrated by PARET/ANL simulations, provide effective redundant safety coverage.

All accident categories studied showed full and often multiple coverage in the avoidance of bulk coolant boiling except during the withdrawal of shim/safety rods from low power. In this case coolant boiling is expected prior to the transient termination by MNR safety systems.

6.2 Recommendations for future work

6.2.1 <u>Consider quantifying core bypass flow</u>

The PARET/ANL simulations predict that, as expected, the onset of saturated bulk boiling within the coolant channels is sensitive to the magnitude of the channel coolant flow rate. The coolant channel flow rate during forced convection operation of MNR is an operator controllable variable, however, operators measure only the total core flow downstream of the core plenum. Since the core bypass flow is a component of total core coolant flow it would be very useful if bypass core flow could be quantified and a more accurate prediction of coolant channel flow could then be made. In the absence of such measurements the SOE document and PARET/ANL modelling of MNR make what are probably extremely conservative estimates of bypass flow [4].

6.2.2 Consider simulating MNR transients with another code

The trip maps presented herein are considered boiling maps rather than safety maps since boiling in MTRs is not likely to have fission product release consequences if encountered. An assessment of a "lack of coverage" in terms of avoidance of bulk boiling in the context of safety limits requires further accident safety analysis. Extensive experimental studies have shown that coolant boiling is a highly predictable fast-acting source of negative reactivity [8]. These experimental results have previously been incorporated into the MNR safety case [2].

As such, trip maps generated with bulk saturated boiling as a thermal limit represent an extremely conservative evaluation of MNR safety systems. The onset of saturated bulk boiling was adopted as a practical thermal boundary in this transient analysis because of the inability of PARET/ANL to simulate beyond the generation of significant void.

If another transient simulation software package becomes available or an alternative analysis methodology is identified which is capable of accurately modeling two-phase coolant flow, late stage transient simulations approaching the thermal safety limit of fuel clad blistering could be conducted. However, this study of MNR safety systems based upon PARET/ANL transient simulations provides a conservative analysis of early stage MNR reactivity initiated accident transients.

7. References

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