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CATHENA Simulation of the January 1994 Fuelling Incident

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1. Introduction

The January 94 fuelling incident involved the insertion of a fuel assembly (worth an estimated Δk of 24.8 mk), over an estimated 20 second period, to a partially assembled core sitting at an initial k_{eff} of 0.983 and an initial power of 13 mW. Point kinetics simulation of this case concluded that the best estimate peak power was approximately 8.4 MW [TR97-03]. The purpose of a CATHENA simulation of this event is to estimate the thermal response to this base case power pulse and variations on this base case.

2. Model Setup

The core was represented by average 18 plate assemblies, average 10 plate assemblies, shim control assemblies, plus one 10 plate peak assembly and one 18 plate peak assembly as described in detail in [TR97-02. The peak to average powers used were that of core 48c: 2.21 for the 18 plate assembly and 1.98 for the 10 plate assembly. This was considered representative of the relative assembly powers at the time of the incident. An cosine axial power distribution was assumed, thus yielding a plate power peak to average of 3.47 and 3.11 for the 18 and the 10 plate assemblies respectively. The power pulse can be defined via input or use can be made of CATHENA's point kinetics model. Herein, the power pulse was supplied as input based on point kinetics calculations [TR97-03].

The CATHENA simulation was performed in two steps. First a steady state run was performed with the reactor power at a nominally low power (1 watt) with the flapper open, the HTS pump turned off and with valves V-1 and V-12 closed to isolate both the pool and the HUT. CATHENA correctly simulated the quiescent, isothermal conditions. This simulates the conditions just prior to the power excursion event: no core flow and a core temperature of 24°C.

The second step is to perform the fuel assembly insertion transient starting from steady state. A linear ramp was assumed.

3. Simulation Results

The steady state run input file and output listings are given in appendix 1. A number of transient runs were performed for the various power pulses. Typical transient input file and output files are given in appendix 1. For the base case of a peak power of 8.4 MW, the peak temperature in the highest power fuel assembly was approximately 103.1°C in the 10 plate assembly and 83.9°C in the 18 plate assembly, which is a rather benign response. Figure 1 shows the power as a function of time. The power input is clearly a pulse of short duration. Figure 2 shows the resultant fuel and coolant temperature response in the hottest 10 plate assembly as a function of time. Peak coolant temperature lagged the fuel temperature as expected and rose only to 27.2°C and 29.2°C in the 10 and 18 plate assemblies respectively before the fuel temperature began to decrease. Subsequent peak coolant temperatures were 37.4°C and 42.1°C in the 10 and 18 plate assemblies respectively. This is well below the saturation temperature of 117°C and the fuel clad melting temperature of 650°C [ELL93]. To account for modelling and core measurement uncertainties, a number of CATHENA runs were performed based on the power pulses defined in [TR97-03]. The resulting peak fuel, sheath surface and fluid temperatures as a function of peak power are shown in table 1; figures 2 to 4 show representative 10 plate temperature responses.

For the first three cases, the peak sheath temperatures are insufficient to cause significant boiling, although the third case (20.1 MW peak power) appears to be on the verge of coolant phase transition. For the fourth case (26 MW peak power) two-phase flow appears in the hot channels.

From the above, it is important to note the following:

1. The power pulse has a limited duration and energy, ie, the power supply is not continuous, and the fuel and clad temperatures are already declining before the coolant temperature has significantly changed. Consequently, boiling, if it does occur, is not accompanied by the usual dryout crisis and subsequent rise in fuel temperatures, ie., boiling is not a precursor to fuel damage in this instance.

2. Peak powers more than 26 MW will generate two-phase flow. Since bubbles were not detected, peak powers substantially more than 26 MW are not supported by the physical evidence.

3. Detectable boiling occurs at peak powers well below that needed to generate fuel temperatures associated with the onset of fuel damage (450°C or more).

We conclude that even if the reactor physics estimates are in error, the peak power cannot be substantially more than 26 MW and that detectable boiling would have taken place well before the onset of fuel damage.

4. Transient Flux Peaking Effects

The one remaining question regarding incident simulation is the adequacy of the point kinetics model for such a fast transient. Potentially, the higher order spatial modes could be excited, leading to substantially different flux distributions during the transient than for the steady state. There are no three dimensional transient reactor physics codes available that have undergone quality assurance. MNR does have access to an in-house code system under development. This distributed code system, MACSIM, is a 3D, transient simulation of the multigroup neutron diffusion equations, including delayed precursors, Xenon and burnup. The incident was directly simulated. The shim rods were inserted 15% and a fuel assembly was inserted at location 3B. The power ramp was similar to that presented in figure 3. The results of a simulation of the incident show that the power distribution is virtually unchanged as the power ramps up from a low power steady state past the high power trip and beyond, justifying the use of point kinetics.

The fuel assembly was being inserted into grid location 3B at the time of the incident. The maximum power location is 4C. Since we are only interested in determining whether there is a significant power profile change during the transient, the power profile plots were normalized to the maximum power assembly at each selected time. Figure 5 shows the normalized power distribution at the beginning of the transient. Figure 6 shows the normalized distribution at a typical high power. Figure 7 is the ratio of the normalized powers, showing that the relative powers are virtually identical except for location 4B where the fuel is being inserted. Figure 8 shows the axial power profile (normalized to the total assembly power) for the maximum power assembly (4C). The graph shows the profiles at various stages in the transient. Note that the axial profile is not altered by the transient. To study the power profiles in more detail, we look at grid row B in figure 9. The rise in power at location 3B is evident. Note that the neighbouring locations are unaffected. Figure 10 shows the same effect but from the view of a section through grid row 3. Figures 11 and 12 focus on C4. Note that the relative power grid row C and grid row 4 are unaffected by the rapid transient. Thus, the max power assembly (4C) does not experience any transient peaking and the assumption of a peak to average power ratio based on a steady state power map is justified.

5. Verification

Verification includes:

- The independent development of point kinetics codes and subsequent analysis by two McMaster specialists.
- An independent review by AECL of an early versions of one of the point kinetics codes.
- CATHENA verification as part of the ongoing model development under the guidance of AECL.

6. Conclusion

The CATHENA simulations confirm that the thermal response to the power pulse was benign. The MACSIM simulation confirms that the power spatial distribution is virtually unchanged during the rapid transient and that point kinetics adequately models the event.

7. References

ELL93 P.G. Ellison, et al, "Aluminum-Uranium Fuel-Melt Behavior During Severe Nuclear Reactor Accidents", Nuclear Safety, Vol.34, No.2, April-June 1993.

TR97-03 M.P. Butler, "Final Report on the January 1994 Fuelling Incident", McMaster University Nuclear Reactor, MNR Technical Report 97-03, April 28, 1997.

TR97-04 Wm. J. Garland, "Thermalhydraulic Modelling of MNR", McMaster University Nuclear Reactor, MNR Technical Report 97-04, April 28, 1997.

Table 1 Peak temperature vs. Peak Power

Case			Assembly type	Maximum Temperature (°C)		
Peak Power (MW)	Insertion time (sec)	Assembly worth (mk)		Fluid	Sheath Surface	Fuel centreline
8.4	20.0	24.8	18 plate	42.1	82.8	83.9
			10 plate	37.4	100.9	103.1
12.1	10.0	24.8	18 plate	40.1	80.3	81.4
			10 plate	35.9	96.9	99.1
20.1	20.0	26.0	18 plate	43.7	96.4	98.1
			10 plate	38.6	116.8	120.2
26.1	15.0	26.0	18 plate	n/a	113.8	115.7
			10 plate	n/a	134.0	141.7

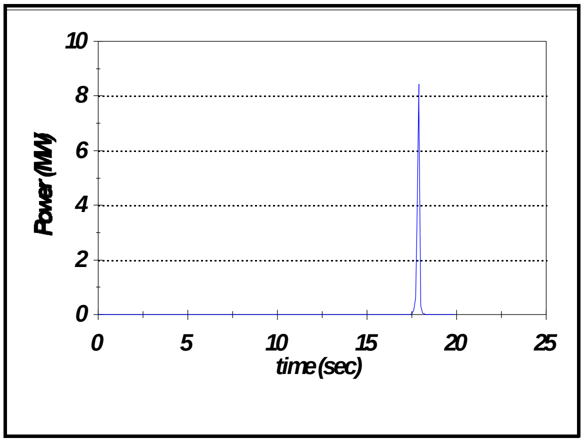

Figure 1 Power vs. Time for the base case

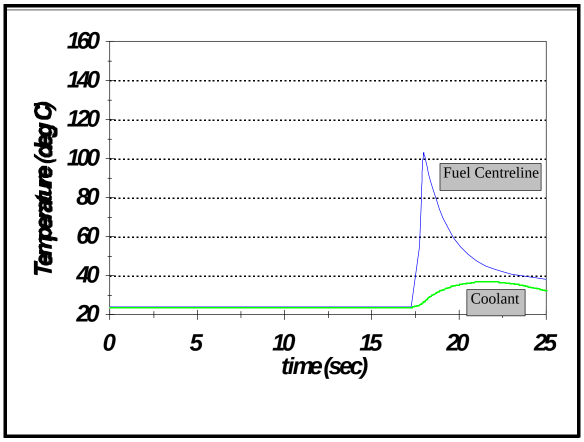

Figure 2 Peak fuel and coolant temperature response for the insertion of a 24 mk assembly in 20 seconds (base case)

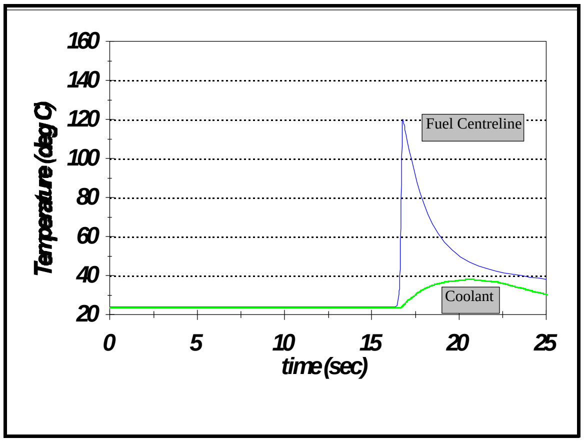

Figure 3 Peak fuel and coolant temperature response for the insertion of a 26 mk assembly in 20 seconds

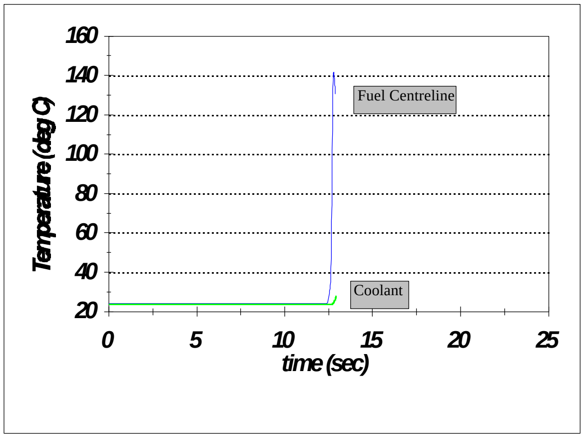

Figure 4 Peak fuel and coolant temperature response for the insertion of a 26 mk assembly in 15 seconds

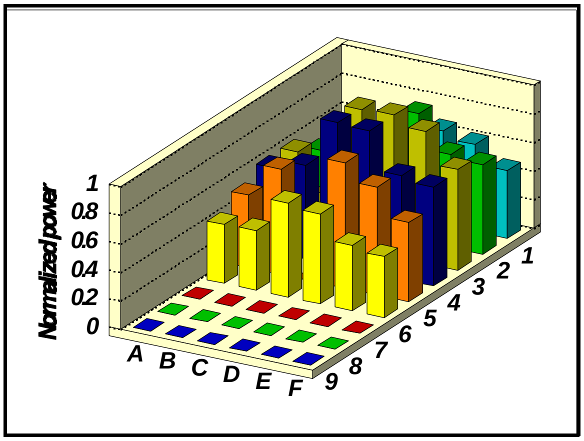

Figure 5 Normalized power map at the beginning of the transient (very low power)

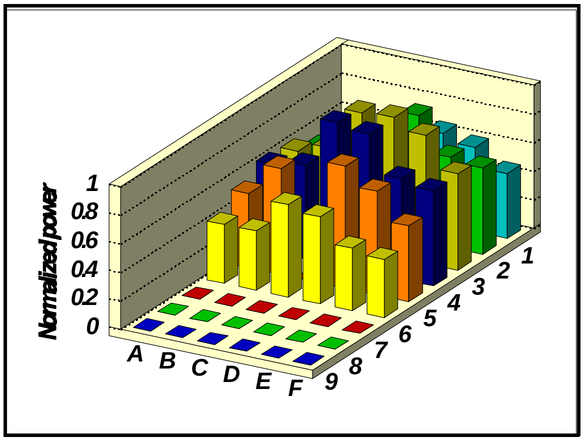

Figure 6 Normalized power map at high power

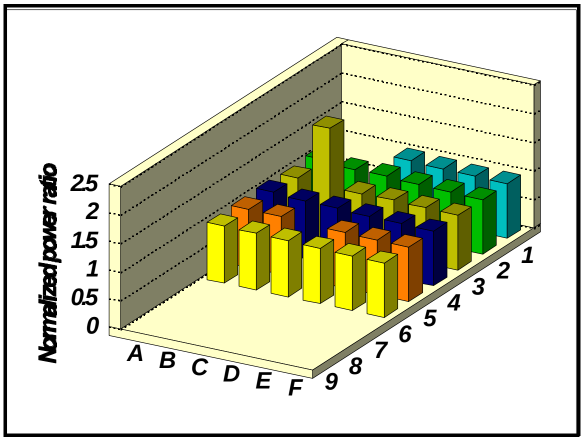

Figure 7 Ratio of normalized power showing the localized effect of the fuel insertion

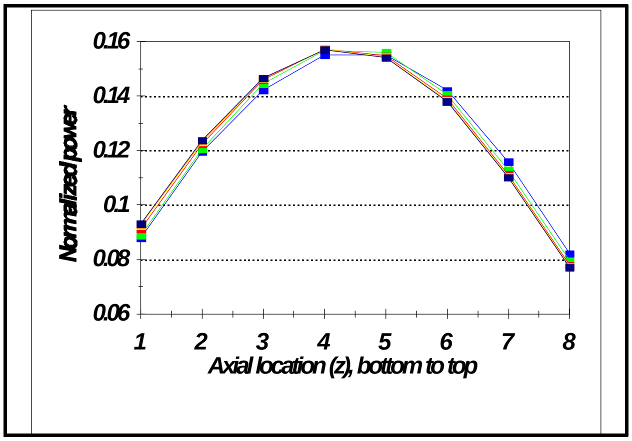

Figure 8 Axial power profile for 4C at various times.

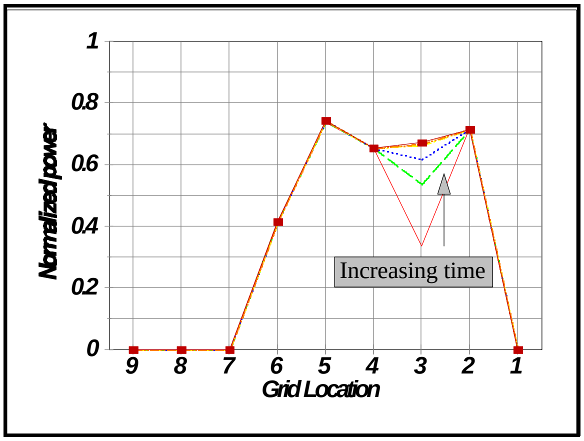

Figure 9 Normalized power in grid row B

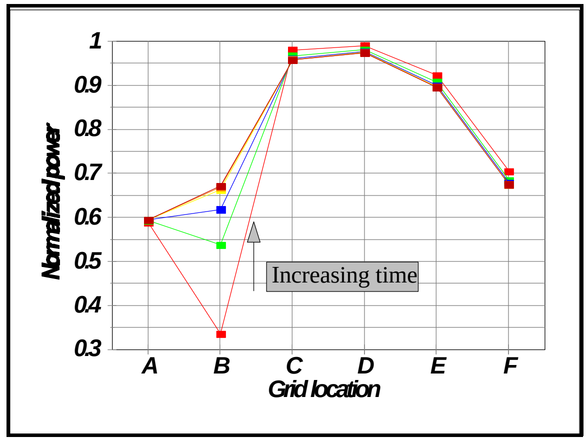

Figure 10 Normalized power in grid row 3

Figure 11 Normalized power in grid row C

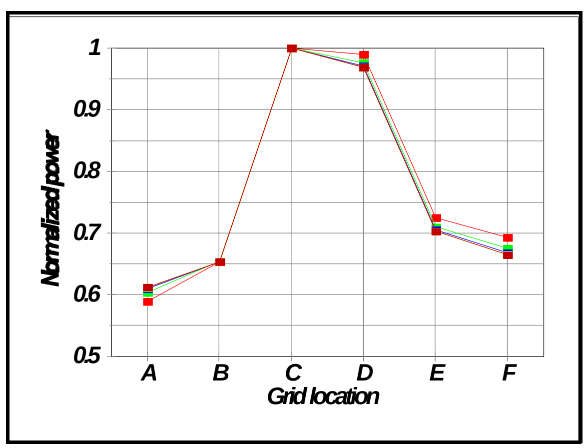

Figure 12 Normalized power in grid row 4

APPENDIX 1 CATHENA Input and Output files

Table of Contents:

pkss1a.inp	Steady state input file
pkss1a.out	Output file (selected core parameters vs. time)
pkss1-core.out	Output file (selected HTS parameters vs. time)
pkss1a.lis	Full output listing
pktran2a.inp	Transient input file
pktran2-mnrhot.out	Output file (selected hot 18 plate assembly parameters vs. time)
pktran2-ptrhot.out	Output file (selected hot 10 plate assembly parameters vs. time)
pktran2a.lis	Full output listing

Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor-jan94/rev2.