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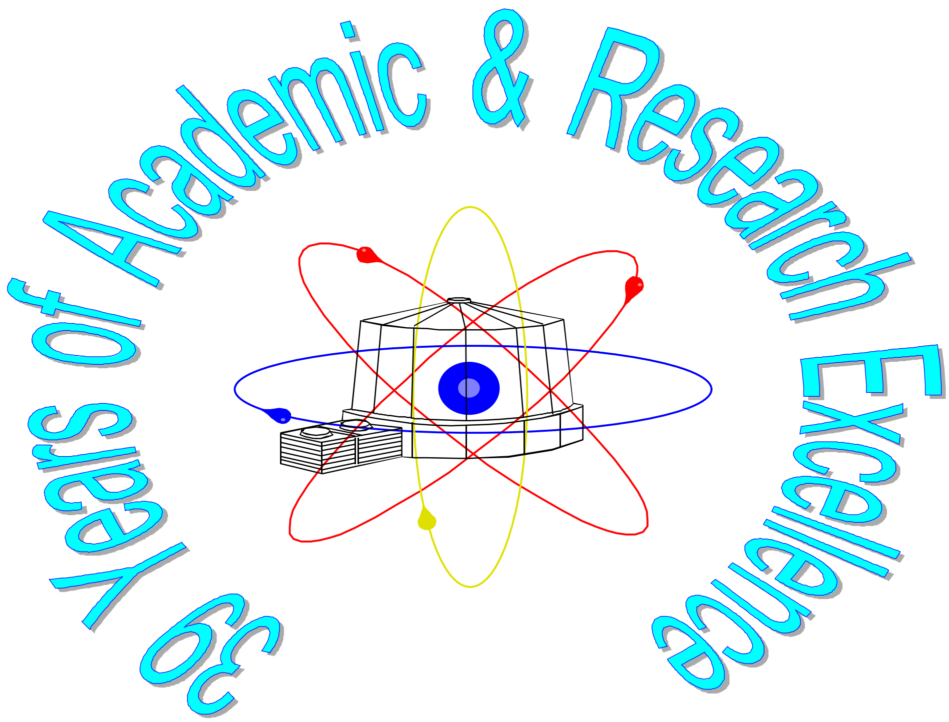
Technical Report 98-07

Loss of Regulation Analysis for the McMaster Nuclear Reactor



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Loss of Regulation Analysis for the McMaster Nuclear Reactor

1 Introduction

A systematic review of initiating events [TR 1998-06] led to the identification of a number of possible serious process failures worthy of further investigation. One of these failure mode categories is Loss of Regulation (LOR), investigated herein. The initial estimates of the safety system failure rates indicate that the frequency is below 1×10^{-6} by several orders of magnitude. Thus, it is not reasonable to require that the shim-safety rods are not available in the event that a LOR occurs; that is, reactor shutdown is essentially assured for these events. Nevertheless, a number of defined scenarios were studied, irrespective of their probability of occurrence. These are:

- LOR due to Regulating Rod Failure
- LOR due to Sample Handling Error
- LOR during a reactor startup.

For the first two events, a number of cases were analysed to cover off the possibility of failure of any single safety system. The last event is as defined in the existing Safety Analysis Report.

Of relevance to failure event scenarios are the MNR safety systems:

- SDS1: a single bank of 5 shim-safety rods held up by electromagnets that are subject to the following trips:
  - HP: high power, 125% full power
  - reactor period < 4 seconds[1]
  - LFP: low flow in the primary circuit, < 1460 USGPM
  - FO: flapper open, occurs at flows < ~1100 USGPM
  - PPF: primary pump failure
  - LPL: low pool level, 12" below nominal pool level
- SDS2: motorized insertion of the shim-safety rod drive mechanisms (rod reversal). Once initiated, this reversal can only be overridden by manual intervention. It is initiated by:
  - reactor period < 10 seconds
  - HP: high power, 110% full power
  - large servo error
- ECC: short to medium term ECC. The reactor pool water serves as a passive ECC that is immediately available to provide downflow through the core (indeed, gravity driven downflow is the normal cooling mode). In the event of low core flow, the plenum flapper at the base of the core is no longer held closed by the pressure difference generated by the core flow and, hence, the flapper opens under the influence of gravity allowing thermosyphoning flow up through the core.

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[1] The reactor period is deduced from the log rate as follows: $\frac{1}{\tau} = \frac{\ln(n_2/n_1)}{t_2 - t_1}$, where the subscripts 1 and 2 refer to sampling times. Thus a log rate of 0.1 sec^{-1} is equivalent to a period of 10 seconds.

- LTECC: long term ECC. Because of the large pool inventory of cooling water, it is deemed sufficient that long term ECC be provided manually via the city water supply.
- Containment. MNR has a full containment building held at a pressure lower than atmospheric.

2 LOR due to Regulating Rod Failure

The regulating rod reactivity worth is limited to between 4 and 6 mk by operating procedures. The postulated failure is that, while at 100% FP, the regulating system fails when the regulating rod is being withdrawn at its maximum rate of 67 cm (full stroke) per minute = 6 mk / minute = 0.1 mk / second from a fully inserted position (a conservative but unlikely scenario).

2.1 Single Mode Failure (ie, no other system failures)

CATHENA simulation (run lor8a) shows that there will be a reverse at 110% FP in 4.6 seconds which terminates the transient. The peak power is 112% FP at 9.0 seconds. Thus, this event is benign.

2.2 Loss of SDS1

As per the results of the Single Mode simulation, SDS1 is not invoked since the SDS2 (reverse) terminates the event. A CATHENA simulation (run lordf6b) shows that there will be a reverse at 110% FP in 6.2 seconds giving a peak power of 112 % FP at 9.0 seconds as per lor8a. Hence, this event is benign.

2.3 Loss of SDS2

When SDS2 is unavailable, the reactor trips on SDS1 at 125 % FP at 8.6 seconds with essentially no power overshoot (peak power = 125.7 % FP, run lordf7a). Hence, this event is benign.

2.4 Loss of ECC

ECC is not required for this event, hence the event is moot.

2.5 Loss of LTECC

LTECC is not required for this event, hence the event is moot.

2.6 Loss of Containment

Containment is not required for this event, hence the event is moot.

3 LOR due to Sample Handling Error

Samples are irradiated in the reactor core as a matter of course. Operating procedures limited the reactivity worth of these samples to ±2 mk. The most rapid reactivity insertion is deemed to occur when a sample slips off the handling tool and drops into the sample holder position. This should take at least 0.1 seconds. If the sample is slowly withdrawn or inserted, the regulating system compensates. A rapid withdrawal or insertion will invoke a prompt jump and a subsequent exponential power rise or fall.

3.1 Single Mode Failure (ie, no other system failures)

Point kinetics simulation shows that if a reactivity insertion of 2 mk is made in 2 seconds or longer, the rate trip is not invoked and the reactor trips on overpower with a peak power just over the trip setpoint. A rapid reactivity insertion (less than 2 seconds) leads to a rate trip before the power has had a chance to rise even 1% beyond nominal conditions. The result for rapid insertions was not sensitive to insertion time since the principle effect of a rapid insertion is to create a prompt jump of magnitude $\beta/(\beta-\rho) \approx 0.007 / 0.005 = 1.4$, invoking a rate trip and then an overpower trip. Thus this event is benign.

CATHENA runs were performed to confirm the in-house point kinetics calculations. SDS1 (trip on 125% overpower or a period less than 4 seconds) and SDS2 (reverse on 110% overpower or a period less than 10 seconds) are active. A 50 millisecond dead time and a 78 mk depth in 0.50 seconds is assumed for the trip. The reverse is a powered insertion of the shim-safety rods (600 seconds for a complete insertion from a fully withdrawn position). The maximum simulation time step was set at 0.1 seconds, representing the time resolution limit for some of the times quoted below.

The first run (lorsf7a) assumes a 2 mk ramp insertion in 2 seconds. The SDS2 reverse was invoked on high rate at 0.01 seconds and on high power at 0.8 seconds. The reverse is slow acting and before the transient could be turned around, SDS1 tripped on high power, terminating the event almost immediately. Peak power was 128.9 % FP at 1.5 seconds. Peak fuel temperature for the 18 plate assemblies was 65.0°C (5°C above nominal) at 1.6 seconds. Peak fuel temperature for the 10 plate assemblies was 71.0°C (6°C above nominal) at 1.6 seconds. By all measures, this event is benign, as expected.

The second run (lorsf8a) assumes a 2 mk ramp insertion in 1 seconds. The SDS2 reverse was invoked on high rate at 0.006 seconds and SDS1 tripped on high rate at 0.028 seconds. The reverse is slow acting and before it could turn the transient around, SDS1 tripped on high rate, terminating the event almost immediately. Peak power was 102 % FP at .08 seconds. Fuel temperatures did not rise above their nominal values. By all measures, this event is also benign, as expected.

A third run (lorsf9a) assumes a 2 mk ramp insertion in 0.5 seconds. The results were similar to the 1 second insertion. The SDS2 reverse on rate occurred at 0.003 seconds and the SDS1 rate trip occurred at 0.008 seconds. Peak power was 102.8 % FP This event is benign.

The fourth run (lorsf10a) assumes a 2 mk ramp insertion in 0.1 seconds. The results were similar to the previous two runs. The SDS2 reverse on rate occurred at 0.002 seconds and the SDS1 rate trip occurred at 0.003 seconds. Peak power was 110 % FP This event is benign.

3.2 Loss of SDS1

If SDS1 is not available, the event will be terminated by SDS2, albeit somewhat slowly compared to the tripped case. For the 2 mk, 2 second ramp (run lordf2a), the period reverse was initiated at 0.01 seconds. The reverse turned the transient around at 5.2 seconds at a peak neutron power of 150% FP Peak fuel temperature for the 18 plate assemblies was 73.1°C (13°C above nominal) at 7.2 seconds. Peak fuel temperature for the 10 plate assemblies was 81.3°C (16°C above nominal) at 7.2 seconds. Hence this event is benign.

For the 2 mk, 1 second ramp (run lordf1a), the period reverse was initiated at 0.003 seconds. The reverse turned the transient around at 5.8 seconds at a peak neutron power of 154% FP Peak fuel temperature for the 18 plate assemblies was 74.0°C (14°C above nominal) at 6.8 seconds. Peak fuel temperature for the 10 plate assemblies was 82.5°C (17.2°C above nominal) at 6.8 seconds. Hence this event is benign.

A faster insertion of 0.5 seconds (run lordf4a) caused a SDS2 rate reverse at 0.003 seconds and a peak power of 156 % FP For an insertion of 0.1 seconds (run lordf5a), the reverse occurred at 0.002 seconds and the peak power was 158 % FP Both events are benign.

A relatively slow insertion of 4 seconds (run lordf3a) gave a high power reverse at 1.244 seconds and a peak power of 151 % FP This event is benign.

3.3 Loss of SDS2

For a slow sample withdrawal, the reactor will trip at 125% FP via SDS1, shutting down the reactor. A fast sample withdrawal invokes a trip when the period drops below 4 seconds. Since SDS2 is much slower acting than SDS1 and since SDS1 is quite effective in terminating this LOR event, the loss of SDS2 is inconsequential. The transient will be as per the Single Mode failure LOR. Hence this event is benign.

3.4 Loss of ECC

ECC is not required for this event, hence the event is moot.

3.5 Loss of LTECC

LTECC is not required for this event, hence the event is moot.

3.6 Loss of Containment

Containment is not required for this event, hence the event is moot.

4 LOR during a reactor startup

The circumstance for this event is a regular startup following a week-end shutdown; thus, the core is in a xenon-free condition and as cold as it is likely to be. Conditions are for a nominal operating power of 5 MW(th) and are normal except as specified below. This includes all instrument settings and the currents for the shim-safety rod magnets. The primary coolant flow is off and the core flow is zero. The shim-safety rods are being withdrawn at the maximum nominal rate and all alarms and reverses fail, except for the high power trip at 125% FP. The resulting power excursion was simulated as reported elsewhere [TR 1998-11]. The initial pool and core temperature was 31°C. For a core of HEU fuel, from a 3 mW starting power, a peak power of 9.04 MW occurred at 74.5 seconds. The integrated power over time for the core, ie the energy added by the power pulse, was 1.88×10^6 joules. For a core of LEU fuel, from a 3 mW starting power, a peak power of 6.98 MW occurred at 73.7 seconds. The integrated power over time for the core was 1.84×10^6 joules. Both cases were simulated with CATHENA.

A CATHENA run (lorstrup3a) was performed using the HEU power profile as input. This core contained a high power HEU fuel assembly and a high power LEU fuel assembly so that a direct comparison could be made. Peak fuel temperature for the 18 plate HEU assemblies was 83.2°C at 74.5 seconds and fluid temperature responded accordingly after a few seconds with a peak temperature of 44.8°C. Peak fuel temperature for the 18 plate LEU assemblies was 92.8°C at 74.5 seconds and the fluid temperatures peaked at 45.4°C.

A second CATHENA run (lorstrup4a) was performed using the LEU power profile as input. As in the previous case, this core contained a high power HEU fuel assembly and a high power LEU fuel assembly. Peak fuel temperature for the 18 plate HEU assemblies was 81.3°C at 73.7 seconds and fluid temperature responded accordingly after a few seconds with a peak temperature of 44.3°C. Peak fuel temperature for the 18 plate LEU assemblies was 90.3°C at 73.7 seconds and the fluid temperatures peaked at 45.0°C.

By all measures, these events are benign and the differences between the HEU and LEU assemblies are inconsequential compared to the heat transfer margins.

By way of comparison, [TR 1998-11] reports that simulations of the above power pulses using an in-house code yields a peak fuel temperature for the 18 plate HEU assemblies of 83.6°C and a maximum fluid temperature of 53.0°C. For the LEU core case, peak fuel temperature for the 18 plate LEU assemblies was 87.9°C and the fluid temperatures peaked at 53.4°C. This is in substantial agreement given the differences in modelling assumptions of the two codes.

For the purposes of bounding the calculation, the maximum temperature rise that could be expected for an input energy of 1.88×10^6 joules can be estimated by supposing that all the energy is deposited into the fuel meat with no conduction into the clad or coolant. A less conservative assumption would be if the energy were deposited into the fuel meat and clad with no conduction to the coolant.

In general, the temperature rise is given by:

$$\Delta T = \frac{\text{energy}}{\text{(volumetric heat capacity) x volume}} = \frac{Q}{C_p V}$$

For HEU 18 plate fuel meat, C_p = 3.688 J / cm^3 °C [OBE69] while for LEU, C_p = 2.351 J / cm^3 °C [SNE87]. For the aluminum clad, C_p = 2.441 J / cm^3 °C [SNE87]. The fuel meat volume [TR 1997-04] is

$$V_{\text{fuel meat}} = 0.051\,\text{cm x } 6.23\,\text{cm x } 60.0\,\text{cm} = 19.06\,\text{cm}^3 \text{ per fuel plate}$$
$$= 305.0\,\text{cm}^3 \text{ for 16 plates}$$

and the clad volume is

$$V_{\text{clad}} = 0.038\,\text{cm x } 6.23\,\text{cm x } 60.0\,\text{cm x } 2 = 28.41\,\text{cm}^3 \text{ per fuel plate}$$
$$= 454.5\,\text{cm}^3 \text{ for 16 plates}$$

At 2 MW nominal power, the peak power assembly is approximately 125 kW. Thus the energy input per assembly for a Q of 1.88 x 10^6 joules is

$$Q_{\text{assembly}} = 1.88\,\text{x}\,10^6\,\text{J x } 125\,\text{kW} / 2000\,\text{kW} = 1.17\,\text{x}\,10^5\,\text{J}$$

Thus the maximum temperature rise in the fuel is

$$\Delta T = \frac{1.17\,\text{x}\,10^5}{3.688\,\text{x}\,305.0} = 104.1\,°\text{C (HEU with energy deposited into fuel meat only)}$$

$$\Delta T = \frac{1.17\,\text{x}\,10^5}{2.351\,\text{x}\,305.0} = 163.2\,°\text{C (LEU with energy deposited into fuel meat only)}$$

$$\Delta T = \frac{1.17\,\text{x}\,10^5}{3.688\,\text{x}\,305.0 + 2.440\,\text{x}\,454.5} = 52.4\,°\text{C (HEU with energy deposited into fuel and clad)}$$

$$\Delta T = \frac{1.17\,\text{x}\,10^5}{2.351\,\text{x}\,305.0 + 2.440\,\text{x}\,454.5} = 64.1\,°\text{C (LEU with energy deposited into fuel and clad)}$$

Because of the lower heat capacity of the LEU fuel meat compared to that of HEU, the temperature is higher in the LEU. However, the rise is well below the value needed to cause fuel damage.

Both the CATHENA and in-house code simulation results fall between the bounding cases of the energy is deposited in (a) the fuel meat only and (b) the meat and the clad.

5 Summary of Results

As summarized in the table below, all events analysed are benign.

Event	Single Mode	Dual Mode				
		No SDS1	No SDS2	No ECC	No LTECC	No Containment
Reg Rod LOR	benign	benign	benign	benign	benign	benign
Sample LOR	benign	benign	benign	benign	benign	benign
Reactor Startup LOR	benign	not applic.	not applic.	not applic.	not applic.	not applic.

References

OBE69 C.F. Obenchain, "PARET -- A Program for the Analysis of Reactor Transients", AEC Research and Development Report IDO-17282, U.S. Atomic Energy Commission, January 1969.

SLA94 J. Slaby and J.T. Rogers, “Experimental and Analytical Modelling of a Loss-of-Pool Water Accident in an SES-10 Reactor”, Dept. of Mech. & Aerospace Engineering, Carlton University, Ottawa, July, 1994.

SNE87 J. L. Snelgrove, R.F. Domagala, G.L. Hofman, T.C. Wiencek, G.L. Copemand, R.W. Hobbs, and R.L. Senn, “The Use of U3Si2 Dispersed in Aluminum in Plate-type Fuel Elements for Research and Test Reactors, Argonne National Laboratory, ANL/RERTR/TM-11, October 1987.

TR 1997-04 Wm. J. Garland, “Thermalhydraulic Modelling of MNR”, McMaster University Nuclear Reactor, Technical Report MNR-TR 97-04, approx. 60 pages, June15, 1997.

TR 1998-06 Wm. J. Garland, “Probabilistic Safety Analysis for the McMaster Nuclear Reactor”, McMaster University Nuclear Reactor, Technical Report MNR-TR 1998-06 (in draft).

TR 1998-11 M.P. Butler, “Startup Accident Transients for HEU and LEU Fuel”, McMaster University Nuclear Reactor, Technical Report MNR-TR 1998-11.

Appendix 1 CATHENA Input and Output Files

Table of Contents:

Single Mode Failure Runs (LOR due to Regulating Rod Failure):

lor8a.inp	Transient input file, 6 mk insertion in 60 seconds.
lor8a-pk.out	Output file (selected core power parameters vs. time)
lor8a-mnrhot.out	Output file (selected 18 plate assembly parameters vs. time)
lor8a-ptrhot.out	Output file (selected 10 plate assembly power parameters vs. time)
lor8a.lis	Full output listing

Archive directory (MNR- garland) d:\cath-pc\lor\rev3\trans.

Dual Mode Failure Runs (LOR due to Regulating Rod Failure):

lordf6b.inp	Transient input file, 6 mk insertion in 60 seconds.
lordf6b-pk.out	Output file (selected core power parameters vs. time)
lordf6b-mnrhot.out	Output file (selected 18 plate assembly parameters vs. time)
lordf6b-ptrhot.out	Output file (selected 10 plate assembly power parameters vs. time)
lordf6b.lis	Full output listing

Archive directory (MNR-garland) d:\cath-pc\lor\rev3\trans.

lordf7a.inp	Transient input file, 6 mk insertion in 60 seconds.
lordf7a-pk.out	Output file (selected core power parameters vs. time)
lordf7a-mnrhot.out	Output file (selected 18 plate assembly parameters vs. time)
lordf7a-ptrhot.out	Output file (selected 10 plate assembly power parameters vs. time)
lordf7a.lis	Full output listing

Archive directory (MNR-garland) d:\cath-pc\lor\rev3\trans.

Single Mode Failure Runs (LOR due to Sample Handling Error):

lorsf7a.inp	Transient input file, 2 mk insertion in 2 seconds.
lorsf7a-pk.out	Output file (selected core power parameters vs. time)
lorsf7a-mnrhot.out	Output file (selected 18 plate assembly parameters vs. time)
lorsf7a-ptrhot.out	Output file (selected 10 plate assembly power parameters vs. time)
lorsf7a.lis	Full output listing

Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor/rev3/trans-sf.

lorsf8a.inp	Transient input file, 2 mk insertion in 1 seconds.
lorsf8a-pk.out	Output file (selected core power parameters vs. time)
lorsf8a-mnrhot.out	Output file (selected 18 plate assembly parameters vs. time)
lorsf8a-ptrhot.out	Output file (selected 10 plate assembly power parameters vs. time)
lorsf8a.lis	Full output listing

Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor/rev3/trans-sf.

lorsf9a.inp Transient input file, 2 mk insertion in 0.5 seconds.
lorsf9a-pk.out Output file (selected core power parameters vs. time)
lorsf9a-mnrhot.out Output file (selected 18 plate assembly parameters vs. time)
lorsf9a-ptrhot.out Output file (selected 10 plate assembly power parameters vs. time)
lorsf9a.lis Full output listing
Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor/rev3/trans-sf.

lorsf10a.inp Transient input file, 2 mk insertion in 0.1 seconds.
lorsf10a-pk.out Output file (selected core power parameters vs. time)
lorsf10a-mnrhot.out Output file (selected 18 plate assembly parameters vs. time)
lorsf10a-ptrhot.out Output file (selected 10 plate assembly power parameters vs. time)
lorsf10a.lis Full output listing
Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor/rev3/trans-sf.

Dual Mode Failure Runs (LOR due to Sample Handling Error + Loss of SDS1):

lordf1a.inp Transient input file, 2 mk insertion in 1 seconds.
lordf1a-pk.out Output file (selected core power parameters vs. time)
lordf1a-mnrhot.out Output file (selected 18 plate assembly parameters vs. time)
lordf1a-ptrhot.out Output file (selected 10 plate assembly power parameters vs. time)
lordf1a.lis Full output listing
Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor/rev3/trans-df.

lordf2a.inp Transient input file, 2 mk insertion in 2 seconds.
lordf2a-pk.out Output file (selected core power parameters vs. time)
lordf2a-mnrhot.out Output file (selected 18 plate assembly parameters vs. time)
lordf2a-ptrhot.out Output file (selected 10 plate assembly power parameters vs. time)
lordf2a.lis Full output listing
Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor/rev3/trans-df.

lordf3a.inp Transient input file, 2 mk insertion in 4 seconds.
lordf3a-pk.out Output file (selected core power parameters vs. time)
lordf3a-mnrhot.out Output file (selected 18 plate assembly parameters vs. time)
lordf3a-ptrhot.out Output file (selected 10 plate assembly power parameters vs. time)
lordf3a.lis Full output listing
Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor/rev3/trans-df.

lordf4a.inp Transient input file, 2 mk insertion in 0.5 seconds.
lordf4a-pk.out Output file (selected core power parameters vs. time)
lordf4a-mnrhot.out Output file (selected 18 plate assembly parameters vs. time)
lordf4a-ptrhot.out Output file (selected 10 plate assembly power parameters vs. time)
lordf4a.lis Full output listing
Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor/rev3/trans-df.

lordf5a.inp Transient input file, 2 mk insertion in 0.1 seconds.

lordf5a-pk.out Output file (selected core power parameters vs. time)
lordf5a-mnrhot.out Output file (selected 18 plate assembly parameters vs. time)
lordf5a-ptrhot.out Output file (selected 10 plate assembly power parameters vs. time)
lordf5a.lis Full output listing
Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor/rev3/trans-df.

Reactor Startup (LOR due to Shim-Safety Rod Failure):
lorstrup3a.inp Transient input file, defined power history for an HEU core.
lorstrup3a-pk.out Output file (selected core power parameters vs. time)
lorstrup3a-mnrhot.out Output file (selected 18 plate HEU assembly parameters vs. time)
lorstrup3a-leuhot.out Output file (selected 18 plate LEU assembly parameters vs. time)
lorstrup3a-ptrhot.out Output file (selected 10 plate assembly power parameters vs. time)
lorstrup3a.lis Full output listing
Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor-startup/rev1/trans.

lorstrup4a.inp Transient input file, defined power history for a LEU core.
lorstrup4a-pk.out Output file (selected core power parameters vs. time)
lorstrup4a-mnrhot.out Output file (selected 18 plate HEU assembly parameters vs. time)
lorstrup4a-leuhot.out Output file (selected 18 plate LEU assembly parameters vs. time)
lorstrup4a-ptrhot.out Output file (selected 10 plate assembly power parameters vs. time)
lorstrup4a.lis Full output listing
Archive directory (AECL-SP): herzberg:u94/garlandw/cathena/lor-startup/rev1/trans.