# Calculation of the Safety-Related Benchmark Problem - IAEA 10 MW : Transient Calculations.

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# ABSTRACT

Safety-related benchmark calculations for an idealized, light water, pool-type reactor, which was described in the IAEA - Safety and Licensing Guidebook , were performed to compare the computational methods used at IPEN-CNEN/SP with those used by various organizations. The calculations with the PARET computer code included postulated transients initiated by loss-of-flow and reactivity insertions. The applied computational methods were availed as an opportunity to improve the methodology for transient calculations of the IEA-R1 research reactor, regarding its power upgrading from 2MW to 5MW and its conversion from the use of Highly Enriched Uranium (HEU) to the use of Low Enriched Uranium (LEU) fuels. Two loss-of-flow transients were analyzed : the fast and the slow transient for both HEU and LEU fuels. No discrepancies were found between our results and those from other organizations. For the reactivity insertion transients, some differences were detected due to the value of the moderator temperature coefficient generated in a previous steady-state calculation. Replacing this coefficient by the value generated at ARGONNE, all the transient results show good agreement with those from other organizations.

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## 1. INTRODUCTION

Safety-related benchmark calculations of loss-of-flow and reactivity insertion transients were performed with the PARET computer code[1] using steady-state neutronic data generated at IPEN-CNEN/SP. The calculations were made in accordance with the problem specifications in the Appendice G-0 of the IAEA - Safety and Licensing Guidebook[2]- for an idealized 10 MW light-water, pool-type reactor.

A fast and a slow loss-of-flow transient and a fast and a slow reactivity insertion transient were analyzed for both HEU and LEU fuels.

The model used for the different transient calculations was mainly based in the PARET computer code, that provides a coupled thermal, hydrodynamic, and point kinetics capability. The PARET code was designed for predicting the course and consequences of nondestructive accidents in research and test reactor cores. The steady-state neutronic data were obtained in a previous paper[3], that show the kinetics parameters, temperature and void coefficients, and peak factors for this problem.

The static parameters, used as PARET input data, are showed in Table 1. Some preliminary calculations were made in order to determine the isothermal reactivity feedback coefficients. The remaining input parameters were obtained from the problem specifications in the IAEA Safety and Licensing Guidebook.

Table 1 : Reactivity Coefficients and Kinetic Parameters for HEU and LEU cases.

| Fuel | $\beta_{EFF}$ | $\Lambda (\mu s)$ | Moderator Temperature (\$/°C) | Void/Density (\$/%void) | Doppler (\$/°C) |
|---|---|---|---|---|---|
| HEU | 7.732E-3 | 56.19 | 1.74E-2 | 0.3167 | 7.68E-5 |
| LEU | 7.403E-3 | 44.72 | 2.91E-2 | 0.5705 | 3.70E-3 |

## 2. TRANSIENT CALCULATIONS

The core representation considers one channel to represent the hottest plate and its associated flow channel and one "average" channel to represent the remaining fuel plates in a volume weighted sense. The axial power distribution was represented by a chopped cosine with 21 axial regions. The axial power peaking factor was 1.5 for both the "average" channel and the hot channel. For the hot channel, this axial distribution was multiplied by the other specified hot channel factors ( 1.4 (Nuclear) x 1.2 (Engineering) = 1.68 ). The Bergles-Rohsenow correlation was selected for detecting onset of nucleate boiling, the transition model with the McAdams correlation was included for fully developed two-phase flow, and the Seider-Tate correlation was used for the single-phase forced convection regime.

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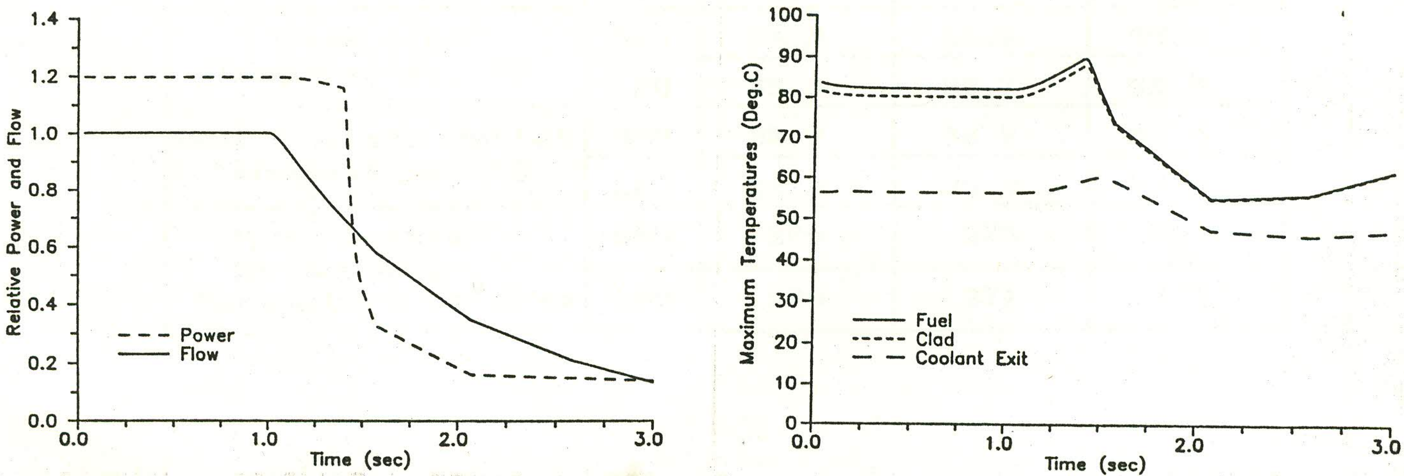
### 2.1 Fast Loss of Flow Transients

It was assumed that the reactor is operating at its maximum power level of 120% (12 MW) when the accident occurs. The coastdown of the primary flow rate is approximated by an exponential function with a time constant of 1 s. The reactor scram is initiated at 85% of nominal flow rate (1000 $m^3/h$), with a 200 ms delay before linear shutdown reactivity insertion of -$10 in 1/2 s. The calculations are terminated at a relative flow rate of 15% because at this level the natural circulation flaps are assumed to open automatically causing a flow reversal. Table 2 shows the principal results obtained in this transient and compare them with those obtained by other organizations. Figure 1a shows the time variation of the relative power and flow rate. Figure 1b shows the time variation of the maximum temperatures in the fuel, clad, and coolant at exit for the HEU core. Figures 1c and 1d refer to similar results for the LEU core.

Table 2 : Fast Loss-of-Flow Transient Results

| | FUEL | IPEN | ANL | INTERATOM |
|---|---|---|---|---|
| Power Level at Scram, MW | HEU | 11.9 | 11.9 | 11.5 |
| | LEU | 11.7 | 11.9 | 11.4 |
| Peak Fuel Temperature, °C | HEU | 90.0 | 89.2 | 91.0 |
| | LEU | 89.8 | 90.3 | 91.9 |
| Peak Clad Temperature, °C | HEU | 88.2 | 87.5 | 89.5 |
| | LEU | 86.9 | 87.5 | 89.3 |
| Peak Coolant Outlet Temperature, °C | HEU | 60.3 | 60.3 | 56.5 |
| | LEU | 59.8 | 60.3 | 56.4 |
| Min. Bubble Detachment Parameter, $cm^3K/Ws$ | HEU | 234 | 234 | 257 |
| | LEU | 242 | 235 | 258 |

Figure 1 : Transient Responses - Fast Loss of Flow



(a) HEU - Relative Power and Flow

(b) HEU - Maximum Temperatures

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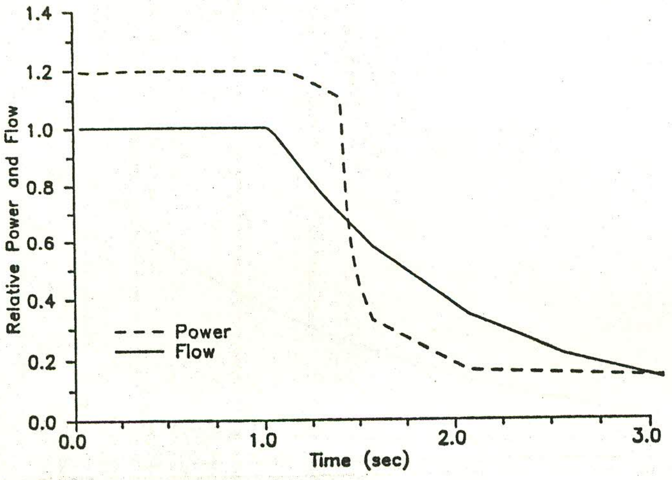
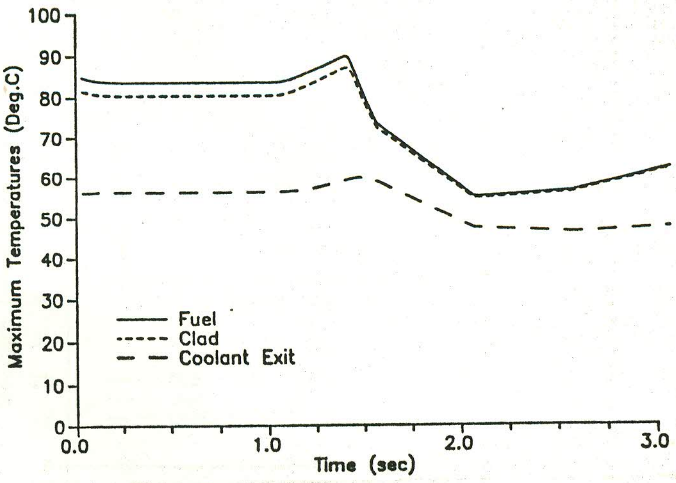


(c) LEU - Relative Power and Flow



(d) LEU - Maximum Temperatures

## 2.2 Slow Loss-of-Flow Transients

In this case, the flow is reduced as exp(-t/T), with T=25 seconds. The other considerations are the same of the previous case. Table 3 provides the most relevant results. Figure 2 shows the evolution of the power, relative flow rate and maximum temperatures for both cores.

Table 3 : Slow Loss-of-Flow Transient Results

| | FUEL | IPEN | ANL | INTERATOM |
|---|---|---|---|---|
| Power Level at Scram, MW | HEU | 11.6 | 11.6 | 11.6 |
| | LEU | 11.2 | 11.6 | 11.5 |
| Peak Fuel Temperature, °C | HEU | 86.4 | 85.8 | 87.4 |
| | LEU | 86.2 | 86.8 | 88.2 |
| Peak Clad Temperature, °C | HEU | 84.5 | 83.9 | 85.8 |
| | LEU | 83.3 | 83.7 | 85.5 |
| Peak Coolant Outlet Temperature, °C | HEU | 58.9 | 58.9 | 55.6 |
| | LEU | 58.3 | 58.8 | 55.4 |
| Min. Bubble Detachment Parameter, $cm^3K/Ws$ | HEU | 270 | 270 | 293 |
| | LEU | 280 | 271 | 295 |

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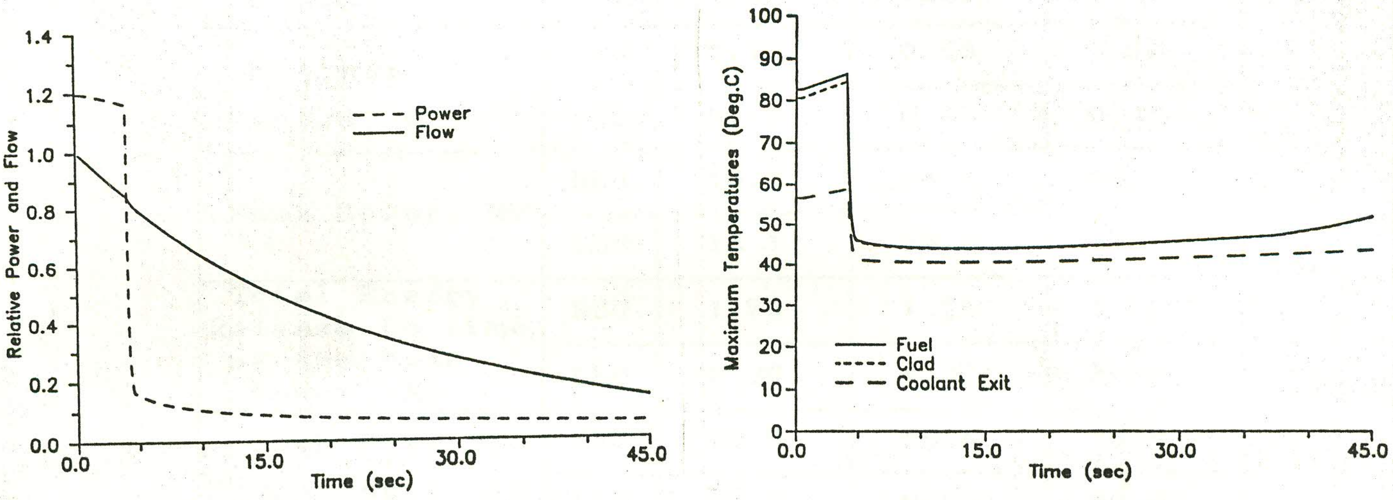
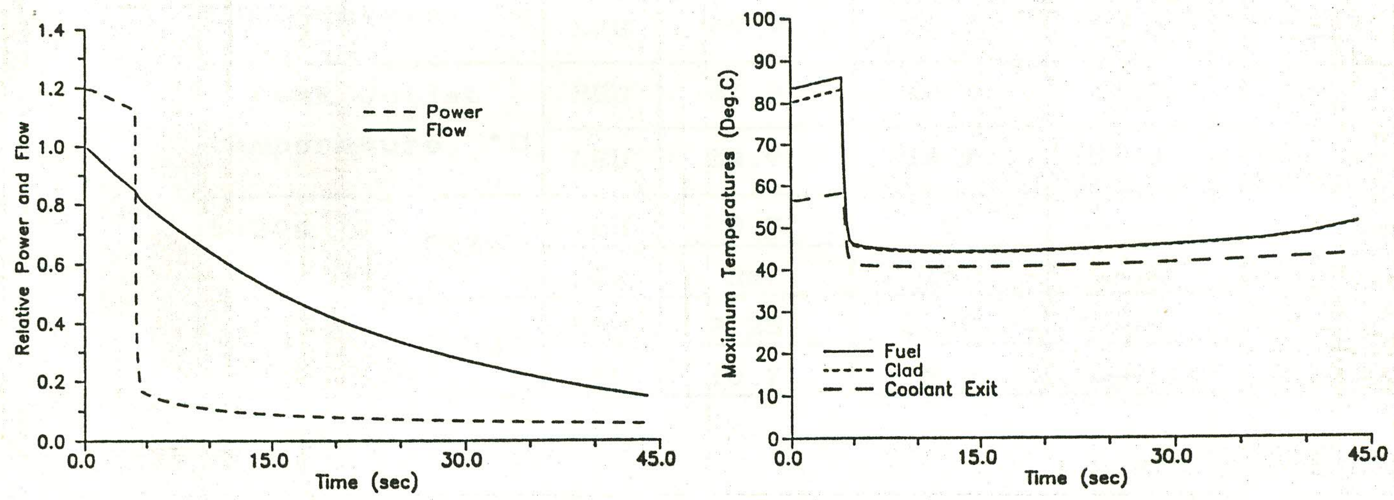
Figure 2 : Transient Responses - Slow Loss of Flow



(a) HEU - Relative Power and Flow (b) HEU - Maximum Temperatures



(c) LEU - Relative Power and Flow (d) LEU - Maximum Temperatures

## 2.3 Slow Reactivity Insertion Transients

The transient begins with a ramp reactivity insertion rate of \$0.1/s for the HEU core and of \$0.09/s for the LEU core, with the reactor critical at an initial power of 1 watt and with nominal flow rate of 1000 $m^3$/h. The safety system trip set point is at 12 MW, and a time delay of 25 ms is considered before the linear shutdown reactivity insertion of -\$10 in 1/2 s. Table 4 provides the most important results and compares them with those obtained by other organizations. Figure 3a shows the time evolution of the power for the HEU and LEU cores. Figures 3b, 3c, and 3d show, respectively, the maximum time variation of the temperatures in the fuel, clad and coolant exit for both cores.

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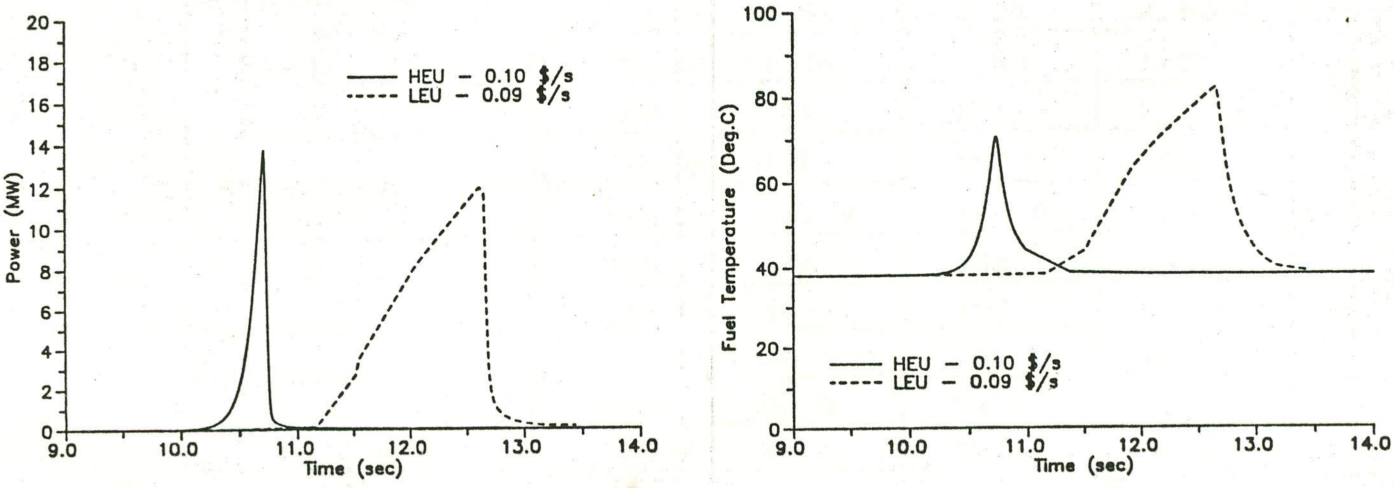
Table 4 : Slow Reactivity Insertion Transient Results

| | FUEL | IPEN | ANL | INTERATOM |
|---|---|---|---|---|
| Minimum Period, s | HEU | 0.10 | 0.10 | 0.10 |
| | LEU | 0.12 | 0.11 | 0.11 |
| Peak Power, MW | HEU | 13.7 | 14.1 | 14.4 |
| | LEU | 12.1 | 12.4 | 12.4 |
| Total Energy Release to time of the Peak Power, MJ | HEU | 1.70 | 1.74 | 1.53 |
| | LEU | 9.30 | 4.55 | 5.94 |
| Peak Fuel Temperature, °C | HEU | 70.5 | 70.6 | 70.5 |
| | LEU | 82.0 | 80.6 | 80.8 |
| Peak Clad Temperature, °C | HEU | 69.1 | 69.0 | 69.2 |
| | LEU | 78.9 | 77.7 | 78.1 |
| Peak Outlet Temperature, °C | HEU | 47.9 | 48.1 | 45.2 |
| | LEU | 54.9 | 53.9 | 51.1 |
| t=20s P(KW) | HEU | 5.5 | 5 | —— |
| | LEU | 33 | 15 | —— |
| E(MJ) | HEU | 2.25 | 2.29 | —— |
| | LEU | 10.7 | 5.3 | —— |

Figure 3 : Transient Responses - Slow Reactivity Insertion



(a) Power Generated in the Fuel

(b) Fuel Center Line Temperature

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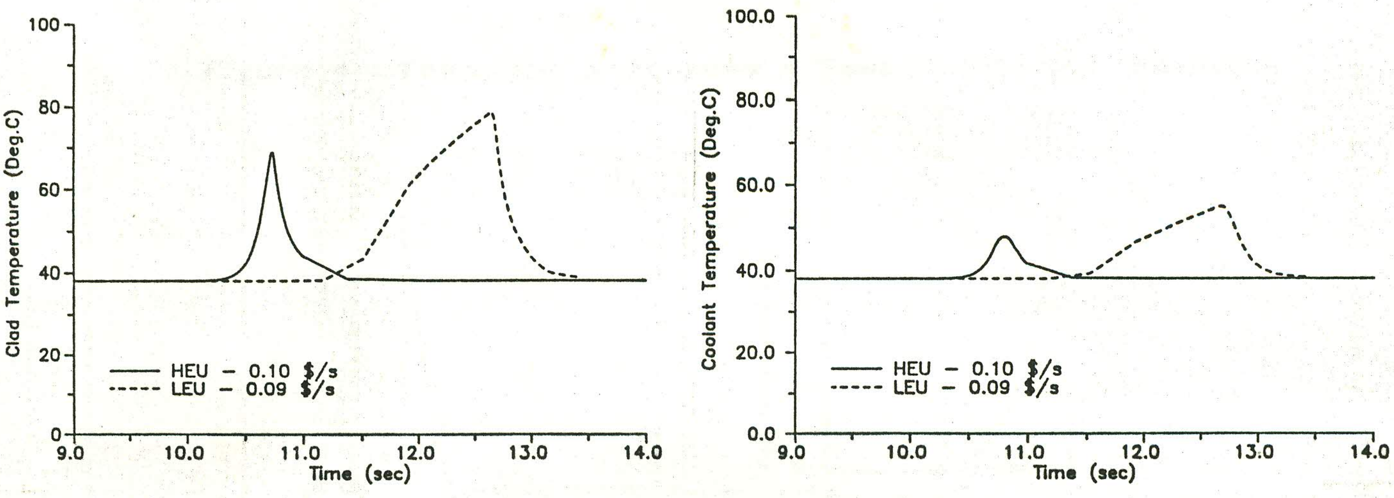


(c) Clad Temperature

(d) Coolant Outlet Temperature

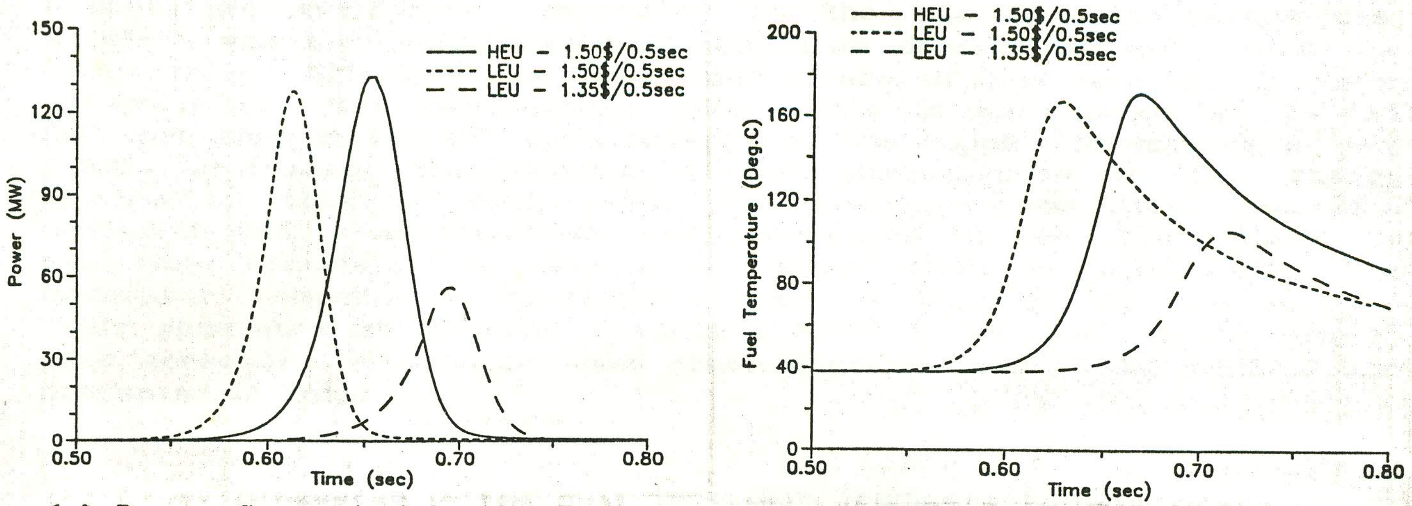
## 2.4 Fast Reactivity Insertion Transients

The transient begins with a ramp reactivity insertion rate of $1.50 in 1/2 s for both HEU and LEU cores and a ramp reactivity insertion rate of $1.35 in 1/2 s only for the LEU core. The other considerations are the same as those of the previous case. Table 5 and Figure 4 show the relevant results for this problem.

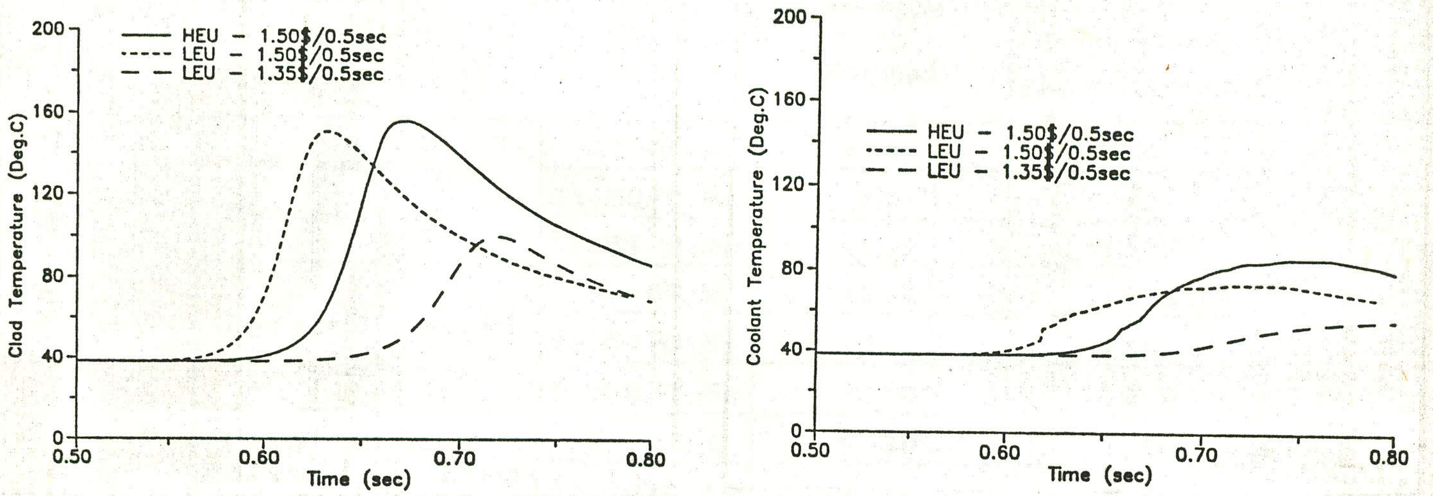
Table 5 : Fast Reactivity Insertion Transient Results

| | FUEL | | IPEN | ANL | INTERATOM |
|---|---|---|---|---|---|
| Minimum Period, ms | HEU | | 14 | 15 | 14 |
| | LEU | $1.50 | 12 | 12 | 12 |
| | | $1.35 | 16.9 | 17.0 | 17.0 |
| Peak Power, MW | HEU | | 133 | 132 | 135 |
| | LEU | $1.50 | 128 | 148 | 144 |
| | | $1.35 | 56.0 | 63.2 | 62.9 |
| Total Energy Release to time of the Peak Power, MJ | HEU | | 3.44 | 3.26 | 3.14 |
| | LEU | $1.50 | 2.53 | 2.95 | 2.83 |
| | | $1.35 | 1.36 | 1.54 | 1.59 |
| Peak Fuel Temperature, °C | HEU | | 171 | 171 | 173 |
| | LEU | $1.50 | 167 | 183 | 186 |
| | | $1.35 | 105.9 | 114.8 | 111.0 |
| Peak Clad Temperature, °C | HEU | | 156 | 156 | 160 |
| | LEU | $1.50 | 151 | 157 | 168 |
| | | $1.35 | 99.9 | 108.0 | 105.1 |
| Peak Outlet Temperature, °C | HEU | | 86.0 | 84.0 | 70.7 |
| | LEU | $1.50 | 73.0 | 82.0 | 63.2 |
| | | $1.35 | 55.8 | 58.2 | 52.0 |

Figure 4 : Transient Responses - Fast Reactivity Insertion



(a) Power Generated in the Fuel (b) Fuel Center Line Temperature



(c) Clad Temperature (d) Coolant Outlet Temperature

## 3. DISCUSSIONS AND CONCLUSIONS

The most important conclusions for actual core conversion from HEU to LEU fuel can be drawn from the results in Appendice G of the IAEA - Safety and Licensing Guidebook. For the loss-of-flow and reactivity insertion transients, the results obtained in this paper with the methodology applied at IPEN-CNEN/SP when compared with those of the Appendice G are generally favorable.

For the loss-of-flow transients, Tables 2 and 3 show that these results are in good agreement with those from other organizations. Figures 1 and 2 show that both HEU and LEU cores have similar behavior for the fast and slow transients. No damage is expected for these cores.

The results for the investigations of the reactivity insertion transients (Tables 4 and 5) show some discrepancies when compared with those from other organizations. These discrepancies, noted only for

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the LEU core, resulted from the value used for the moderator temperature coefficient, generated in the steady-state calculations, in which was only considered the moderator density variation with the temperature neglecting the important effect of the neutron spectrum hardening with the temperature. This effect is more important in the LEU core than in the HEU core because of the Doppler broadening of the U-238 resonances. The results showed discrepancies in the energy release to time of peak power for the slow reactivity insertion transient and in all the calculated parameters for the fast reactivity insertion transient. It should be noted that replacing only the moderator temperature coefficient used in this calculations by the value generated at ARGONNE ( 1.082E-2 $/°C ), all the results are in good agreement with those from other organizations. These results are presented in Table 6.

Table 6 : Reactivity Insertion Transient Results

| | | Normal | Temp.Coef. from ARGONNE |
|---|---|---|---|
| Minimum Period, ms | $0.09/s | 120 | 120 |
| | $1.50/0.5s | 12 | 12 |
| | 1.35$/0.5s | 16.9 | 16.9 |
| Peak Power, MW | $0.09/s | 12.1 | 12.2 |
| | $1.50/0.5s | 128 | 138 |
| | 1.35$/0.5s | 56.0 | 59.8 |
| Total Energy Release to time of the Peak Power, MJ | $0.09/s | 9.30 | 5.60 |
| | $1.50/0.5s | 2.53 | 2.76 |
| | 1.35$/0.5s | 1.36 | 1.52 |
| Peak Fuel Temperature, °C | $0.09/s | 82.0 | 80.1 |
| | $1.50/0.5s | 167 | 176 |
| | 1.35$/0.5s | 105.9 | 110.6 |
| Peak Clad Temperature, °C | $0.09/s | 78.9 | 77.8 |
| | $1.50/0.5s | 151 | 154 |
| | 1.35$/0.5s | 99.9 | 104.2 |
| Peak Outlet Temperature, °C | $0.09/s | 54.9 | 54.0 |
| | $1.50/0.5s | 73.0 | 77.7 |
| | 1.35$/0.5s | 55.8 | 57.2 |

## 4. FINAL REMARKS

The results obtained with the methodology utilized at IPEN-CNEN/SP for loss-of-flow transient calculations compare well with those from other organizations. For reactivity insertion transients, the results showed some discrepancies due to the inaccurate moderator temperature coefficient. Currently, an effort is being made to improve the estimate of this parameter.

## REFERENCES

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