ANL/RERTR/TM-06/01

FUEL PLATE SURFACE TEMPERATURE IN A FULLY-UNCOVERED FUEL ASSEMBLY AFTER A LOSS-OF-COOLANT ACCIDENT IN AN MTR-TYPE RESEARCH REACTOR

Nuclear Science & Engineering Division

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Summary

A methodology and model that were developed in the 1960s for calculating the peak fuel temperature in an MTR fuel assembly in a reactor core that has been fully-uncovered in a hypothetical loss-of-coolant accident (LOCA) are revived and updated in this report. The semi-empirical one-node model is based on experiments on fuel elements for the Oak Ridge Research Reactor (ORR) and the Low Intensity Testing Reactor (LITR) that were done in the 1950s and 1960s at the Oak Ridge National Laboratory. The peak plate temperature in 18 LOCA tests in the ORR and two of 24 tests in the LITR, calculated using the model, are compared with experiments.

The original model was used in LOCA analyses for the Omega West Reactor (OWR) at Los Alamos National Laboratory with HEU fuel and for three cores of the University of Virginia Reactor (UVAR) with both HEU and LEU fuels. The LOCA analyses for UVAR using this model were accepted for licensing purposes by the US Nuclear Regulatory Commission for an assembly containing 12 HEU fuel plates in 1970, an assembly containing 18 HEU fuel plates in 1984, and an assembly containing 22 LEU silicide fuel plates in 1994.

The analyses done for the OWR and UVAR are repeated here and compared with data in the original reports in order to establish the validity of the model revived in this report. The model is then used in a subsequent LOCA analysis for the HEU and LEU cores of the RPI MTR-type reactor in Portugal. It can also be applied to other MTR-type reactors with designs similar to the LITR.

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1 Introduction

The loss-of-coolant accident (LOCA) has been the design-basis accident and analyzed since the earliest history of nuclear reactor. In the LOCA analysis, a double-ended pipe rupture is assumed to remove the coolant (water) from the reactor tank, uncovering all or part of the fueled length of fuel assemblies. This leaves largely heat convection to air as the mode of cooling the fuel plates in the case of full uncovering, or leaves only heat convection to water vapor as the mode of cooling the fuel plates in the case of partial uncovering (because air cannot enter the fuel assembly inlet). Structural heat conduction and radiation cooling modes are present in both cases. The purpose of this report is to review and revive the earlier methods for fully uncovered LOCA analysis in research and test reactors, develop a computer program and verify and validate it using the data available from several LOCA tests. The program is then used for LOCA calculations in the Portuguese Research Reactor (RPI) as part of its conversion analysis.

An early analytical study of decay heat removal from a single plate-type fuel assembly (i) taken out of the reactor into the atmosphere, and (ii) in the reactor after LOCA was reported in 1958 by Grimble and Le Tourneau [1]. A single-node equation for the axial peak fuel plate surface temperature of an irradiated fuel element cooled in stagnant air was reported by Wett in 1960 based on 18 tests in the Oak Ridge Research Reactor (ORR) [2]. In these tests, the measured assemblies were not sitting on the grid plate in the reactor core. They were taken out of the core and hung in air by a crane. Wett's equation is the starting point of a computer program developed in the current work for LOCA calculation. All 18 tests done in the ORR are calculated and reported here.

During 1951 to 1953, 24 loss-of-water tests were performed in the Low Intensity Testing Reactor (LITR) in which the assemblies remained sitting on the grid plate in the reactor core, and are therefore more relevant to LOCA analysis [3]. Two of these tests, Test 17 and Test 18, are calculated using the program in the current work. Test 17 is basically used to adjust the fuel assembly heat loss term in Wett's equation to account for the difference between the LITR tests and the ORR tests, i.e., the fuel assembly remaining in-core in the LITR tests compared to the fuel assembly hung out-of-core in the ORR tests. Test 18 is calculated using the program to confirm the adjustment made.

The LOCA analyses for the Omega West Reactor (OWR) reported in 1969 [4], for the 12-plate HEU U-Al alloy fuel University of Virginia Reactor (UVAR) reported in 1970 [5], the 18-plate HEU U-Al alloy fuel UVAR in 1984, and the 22-plate LEU U_3Si_2 fuel UVAR in 1994 were all based on the above one-node model, i.e., Wett's equation with the adjusted fuel assembly heat loss term (see Table 1). In the current report, the LOCA in these two reactors is calculated and reproduced using the computer program developed. Finally, the validated program is used to analyze LOCA in the Portuguese Research Reactor.

2 One-Node LOCA Model For a Fuel Assembly Hung Out of the Reactor Core

In July-October 1959, J. F. Wett developed a one-node model to calculate the maximum plate surface temperature in an irradiated fuel assembly of the ORR when the fuel assembly is hung in air out of the reactor core, thus simulating LOCA with scram [2]. He hung irradiated fuel assemblies (irradiated in the ORR during power operation, and subsequently cooled after reactor shutdown for 19.25 to 780 hours in water) in stagnant air by a crane in the Oak Ridge hot cell (maintained at 90 °F), and measured the steady-state and transient axial temperature distribution of the fuel plates. Table 2 shows all the 18 tests reported [2]. He used the steady-state axial peak plate temperature data and a semi-empirical correlation, Eq. (1), for the heat transfer coefficient times heat transfer area for a fuel assembly. See Nomenclature provided after section 9. Using Eq. (2) to find the heat loss rate from a fuel assembly, he derived Eq. (3) to express the heat balance between decay heat generation rate (obtained by the Way-Wigner relation) and heat loss rate in the steady state when the fuel assembly was cooled by stagnant air while hanging in the Oak Ridge hot cell.

$$hA \propto a\theta^n + b \qquad where\ a = 0.0064, \quad n = 0.72, \quad b = 0.5 \tag{1}$$

$$q = hA\theta \tag{2}$$

$$\theta(a\theta^n + b) = 1.37\times10^4[t^{-0.2} - (T+t)^{-0.2}]\frac{\overline{\phi_i} W_i P'}{\overline{\phi_c} W_c} \tag{3}$$

In Eq. (3), the quantity $\frac{\overline{\phi_i} W_i\, P'}{\overline{\phi_c} W_c}$ is the operating power of the fuel assembly as given by Eq. (4), and the quantity in square brackets arises from the ratio of decay power to operating power of the fuel assembly as given by the Way-Wigner relation, Eq. (5) [6]. The unit of the reactor power P' is not specified by J. F. Wett in the report [2]. *It is noted that reference [2] incorrectly shows the coefficient of Eq. (3) as 1.37x10*^{3}*.* Equation (3) as given here was checked by comparing it with a companion equation given in reference [2] that uses the decay energy release curves presented by Perkins and King in the units of MeV/sec-Watt [7].

$$P_0 = \frac{\overline{\phi_i} W_i\, P'}{\overline{\phi_c} W_c} \tag{4}$$

$$\frac{P}{P_0} = 0.0622[t^{-0.2} - (T+t)^{-0.2}] \qquad for \quad t \ge 10 \sec \tag{5}$$

We can rewrite Eq. (3) as Eq. (6) below, with the help of Eq. (4). Using Eq. (5), we can rewrite Eq. (6) as Eq. (7), which expresses the steady-state balance of decay power and heat loss rate for the fuel assembly.

$$\theta(a\theta^n + b) = 1.37\times10^4[t^{-0.2} - (T+t)^{-0.2}]P_0 \tag{6}$$

$$P = 0.0622\,[\mathrm{t}^{-0.2} - (T+t)^{-0.2}]P_0 = \frac{0.0622}{1.37\times10^4}\theta\,(a\theta^n + b) \tag{7a}$$

$$P = 0.0622\,[\mathrm{t}^{-0.2} - (T+t)^{-0.2}]P_0 = 4.54\times10^{-6}\,\theta\,(a\theta^n + b) \tag{7b}$$

The numerical factor 4.54x10^{-6} in the heat loss rate on the right hand side of Eq. (7b) was determined specifically for the *hanging* ORR fuel assembly. It must be adjusted for other *similar* reactors based on the heat transfer area in the fuel assembly compared to that in the ORR fuel assembly. The numerical factor must also be adjusted if the fuel assembly remains in-core seated on the grid plate instead of hanging out of core (see section 3).

The preceding analysis represents a quasi-steady-state condition in which changes in temperature with time are negligibly slow. During a transient starting from an initial fuel assembly peak temperature, the change in the fuel assembly peak temperature as function of time is determined by the following differential equation.

$$M\,C_p \frac{d\theta}{dt} = P - 4.54\times10^{-6}\theta(a\theta^n + b) \qquad \text{for an out-core ORR fuel assembly} \qquad (8)$$

The right hand side of Eq. (8) is the decay power minus the heat loss rate for the fuel assembly.

Analysis of the 18 Tests Using the One-Node Model: A program, *1NODE-LOCA*, has been written to solve Eq. (8) numerically, using the Cash-Karp Runge-Kutta method. The input data for the program is described in Appendix A. All 18 tests done by hanging the irradiated ORR assemblies in air have been analyzed using the program. The input data used for each test is given in Appendix B. The fuel assembly heat capacitance in Eq. (8) includes the fuel meat, cladding, and the fuel assembly structure that is thermally well connected (having good thermal conduction paths) to the fuel plates. The measured axial temperature distribution for each test is reported when the fuel assembly became in equilibrium (decay power = heat loss rate) with the hot cell air [2]. The measured axial peak temperature was obtained by fitting a quadratic over three of the reported plate temperatures (near the peak) along the fuel assembly length (see Table 2). The operating power of each fuel assembly was obtained from U235 mass and neutron flux in the fuel assembly, assuming an operating power of 1.0 MW in the fuel assembly ORR-164 (Table 2). The fuel assembly ORR-164 was assumed to have an average power of 1.0 MW (i.e., 30 MW reactor power/30 assemblies). The ambient air temperature, i.e., the Oak Ridge hot cell temperature, was 90 °F, and this is the initial temperature of fuel plate surface in the transient calculation. This is because the water temperature in the tank (nearly equal to the ambient temperature) keeps the fuel plates cooled to its own temperature as long as the plates are covered by the water.

Table 2 compares the calculated equilibrium peak temperature with the measured value reported in reference [2]. The maximum difference occurs in Test 17, with a calculated temperature of 586 °F compared to a measured value of 518 °F. This means a calculated-to-measured ratio (C/M) for temperature rise of 1.16, i.e., (586 - 90)/(518 - 90). The program is working as expected because the model is reported to have a C/M ratio for temperature rise of 1.091±0.088 [2].

To analyze out-of-core hanging assemblies, the numerical factor $4.54\text{x}10^{-6}$ in the heat loss term on the right hand side of Eq. (8) must be adjusted for other *similar* reactors based on the heat transfer area in the fuel assembly compared to that in the ORR fuel assembly.

3 One-Node LOCA Model For a Fuel Assembly Remaining In-Core on Grid Plate

The numerical factor $4.54\text{x}10^{-6}$ in the heat loss rate term on the right hand side of Eq. (8) was found for a fuel assembly hanging out of core. As described below, this factor is found to be $1.30\text{x}10^{-6}$ for a fuel assembly remaining seated in-core on the grid plate, using the measured fuel plate peak surface temperature variation during loss-of-water tests in the LITR [3]. The model is then written as Eq. (9).

$$M\,C_p \frac{d\theta}{dt} = P - 1.30 \times 10^{-6}\,\theta(a\theta^n + b) \qquad \text{for an in-core LITR fuel assembly} \qquad (9)$$

The reduction in the value of the factor indicates that the heat transfer is poorer for an in-core fuel assembly than that for a fuel assembly hanging out-core in stagnant atmosphere. It is noted that when the fuel assembly is on the grid plate, there is heat loss by conduction to the grid plate and other reactor structure, and this heat loss mode is not available for a hanging fuel assembly. The heat conduction path is down the fuel assembly to the grid plate, through the skirt plates on which the grid plate rests, to the lower support casting and upward into the beryllium reflector in the tank. However, in the LITR tests, there is so much deterioration in the heat loss rate by natural convection that the factor becomes smaller for an in-core fuel assembly. It was also found in the LITR tests that the chimney effect activated by opening a large valve at the bottom of reactor tank and a manhole at the top, caused a noticeable cooling of the fuel plates. The factor 1.30×10^{-6} does not include the chimney effect.

General Description of LOCA Tests in the LITR: During 1951 to 1953, a series of 24 loss-of-water tests were performed in the LITR, with all fuel assemblies remaining in-core seated on the grid plate [3]. In these tests, the pre-test operating power of the reactor was varied from 0.0225 to 2.300 MW (see Table 3). The general plan for each test was to operate the reactor at a constant power for the operating time planned for the test (varying from 2 to 142 hours in the series of tests), then to shutdown the reactor by draining the water (not by dropping control rods) and to continue the temperature measurement for about 2 hours, which was sufficient time for the fuel temperature to reach the maximum and begin to decrease. The two severest tests (Test 17 and Test 18) of this series are analyzed below.

The sequence of operations for a typical test is that approximately 5 minutes prior to the end of the steady operating time, the cooling water pumps were stopped and the inlet and outlet valves were closed to prevent water leakage back into the reactor [8]. A manhole cover at the tank top was opened to allow air to enter the tank when the water drains out. Next, a 6-inch remotely operated gate valve at the tank bottom was opened to begin the draining. The fuel plate temperature recorders were started at the time of opening the gate valve. In about 2.5 minutes the water level lowered from the top of the tank to a level *one foot above the fuel plates*, with the reactor operating at constant power as the water level above the reactor core dropped. The removal of water below this level (i.e., removal of the upper reflector) caused the reactor to become sub-critical and shutdown. During the next 12 seconds the water drained past the fuel plates (as indicated by recorders on ion chambers). After another 30 seconds, the tank was completely empty. Then the drain valve at the bottom of the tank and the manhole at the top were closed to seal the tank and prevent the entrance of additional cooling air.

The draining of water removed the radiation shielding above the reactor. The beam of radiation was directed skyward, and the Health Physics personnel stationed at strategic locations reported that the radiation level gradually increased to a maximum (of several hundred mr/hr during a test with an operating power of 0.3 MW) for a few seconds prior to the shutdown by moderator loss.

Loss-of-Water Test 17 in the LITR: In the test done on May 12, 1952 (Test 17), when the reactor had been operated for 142 hours at 1.0 MW, the primary coolant pump was shut off and a six-inch valve at the bottom of the reactor tank was opened to drain the water until the level in the tank dropped below the fuel assembly bottom. The valve was shut after draining. The safety system was interceded so that the reactor was shut down by loss of water (moderator), and not by insertion of control assemblies. After the reactor shutdown, the valve at the bottom of the tank was closed to prevent any cooling of the fuel plates by the chimney effect. The fuel plate peak surface temperature in the fuel assembly in grid location C-25 was measured as a function of time starting before the draining of the tank and the subsequent shutdown. The measured peak plate surface temperature rose from a minimum of 111 °F (44 °C) at 1.2 minutes after reactor shutdown to a maximum of 478 °F (248 °C) at about 80 minutes, and remained nearly constant until 142 minutes after reactor shutdown when the bottom valve and the top manhole were opened. The resulting chimney effect immediately started cooling the fuel plates, and the temperature dropped to 446 °F (230 °C) 28 minutes later (i.e., 170 minutes after scram). The temperature dropped to 302 °F (150 °C) 12 hours later.

A measurement of surface temperature variation over the length of fuel plates was also obtained in the test by a thermocouple six inches above the thermocouple measuring the axial peak temperature. The six inch upper thermocouple recorded 234 °C (14 °C lower than the axial peak temperature).

The computer program, *1NODE-LOCA*, was used to solve Eq. (9) numerically, using the Cash-Karp Runge-Kutta method. The fuel assembly heat capacitance used in Eq. (9) includes the fuel meat, cladding, the fuel assembly structure that is thermally connected to the fuel plates, and the metal in a rectangular pitch of the grid plate. Appendix C shows a FORTRAN program written to find the masses of UAl_4 and aluminum, and the heat capacitance of a standard fuel assembly of the LITR. The program uses specific heat, density and other data of U-Al alloy fuel from reference [9]. The heat capacitance obtained is shown in Table 1. The ambient temperature is assumed to be 111 °F, equal to the measured initial temperature of the fuel plate surface. The power of the fuel assembly in grid location C-25 is found as:

$$P_0 = (\text{Reactor power, 1.0 MW}) / (\text{Total number of assemblies in core, 23}) \times (\text{Radial power peaking factor, 1.46}) = 0.0635 \text{ MW}$$

The radial power peaking factor equals (assuming each fuel assembly has the same U^{235} mass) the ratio of thermal neutron flux in location C-25 to the average thermal neutron flux in the core. This flux ratio is reported to be 1.29, with a maximum value of 1.63 for location C-25 [10]. A value of (1.29 + 1.63)/2, i.e., 1.46 is used above to find the pre-test operating power of the fuel assembly in location C-25.

The numerical factor in the heat loss rate term in the model was adjusted in the calculation to get a maximum peak plate temperature of 478 °F (equal to the measured value). The value of the factor obtained from this test is used below in the analysis of Test 18, and should closely predict the maximum peak plate temperature in that test. The adjustment was performed using three different equations for decay heat power: (i) the older Way-Wigner relation of 1958, Eq. (5), [6], (ii) the newer ANSI/ANS-5.1 function of 1979 [11], and (iii) the current ANSI/ANS-5.1 function of 1994 [12]. When using the ANSI/ANS-5.1 standards in doing the adjustment, the absorption correction done using the factor G(t) and the one sigma uncertainty in decay heat was not included. The adjusted numerical factor for the Way-Wigner decay heat relation is found to be 1.30×10^{-6}, equal to that reported earlier [4]. The adjusted factor for ANSI/ANS-5.1 decay heat function of 1979 and 1994 is found to be 1.80×10^{-6} (summarized below), and Eq. (9) can be rewritten in terms of the number of fuel plates in the fuel assembly.

$$M\,C_p\,\frac{d\theta}{dt} = P - 1.0\times10^{-7}\,N_p\,\theta(a\theta^n + b)$$ for an in-core LITR fuel assembly using ANSI/ANS-5.1 decay heat (10)

Adjusted Heat Loss Term in the One Node LOCA Model

Equation for Decay Power	Numerical Factor in Heat Loss Term, MW/°F	LITR Test Number	Power of Fuel Assembly C-25, MW	Maximum Plate Surface Temperature in Fuel Assembly C-25, °F	
				Calculated	Measured
Way-Wigner Eq. (5)	1.30×10^{-6}	17	0.0635	464	478
		18	0.0793	508	487
ANSI/ANS-5.1 1979 or ANSI/ANS-5.1 1994	1.80×10^{-6}	17	0.0635	480	478
		18	0.0793	527	487

Tables 4 and 5 show the input data for this test (Test 17), and the calculated peak plate temperature as a function of time after the temperature rise started (i.e., after the fuel plate became uncovered at the thermocouple location). These results are plotted in Fig. 1. Using the Way-Wigner decay heat relation (Table 4), the calculated maximum plate temperature is 464 °F at 85.0 minutes after draining (highlighted). Using the ANSI/ANS-5.1-1994 decay heat function (Table 5), the calculated maximum plate temperature is 480 °F at 55.0 minutes after draining (highlighted).

<u>Loss-of-Water Test 18 in the LITR</u>: Another test was done in the LITR on May 19, 1952 (Test 18) when the reactor had been operated for 138 hours at a higher power (1.25 MW). In this test, the safety system was not interceded as in the previous test on May 12, 1952. The six-inch valve at the bottom of the reactor tank was opened and the primary coolant pump was shut off to drain the water until the level in the tank dropped below the core, as in the previous test. At the same time, the reactor scrammed by the dropping of a shim control rod, apparently caused by low water level. The fuel plate peak surface temperature in the fuel assembly in grid location C-25 was measured as a function of time. The measured peak plate surface temperature rose from 90 °F (32.4 °C) at 2.0 minutes after scram to a maximum of 487 °F (253 °C) at 137 minutes after scram (i.e., 135 minutes after the temperature started rising) [3]. The bottom valve and the top manhole were opened 140 minutes after scram. The resulting chimney effect immediately started cooling the fuel plates, and the temperature dropped to 410 °F (210 °C) 35 minutes later (i.e., 175 minutes after scram).

A measurement of surface temperature variation over the length of fuel plates was also obtained in the test by a thermocouple six inches above the thermocouple measuring the axial peak temperature. The six inch upper thermocouple recorded 241 °C (12.5 °C lower than the axial peak temperature).

The test was analyzed using the value obtained from Test 17 for the factor in the heat loss term of Eq. (9). The power of the fuel assembly in grid location C-25 is found as:

P_0 = (Reactor power, 1.25 MW) / (Total number of assemblies in core, 23)
×(Radial power peaking factor, 1.46) = 0.0793 MW

The radial power peaking factor is 1.46 as in the previous test. Tables 6 and 7 show the input data for the model, and the calculated peak plate temperature as a function of time after the temperature rise started. These results are plotted in Fig. 2. Using the Way-Wigner decay heat relation (Table 6), the calculated maximum peak plate temperature is 508 °F compared to the measured value of 487 °F

(253 °C). Using the ANSI/ANS-5.1-1994 decay heat function (Table 7), the calculated maximum peak plate temperature is 527 °F compared to the measured value of 487 °F (253 °C). This over-prediction is considered to be acceptable.

To analyze in-core assemblies, the numerical factor 1.30×10^{-6} in the heat loss term on the right hand side of Eq. (9) should be adjusted for other *similar* reactors based on the heat transfer area of a fuel assembly compared to that in the LITR fuel assembly. The numerical factor is summarized below for *in-core* assemblies of three reactors: (1) Low Intensity Testing Reactor (LITR), (2) Omega West Reactor (OWR), and (3) University of Virginia Reactor (UVAR). The numerical factor given below for the Oak Ridge Research Reactor is for an *out-of-core* hanging fuel assembly.

(Heat Transfer Coefficient)×Area (hA) Used in the One-Node Model for Some Reactors
Using the Way-Wigner Decay Heat Relation

Reactor Name	*hA*, MW/°F	Reference
Oak Ridge Research Reactor	$4.54 \times 10^{-6}\ (a\theta^n + b)$	Ref. 2
Low Intensity Testing Reactor	$1.30 \times 10^{-6}\ (a\theta^n + b)$	Ref. 4
Omega West Reactor	$1.30 \times 10^{-6}\ (a\theta^n + b)$	Ref. 4
University of Virginia Reactor with 12-plate HEU Fuel Assembly	$0.87 \times 10^{-6}\ (a\theta^n + b)$	Ref. 5

The numerical factor 1.30×10^{-6} for the LITR was determined from LOCA tests, as described above. The coefficient 1.30×10^{-6} for the OWR is the same as that for the LITR. The coefficient 0.87×10^{-6} for the UVAR was obtained simply as 2/3 of the coefficient 1.30×10^{-6} used for the OWR because the UVAR has 12 plates per fuel assembly compared to 18 plates per fuel assembly in the OWR and the reactors are otherwise similar.

4 1NODE-LOCA Program Based on the One-Node Model

The *1NODE-LOCA* computer program, written to solve Eq. (8) or (9) numerically, calculates the peak plate surface temperature as function of time after water draining. It also prints the decay power and the numerical integration error in the calculated temperature. The input description for the program is given in Appendix A. The fuel assembly operating power and the duration of reactor operation prior to the scram due to LOCA are key input data to the program. It can calculate the decay heat power due to a single continuous constant-power operation prior to the LOCA, or due to multiple cycles of operation at a specified power with the reactor shutdown for an input time period between two consecutive operations. The absorption correction and the one sigma uncertainty can be applied by user option. Appendix D describes the method of calculating decay heat power due to multiple cycles of reactor operation and shutdown. The program has an option to use one of three decay heat relations: the Way-Wigner relation, the ANSI/ANS-5.1-1979 function for U^{235} thermal fission, and the ANSI/ANS-5.1-1994 function for U^{235} thermal fission.

The fuel assembly heat capacitance should include that of the fuel meat, cladding, and the fuel assembly structure thermally connected (having good thermal conduction paths) to the fuel plates. The heat capacitance should also include that of the metal in a rectangular pitch of the grid plate because the fuel assembly usually remains in-core seated on the grid plate after LOCA.

The time (after reactor scram) to drain the tank water to uncover the fuel is an input to the program. This input is the time interval E to F in Fig. 3 which shows a typical draining of the reactor tank. A typical variation of fuel plate surface temperature with time is shown in Fig. 4 based on the LITR tests. In Figs. 3 and 4, point D marks the time when the reactor was scrammed, and point E marks the time when the reactor power has fallen to the decay power after the prompt drop. The prompt drop is practically instantaneous because it takes only about 1.6 millisecond for a scramming reactivity of -10 dollars (i.e., -0.065) in U^{235}-fueled water reactors. The point F marks the time at which the fuel plate is uncovered after the water drained out of core completely, leaving the plate at the tank water temperature.

Table 1 lists some reactor design features that are important in deciding the applicability of the one-node model to a reactor. The design data for the Oak Ridge Research Reactor (ORR) was taken from references [13, 14, 15]. The design data for the Low Intensity Testing Reactor (LITR) was taken from references [3, 10]. The design data for the University of Virginia Reactor (UVAR) was taken from reference [5].

The numerical factor $4.54x10^{-6}$ or $1.30x10^{-6}$ on the right side of Eq. (8) or (9) will be referred to as factor C which is the most important parameter in this model. Although the factor C was determined semi-empirically for a particular reactor (i.e., the ORR or the LITR), Eq. (8) or (9) has been used to analyze LOCA in some other similar reactors having minor design differences, by adjusting the factor C in a reasonable way to account for the design differences. For example, Eq. (9) was used in the licensing analysis of the reactors LITR and OWR with $C = 1.30x10^{-6}$, and it was used in the licensing analysis of the reactor UVAR with C = 0.87x10-6 (see Table 1).

A brief description of the purpose of each subroutine in the program follows:

(1) MAIN: The main subprogram reads and edits the input data. It then calls the subroutine SOLVE to numerically integrate the model equation, i.e., Eq. (8) or (9).
(2) SOLVE: This subroutine numerically solves the model equation using the 5^{th} order Cash-Karp Runge-Kutta method. By an internal switch, the subroutine can be changed to use the 4^{th} order Runge-Kutta method for testing purposes.
(3) DERIVS: This subroutine calculates the temperature derivative in the model equation.
(4) RKCK: This subroutine solves the model equation using the 5^{th} order Cash-Karp Runge-Kutta method.
(5) RK4: This subroutine solves the model equation using the 4^{th} order Runge-Kutta method. It is not used routinely. It was used only for testing purposes.
(6) PDECAY2: It computes (using the function subprogram PDECAY) the decay power due to multiple reactor operations at the nominal operating power.
(7) PDECAY: This function subprogram computes the decay power per MW of the nominal operating power, due to a single reactor operation of a given duration at constant power. This calculation is done at a specified time after the scram. The subroutine has an option to choose from the ANSI/ANS-5.1 decay heat standards of 1979 and 1994, or the Way-Wigner relation. It has four options for applying the absorption correction, and an option to add or not add the statistical uncertainty to the decay heat.

5 Application of the Model to the OWR

The one-node model (program *1NODE-LOCA*) was used to analyze a loss-of-coolant accident in the Omega West Reactor (OWR) at the Los Alamos National Laboratory (LANL), using the design data reported in reference [4]. The time (after reactor shutdown) to drain the tank water to uncover the fuel was taken from this reference without change so that the current ANL- calculated plate temperatures could be compared with those reported in the reference, the revised safety analysis of 1969. The reactor had operated at 8.0 MW for 120 hours (accumulating fission products) prior to the LOCA. The operating power of the hottest fuel assembly, in core location 4-E, was 4.19% of the reactor operating power. Table 8 shows the input data and the comparison of results.

$$\text{Fuel assembly power} = 8.0 \text{ MW} \times 0.0419 = 0.335 \text{ MW}$$

The ambient air temperature was assumed to be 115 °F to which the fuel assembly transferred its decay heat. The numerical factor in the heat loss rate term in Eq. (9) for the OWR is the same as that for the LITR, i.e., $1.30\text{x}10^{-6}$ MW/°F because the two reactors have similar assemblies and similar air flow paths after fully uncovering the assemblies in a LOCA. Table 1 compares the two fuel assembly designs. This is in agreement with reference [4]. The heat capacitance *MCp* used in Eq. (9) was found from the OWR design data given in reference [4], using a FORTRAN program similar to that given in Appendix C for the LITR. The result is $3.53\text{x}10^{-3}$ MJ/F (see Table 1). This differs from the value reported in reference [4], i.e., $4.20\text{x}10^{-3}$ MJ/F. It is shown below that this difference is not significant. In any case, the value determined by LANL is considered to be more accurate (because some structural aluminum mass might not have been included in the ANL estimation of fuel assembly heat capacitance), and was used here in all the calculations except one.

The ANL calculations using the heat capacitance of reference [4] agree closely (within 5 °F) with the results reported in the reference. This provides a verification of the *1NODE-LOCA* program.

When the ANL estimate of fuel assembly heat capacitance is used (instead of the LANL estimate) in the calculation for core location 4-E (with an uncovering time of 6 minutes after reactor shutdown), the maximum fuel plate temperature increases from 1316 °F to 1355 °F. This difference (39 °F) is considered to be an acceptable uncertainty in LOCA analysis. The difference also shows that the calculated fuel temperature is not very sensitive to this change in the fuel assembly heat capacitance (from $4.20\text{x}10^{-3}$ to $3.53\text{x}10^{-3}$ MJ/°F).

6 Application of the Model to the UVAR

The LOCA analysis of the University of Virginia Research and Training Reactor (UVAR) is interesting because it has used three different standard fuel assembly designs (a 12-plate HEU design in 1970, a 18-plate HEU design in 1984, and a 22-plate LEU design in 1994), and the reactor was licensed by the US Department of Energy and the Nuclear Regulatory Commission each time based on a LOCA analysis performed by the University of Virginia using the one-node model described above [5, 16]. The University used the older Way-Wigner relation to calculate the decay heat for the 12-plate HEU design, and used the ANSI/ANS-5.1 function of 1979 to calculate the decay heat for the 22-plate LEU design. The ANSI/ANS-5.1 function of 1979 has now been replaced by the ANSI/ANS-5.1 function of 1994. Using the program *1NODE-LOCA* described above, loss-of-coolant analyses are performed below for the 12-plate HEU and the 22-plate LEU designs, and the resulting maximum plate surface temperatures are compared with those obtained by the University for licensing.

6.1 HEU Core of 1970 with 12-Plate Standard Fuel Assemblies

The one-node model (program *1NODE-LOCA*) was used to analyze a loss-of-coolant accident in the 12-plate HEU fuel assembly of the UVAR, using the design data reported in reference [5]. The time (after reactor shutdown) to drain the tank water to uncover the fuel was taken from this reference without change so that the current ANL-calculated plate temperatures could be compared with those reported in the reference (and used in 1970 for licensing the reactor). Table 9 shows this comparison. The reactor had operated at 2.0 MW for 120 hours (accumulating fission products) prior to the LOCA. The operating power of the hottest fuel assembly was obtained from the reactor operating power, using a radial power peaking factor of 1.37, as follows:

Fuel assembly power = 2.0 MW × 1.37 / (14 assemblies in the reactor) = 0.196 MW

The ambient air temperature was assumed to be 100 °F to which the fuel assembly transferred its decay heat. The numerical factor (C) in the heat loss rate term in Eq. (9) for the 12-plate fuel assembly was found in reference [5] by reducing its value for the LITR in proportion of the heat transfer area in a fuel assembly. The heat transfer area is proportional to the number of fuel plates per fuel assembly. The UVAR fuel assembly has 12 plates whereas the LITR fuel assembly has 18 plates. The resulting numerical factor is $1.30 \mathrm{x} 10^{-6} \times 12/18 = 0.87 \times 10^{-6}$ MW/°F (see Table 1). The same value is used in the ANL calculation.

The heat capacitance *MCp* used in Eq. (9) was found from the fuel assembly design data given in reference [5], using a FORTRAN program similar to that given in Appendix C for the LITR. The result is $2.52 \mathrm{x} 10^{-3}$ MJ/°F (see Table 1). This differs from the value reported in reference [5], i.e., $3.50 \mathrm{x} 10^{-3}$ MJ/°F, which was found not directly from the UVAR fuel assembly design data, but by making an adjustment to the heat capacitance of the OWR fuel assembly. Therefore, a set of LOCA calculations was done at ANL for the UVAR using each estimate of the heat capacitance. Table 9 shows both sets of results.

As expected the ANL calculations using the heat capacitance estimate of reference [5] agrees closely (within 2 °F) with the results reported in the reference. This provides a verification of the program. The difference between the other set of ANL calculations and the results reported in the reference varies from 27 to 61 °F. These differences are considered to be an acceptable uncertainty in LOCA analysis. The differences also show that the calculated plate temperature is not very sensitive to a 39% increase in fuel assembly heat capacitance ($2.52 \mathrm{x} 10^{-3}$ to $3.50 \mathrm{x} 10^{-3}$ MJ/°F).

6.2 HEU Core of 1984 with 18-Plate Standard Fuel Assemblies

The one-node model (program *1NODE-LOCA*) was used to analyze a loss-of-coolant accident in the 18-plate HEU fuel assembly of the UVAR, using the design data reported in reference [17, 18]. The operating power of the hottest fuel assembly was assumed to be 0.196 MW, equal to that used in section 6.1 for the 12-plate HEU fuel assembly, for comparison. The time (after reactor shutdown) to drain the tank water to uncover the fuel was varied from 10 to 120 minutes, the same as that used in the analysis of the 12-plate HEU fuel assembly. The reactor had operated at 2.0 MW for 120 hours (accumulating fission products) prior to the LOCA. The ambient air temperature was assumed to be 100 °F to which the fuel assembly transferred its decay heat.

The numerical factor (C) in the heat loss rate term in Eq. (9) for the 18-plate fuel assembly is $1.30 \mathrm{x}\, 10^{-6}$ MW/°F, equal to that for the LITR (see Table 1). The heat capacitance *MCp* used in Eq. (9) was found from the fuel assembly design data (summarized in Table 1) using a FORTRAN program similar to that given in Appendix C for the LITR. The result is $3.10 \mathrm{x} 10^{-3}$ MJ/°F.

Table 10 shows the comparison of the maximum plate surface temperatures between the 18-plate and 12-plate fuel assemblies. For a draining time of 10 minutes after scram, the maximum plate surface temperature in the18-plate fuel assembly is 931 °F, which is 252 °F lower than that in the 12-plate fuel assembly.

6.3 LEU Core of 1994 with 22-Plate Standard Fuel Assemblies

The one-node model (program *1NODE-LOCA*) was used to analyze a loss-of-coolant accident in the 22-plate LEU fuel assembly of the UVAR, using the design data reported in Appendix IV of reference [16]. The operating power of the hottest fuel assembly is reported to be 0.209 MW in the reference. The time (after reactor shutdown) to drain the tank water to uncover the fuel was taken from this reference without change so that the current ANL-calculated plate temperatures could be compared with those reported in the reference (and used in 1994 for licensing the reactor). Table 11 shows this comparison. The reactor had operated at 2.0 MW for 120 hours (accumulating fission products) prior to the LOCA. The ambient air temperature was assumed to be 100 °F to which the fuel assembly transferred its decay heat.

The LOCA calculation documented in reference [16] used ANSI/ANS-5.1-1979 decay heat power, with an absorption correction based on $G_{max}(t)$ given in the standard [11] (reproduced here in Appendix D), and with a factor of 1.02 to account for the one-sigma uncertainty in the decay heat data. Equation (9.65) of reference [16] indicates that the one-sigma uncertainty was added twice to the decay heat. The ANL program *1NODE-LOCA* has an option to use the ANSI/ANS-5.1 decay heat of either 1979 or 1994, with the above mentioned corrections. The use of the ANSI/ANS-5.1 decay heat required a recalibration of the heat loss term in the model.

A recalibration of the numerical factor (C) in the heat loss term of Eq. (9), for use with the ANSI/ANS-5.1 decay heat function, was done by ANL to fit the calculated maximum plate surface temperatures to the measured values in the original LITR tests 17 and 18 (see section 3), and the recalibrated value of C was found to be 1.0×10^{-7} MW/°F per plate, i.e., 2.20×10^{-6} MW/°F for the 22-plate LEU fuel assembly of the UVAR (see Table 1). The recalibration is required because Eq. (9) was originally calibrated to the same LITR tests using the Way-Wigner relation for decay heat. Using the ANSI/ANS-5.1 decay heat function in Eq. (9) without recalibration would give higher than the experimentally measured plate temperatures because the ANSI/ANS-5.1 function gives about 25% higher decay heat than that obtained from the Way-Wigner relation for the same reactor operation.

By a somewhat similar recalibration by the University of Virginia in reference [16], the numerical factor C was found to be 0.9×10^{-7} MW/°F per fuel plate (i.e., 1.98×10^{-6} MW/°F for the 22-plate LEU fuel assembly) for use with the ANSI/ANS-5.1 decay heat instead of the Way-Wigner decay heat. This recalibration was done such that the model calculation using the ANSI/ANS-5.1 decay heat safely enveloped some specific transients calculated by the original model in the Omega West Reactor (OWR) using the old value of C (i.e., 1.30×10^{-6} MW/°F for an 18-plate fuel assembly) with the Way-Wigner decay heat. The University did not directly go back to the original LITR tests results. It based its recalibration on some calculated transient results for the OWR, obtained by the original model.

The heat capacitance *MCp* used in Eq. (9) was found by ANL from the UVAR design data given in reference [16] and fuel properties data in reference [9], using a FORTRAN program similar to that given in Appendix C for the LITR. The masses of U_3SO_2 and aluminum, and the heat capacitance of a standard fuel assembly are (see Table 1):

Mass of U_3SI_2 = 1502 g,	Mass of aluminum = 5953 g
$MC_p = 5609 + 2.89\ T$ J/°C,	where T_c = plate temperature in °C
$MC_p = 3088 + 0.892\ T_f$ J/°F,	where T_f = plate temperature in °F

The ANL-calculated U_3SI_2 mass agrees with that calculated by the University of Virginia and given below [16]. The ANL-calculated aluminum mass is more than that reported by the University. The reason may be that the mass of a rectangular pitch of the grid plate is included in the ANL calculation whereas it may not be included in the University calculation.

Mass of U_3SI_2 = 1505 g,	Mass of aluminum = 5195 g
$MC_p = 4933 + 2.54\ T_c$ J/°C,	where T_c = plate temperature in °C
$MC_p = 2716 + 0.784\ T_f$ J/°F,	where T_f = plate temperature in °F

Therefore, a set of LOCA calculations was done at ANL for the UVAR 22-plate LEU core using both input data estimates (found by the University of Virginia and the ANL). The 1979 ANSI/ANS-5.1 decay heat was used with both input data. Table 11 shows both sets of results.

The ANL calculations using all input data preferences of the University of Virginia (including the heat capacitance and the numerical factor C in the heat loss term) give plate surface temperatures 23 to 36 °F lower than the results reported by the University in reference [16]. Only small differences of about 2 °F were expected as in the case of the UVAR 12-plate HEU core (see Table 9). These differences may be due to a duplicate addition (overestimation) of one-sigma uncertainty to the decay heat in reference [16], as pointed out above. For the smallest draining time (18 minutes), the ANL-calculated maximum plate surface temperature is 949 °F (509 °C) compared to 975 °F (524 °C) reported in the reference. However, differences of this magnitude represent an acceptable uncertainty in LOCA analyses, and this comparison provides a verification of the implementation of the ANSI/ANS-5.1-1979 decay heat in the *1NODE-LOCA* program.

The maximum plate temperature (874 °F) calculated using the ANL input data for the same draining time is 75 °F lower than that calculated (949 °F) using the University of Virginia input data due to two main reasons: input differences in MC_p and in the recalibrated factor C (1.0×10^{-7} MW/°F per plate by ANL recalibration versus 0.9×10^{-7} MW/°F by the University recalibration). By making each input change separately and running the program, it was found that the former alone causes a difference of 27 °F (from 949 to 922 °F), and the latter causes a difference of 48 °F (from 922 to 874 °F). The former temperature change (27 °F) shows that the maximum plate surface temperature is not very sensitive to the 14% increase in fuel assembly heat capacitance (3.02×10^{-3} to 3.44×10^{-3} MJ/°F).

7 Application of the Model to the HEU and LEU Cores of the RPI

The one-node model (program *1NODE-LOCA*) was used to analyze a loss-of-coolant accident in the Portuguese Research Reactor (RPI) using the design data reported in reference [19]. The US Nuclear Regulatory Commission has accepted the use of this model for LOCA analysis in the licensing of several research reactors, e.g., the University of Virginia Research Reactor (UVAR) HEU core with a 12-plate standard fuel assembly in 1970, then the UVAR HEU core using a 18-plate standard fuel assembly in 1984, and again the UVAR LEU core designed with a 22-plate standard fuel assembly (U_3Si_2 fuel) in 1994. Both the highly enriched (HEU) core and low-enriched-uranium (LEU) core were analyzed. The following assumptions were made in this analysis.

1. Just before the hypothetical loss-of-coolant accident, the reactor is assumed to have operated at the nominal power of 1 MW according to the schedule for 10 weeks, 5 days per week, 14 hours per day (total 68 days).

2. At the end this operation, the 12-inch diameter cold leg of the primary circuit is assumed to rupture just outside the pool wall. The whole diameter of the broken cold leg pipe becomes

available for unobstructed discharge. The hydraulic resistance of the diffuser is ignored in the discharge calculation from the cold leg. The whole diameter of the hot leg also becomes available for discharge with hydraulic resistance of all the components in the primary circuit. The primary pump is assumed to stop at time of rupture. This is a very extreme scenario at the RPI.

3. The scram caused by the fall of water level in the pool is assumed to occur as soon as the water level falls 0.133 m below the highest level to which the pool is filled. Figure 5 shows this water level (reactor trip level) in relation to the vertical positions of the core and the rupture. This trip level is 6.79 m above the top of the fuel.

4. Following the scram the reactor power falls suddenly to about 7% of the nominal operating value of 1 MW, and then decreases according to the decay heat curve determined by the operation history of the core. The decay heat power is calculated using the current ANSI/ANS-5.1 standard of 1994 for the RPI scheduled operation described above in assumption 1. The absorption correction to the decay heat power was done conservatively using the $G_{max}(t)$ given in the standard [12], and reproduced here in Appendix D. One-sigma uncertainty was also applied. The calculated decay heat power is given in Table 12 and plotted in Fig. 6. The same decay heat power was used for both the HEU core and LEU core.

5. The falling water removes the decay heat as long as the fuel plates are covered. When the water level in the pool falls below the core and the grid plate, the uncovered fuel plates are left at the temperature of the pool water that passed over the plates last. Due to the location of the rupture in the section of the pool which does not have the reactor, the operator would try to keep the reactor covered under water (for a longer time) by placing the gate in the divider wall between the two sections of the pool. To be conservative it is assumed that the gate is *not* placed in the divider.

6. With the gate not placed in the divider (portioning wall), Fig. 7 shows the water free surface area in the pool used in calculating the pool draining time. The time after scram for the water level to fall below the core and grid plate, i.e., the draining time, is calculated in Appendix E for the RPI pool. With the primary pump in the hot leg stopped before or at the time of scram, the draining time (after scram) of the combined pool is found to be about 707 seconds (11.8 minutes).

7. After the end of the draining time, the fuel plates are left at the pool temperature by the water that drained last. The uncovered plates start to heat up from an initial temperature equal to the pool temperature (or the ambient air temperature). The heat up occurs due to the decay heat at the time because the water cover (the heat sink) is lost, and the heat loss rate from the fuel assemblies by conduction to the aluminum structure in contact and by natural convection to the surrounding air is initially not enough to remove all the decay heat. However, as the plate surface temperatures increase, the combined effect of thermal conduction, convection and radiation to the surrounding structure and air increases, and the heat loss rate of the fuel assembly increases and after some time equals the decay heat power. At this time the fuel plate surface temperature reaches its maximum. After this time the plate surface temperature begins to fall slowly due to the ever-decreasing decay heat power.

8. The time-dependence of the axial peak plate surface temperature in the RPI fuel assembly having the highest decay heat power is calculated using the *1NODE-LOCA* program developed and validated to research reactor LOCA tests. Since the complexity of heat transfer in LOCA

was recognized since the earliest history of nuclear reactor, several unprotected LOCA tests were done on two MTR-type research reactors, similar to the RPI, and the measured axial temperature distribution of fuel plates were used to develop the validated model used for calculating the time dependence of the axial peak plate surface temperature. The US Department of Energy and the Nuclear Regulatory Commission has accepted the use of this LOCA model for licensing several research reactors over the last 50 years, e.g., the Omega West Reactor (OWR) at the Los Alamos Scientific Laboratory for operation at 8 MW in May 1966, the University of Virginia Research Reactor (UVAR) HEU core with a 12-plate standard fuel assembly in 1970, the UVAR HEU core using a 18-plate standard fuel assembly in 1984, and again the UVAR LEU core designed with a 22-plate standard fuel assembly (U_3Si_2 fuel) in 1994.

The highest power standard fuel assembly and the highest power control fuel assembly were analyzed in the RPI HEU and LEU cores. The fuel assembly having the highest operating power is found from the calculated power distribution, i.e., power per fuel plate in each assembly of the core [20]. Among standard fuel assemblies, the assembly N9 has the highest power (0.1187 MW) in the HEU core, and the same assembly has the highest power (0.1129 MW) in the LEU core. These values occur in a depleted core having 8 standard and 5 control fuel assemblies (total 194 fuel plates), with control rod C3 out 10% more. The radial (plate-to-plate) power factor of the assembly N9 is 1.279 in the HEU core, and 1.217 in the LEU core. Among control fuel assemblies, the assembly C3 has the highest power (0.0815 MW) in the HEU core, and the same assembly has the highest power (0.0823 MW) in the LEU core. These values occur in the fresh core having 7 standard and 5 control fuel assemblies (total 176 fuel plates), with all rods out. The radial (plate-to-plate) power factor of the assembly C3 is 1.434 in the HEU core, and 1.448 in the LEU core. The above HEU and LEU N9 and C3 assembly powers were determined as follows:

<u>For HEU Core</u>

Assembly N9 power = 1.0 MW×(18 plates in a fuel assembly)/(194 plates in reactor)×1.279
= 0.1187 MW

Assembly C3 power = 1.0 MW×(10 plates in a fuel assembly)/(176 plates in reactor)×1.434
= 0.0815 MW

<u>For LEU Core</u>

Assembly N9 power = 1.0 MW×(18 plates in a fuel assembly)/(194 plates in reactor)×1.217
= 0.1129 MW

Assembly C3 power = 1.0 MW×(10 plates in a fuel assembly)/(176 plates in reactor)×1.448
= 0.0823 MW

The ambient air temperature was assumed to be 100 °F to which the fuel assembly transfers its decay heat. The numerical factor in the heat loss rate term in Eq. (10) for the RPI standard assembly is the same as that for the LITR, i.e., $1.80x10^{-6}$ MW/°F, because the two reactors have similar 18-fuel-plate assemblies. Table 1 compares the two standard fuel assembly designs. The numerical factor in the heat loss rate term for the 10-fuel-plate control assembly is reduced (from its value for the LITR) in the ratio of the heat transfer area in the control assembly to the area in the standard assembly, i.e., in the ratio of the number of fuel plates in each. Thus the numerical factor for the control assembly is 10/18 times $1.80x10^{-6}$, i.e., $1.00x10^{-6}$ MW/°F.

The heat capacitance *MCp* used in Eq. (10) was found from the RPI design data given in reference [19] (summarized in Table 1), using four FORTRAN programs given in Appendices F and G for the HEU and LEU cores. The heat capacitance includes the masses of aluminum, UAl_3, UAl_4, and U_3Si_2 in all the fuel plates of an assembly, the two side plates, the lower assembly nozzle, and a rectangular pitch of the grid plate. It also includes the two guide plates and the shock absorber in the case of a control assembly. The results are given in Table 13. In the HEU core, the heat capacitance is 3.04x10^{-3} MJ/°F for a standard assembly and 3.15x10^{-3} MJ/°F for a control assembly. In the LEU core, the heat capacitance is 3.12x10^{-3} MJ/°F for a standard assembly and 3.20x10^{-3} MJ/°F for a control assembly.

This analysis of a fully uncovered LOCA in the RPI is conservative because the reactor is located in a big room with plenty of air and its tank is *open* at the top whereas the LOCA tests in the LITR (which form the basis of the model) were performed with the tank closed at the top and bottom, as described in section 3. The tank of the LITR had a manhole at the top and a six-inch draining valve at the bottom which were closed during the tests. The cooling effect of additional air circulation due to opening the manhole and the valve *together* (140 minutes after reactor shutdown) after the fuel plates had reached their maximum temperatures in the tests is also described in section 3. This LOCA analysis of the RPI is conservative because the cooling effect of additional air circulation due to having an open pool in a big room rather than a closed tank is not included in the model.

Table 14 shows the input data and the maximum fuel plate surface temperatures varying the time (after reactor scram) to drain the tank to uncover the fuel from 6 minutes to 1 hour. The results for the assemblies N9 and C3 of the HEU core for 5 different draining times (6, 14, 20, 40 and 60 minutes) are plotted in Figs. 8 and 9. A similar set of curves for the assemblies N9 and C3 of the LEU core are shown in Figs. 10 and 11. It turns out that the control fuel assembly C3 reaches higher temperatures than the standard fuel assembly N9.

As summarized from Table 14, the calculated results for the maximum fuel plate surface temperatures are tabulated below for core uncovering times of 14 minutes after reactor shutdown estimated by the RPI staff and for 11.8 minutes after reactor shutdown estimated by ANL for the limiting standard and control fuel assemblies in the HEU and LEU cores. Since these temperatures are far below the safety limit of 530 °C, there would be no melting of the cladding and no release of radioactivity into the air in the reactor building.

	Time to Uncover Core, min [a]	Standard Fuel Assembly N9, °C		Control Fuel Assembly C3, °C	
		HEU	LEU	HEU	LEU
RPI-staff Estimate	14	362	348	372	373
ANL Estimate	11.8	367	353	377	378

Note a. After reactor shutdown.

<u>Reactor Power Safety Margin in LOCA</u>: The reactor power safety margin in LOCA for the RPI LEU core was calculated to be 1.64 (for 14-minute draining) by running the program for operating powers higher than the nominal, but still keeping the maximum plate temperature in the control assembly C3 below the safety limit of 530 °C. If the LEU fuel core were operated at 1.64 MW following the usual schedule of 14 hours per day, 5 days per week for 10 weeks, then it will reach a maximum plate temperature in LOCA of 529 °C (984 °F).

Some aspects of the results given in Table 14 are discussed below, such as the effects of fuel and cladding thermal conductivities, uncertainties in the decay heat, and the initial fuel plate temperature just after draining.

<u>Discussion of the Results</u>: The maximum plate temperatures reported in Table 14 for the standard fuel assembly N9 in the LEU and HEU cores were all calculated by solving the same equation, i.e., Eq. (10) with N_p equal to 18 (the number of plates in the assembly). The calculated maximum plate

temperatures for the LEU standard fuel assembly N9 are 10 °C lower than those for the HEU standard fuel assembly N9 because of two data that matter in the model, i.e., the power of the fuel assembly and its heat capacitance. Both are adverse for the HEU fuel assembly N9. The operating power of the LEU fuel assembly N9 is lower than the power of the HEU fuel assembly (i.e., 0.1129 MW vs. 0.1187 MW), and the heat capacitance of the LEU fuel assembly is higher than that of the HEU fuel assembly (i.e., $3.12x\ 10^{-3}$ MJ/°F vs. $3.04x\ 10^{-3}$ MJ/°F). The calculation of heat capacitance of each assembly is shown in Table 13. The relative decay power variation with time after scram and all other inputs to the model are identical for both fuel assembly types. A larger heat capacity causes the temperature to increase more slowly so that the maximum plate temperature is *reached later*. When the maximum temperature is reached, the heat removal rate and the decay power generation are equal. Delaying the maximum temperature lowers the decay power at the maximum and thereby lowers the surface temperature needed to remove this decreased power. Similarly, the lower operating power of the LEU assembly vis-à-vis the HEU assembly also leads to a lower maximum temperature.

The model calculates the plate *surface* temperature. When the fuel assembly has reached its maximum surface temperature and a balance is established between heat generation and heat removal, almost all the decay heat is removed by air convection from the plate surface. The meat thermal conductivity does affect the temperature drop across the plate thickness. But this drop is very small when the fuel assembly has reached its maximum temperature. The temperature drop from the meat center to the cladding surface (ΔT_1) was estimated using Eq. (11) to be a few thousandths of 1 °C in the HEU and LEU fuel assemblies N9 and C3 (see Appendix H), thus making the thermal conductivity advantage of the HEU core less important.

$$\Delta T_1 = \frac{P_d}{2\,N_p\,L_f\,w_f}\left(\frac{t_f}{4K_f} + \frac{t_c}{K_c}\right) \tag{11}$$

The *increased* peaking of axial temperature shape due to the lower meat and cladding thermal conductivities in the RPI LEU core, compared to those in the LITR core whose LOCA tests form the basis of the model, is estimated in Appendix H to be a correction of +8 °C to the maximum plate temperatures of the assemblies N9 and C3 given in Table 14.

In calculating the maximum plate temperatures given in Table 14, the absorption correction to the decay heat was made using the maximum factor $G_{max}(t)$ given in the ANSI/ANS-5.1-1994 standard. Second, the decay heat was increased by 2% to add the one sigma uncertainty given in the standard. Third, the decay heat calculation according to the standard depends on the value of E_r, the total recoverable energy per fission of U^{235}, as shown by Eq. (D.6) in Appendix D. An accurate value of E_r (average of 4 evaluated data) given in the standard is 202.2 MeV/fission. However, a conservative value of 200 MeV/fission was used in the calculations resulting in Table 14. This increases the decay heat power by about 1%. If the absorption correction is made using the alternative factor G(t) given in the standard, or the one sigma uncertainty is not added to the decay heat, or E_r is set to 202.2 MeV/fission, then the maximum plate temperatures would be lower than those given in Table 14. The combined effect of these three assumptions was found by running the program to be a decrease of 21 to 23 °C in the maximum plate temperatures of the assemblies N9 and C3 in *either core* for the 14-minite draining case.

In calculating the maximum plate temperatures given in Table 14, the initial plate temperature after draining was set equal to 100 °F (38 °C) that is the temperature of the water in the pool. This is the usual method. If the initial plate temperature were set to a much higher value, say, it were increased by 112 °F to the water vapor temperature of 212 °F (100 °C), it will not result in an increase of 112

°F in the maximum plate temperature. The increase will be much smaller because most of the initial energy in the plates is carried away by air convection and other heat transfer modes during the time interval (of about 45 minutes for the standard fuel assembly N9, or 75 minutes for the control fuel assembly C3) between the initial and the maximum plate temperatures. By running the program, the effect of this change in the initial plate temperature was found to be an increase of 8 to 10 °C in the maximum plate temperatures of the fuel assemblies N9 and C3 in *either core* over the temperatures given in Table 14 for the 14-minute draining time. The increase is only 4 to 6 °C for the 60-minute draining time.

8 Conclusion

A computer program, *1NODE-LOCA*, has been developed for calculating the maximum fuel plate surface temperature in a loss-of-coolant accident (LOCA) in research and test reactors that are similar in design to the Oak Ridge Research Reactor (ORR) or the Low Intensity Testing Reactor (LITR). The program has been validated by analyzing several LOCA experiments in two earlier research reactors, and by reproducing earlier LOCA analyses done for licensing purposes in two other research reactors. Both unprotected and protected accidents can be analyzed using the program. The program was used to calculate the maximum fuel plate surface temperature during a LOCA in the Portuguese Research Reactor (RPI) HEU and LEU cores. Two assemblies, i.e., the highest power standard assembly N9 and the highest power control assembly C3, were analyzed in each RPI core. The maximum plate temperature in the control assembly C3 was found to be higher than that in the standard assembly N9. In the control assembly C3, the maximum plate temperatures are 372 °C and 373 °C in the HEU and LEU cores for a post-scram draining time of 14 minutes to uncover the fuel (see Table 14).

9 Suggestion for Future Work

The NATCON code analyzes the natural circulation of liquid water in plate-type research and test reactors [21]. By adding to this code an option to calculate the natural circulation of air, it will become a companion model for analyzing fully uncovered LOCA. The NATCON code should be improved to use air properties as well as water properties.

Nomenclature

A	= heat transfer area in a fuel assembly, ft^2
C_p	= Specific heat of the fuel assembly, MJ/kg-°F
C	= Numerical factor in the heat loss term of Eq. (8), (9) or (10), MW/°F
h	= heat transfer coefficient from a fuel assembly to ambient air, Btu/hr-ft^2-°F
K_f	= thermal conductivity of the fuel meat, W/m-°C
K_c	= thermal conductivity of the cladding, W/m-°C
L_p	= height of a fuel plate, m
L_f	= axial length of fuel meat in a fuel plate, m
M	= mass of the fuel assembly, kg
N_p	= number of fuel plates in the fuel assembly that is analyzed
P'	= operating power of the reactor, MW
P_0	= operating power of the fuel assembly, MW
P	= decay power of the fuel assembly, MW
P_d	= decay power of the fuel assembly, W
q	= heat transfer rate from the fuel assembly, Btu/hr
t	= decay time measured from reactor shutdown, sec

t_f = thickness of fuel meat in a fuel plate, m
t_c = thickness of a cladding in a fuel plate, m
t_s = thickness of a side plate, m
T = reactor operating time before shutdown, sec
T_a = ambient temperature, °F (It was 90 °F in Wett's experiment in the ORNL hot cell)
$T_{s,peak}$ = axial peak fuel plate surface temperature, °F
W_i = mass of U^{235} in the ith. fuel assembly, gm
W_c = mass of U^{235} in the reactor core, gm
w_p = width of a fuel plate, m
w_f = width of fuel meat in a fuel plate, m
w_s = width of a side plate, m
θ = $T_{s,peak}$ - T_a = difference between the axial peak fuel plate surface temperature and the ambient temperature, °F
$\overline{\phi_i}$ = average neutron flux in the ith. fuel assembly, neutrons/cm^2-sec
$\overline{\phi_c}$ = average neutron flux in reactor core, neutrons/cm^2-sec

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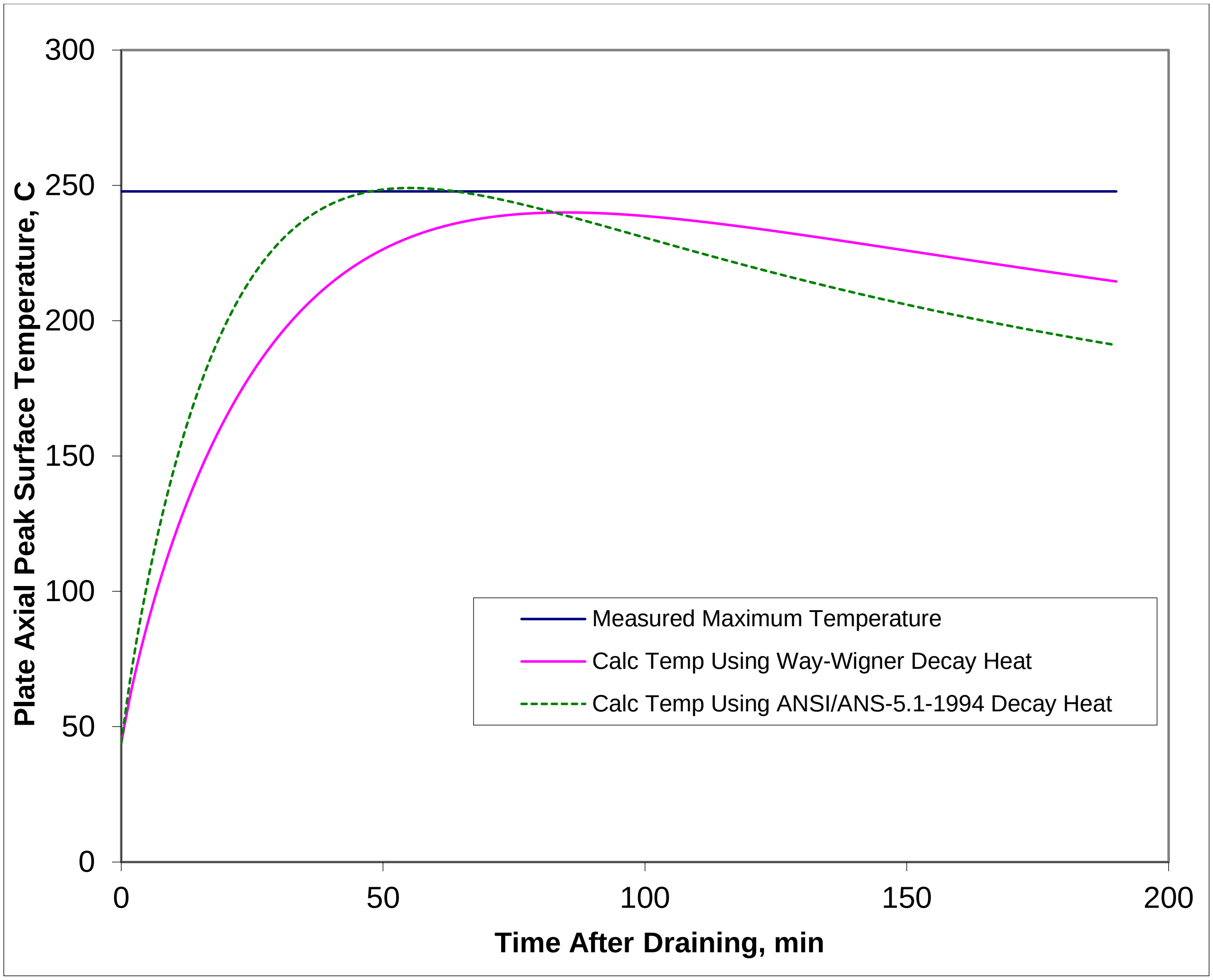


Figure 1. Plate Peak Surface Temperature in the Low Intensity Testing Reactor (LITR) Test 17 (Absorption correction applied using factor G(t) to the ANSI/ANS-5.1 decay heat)

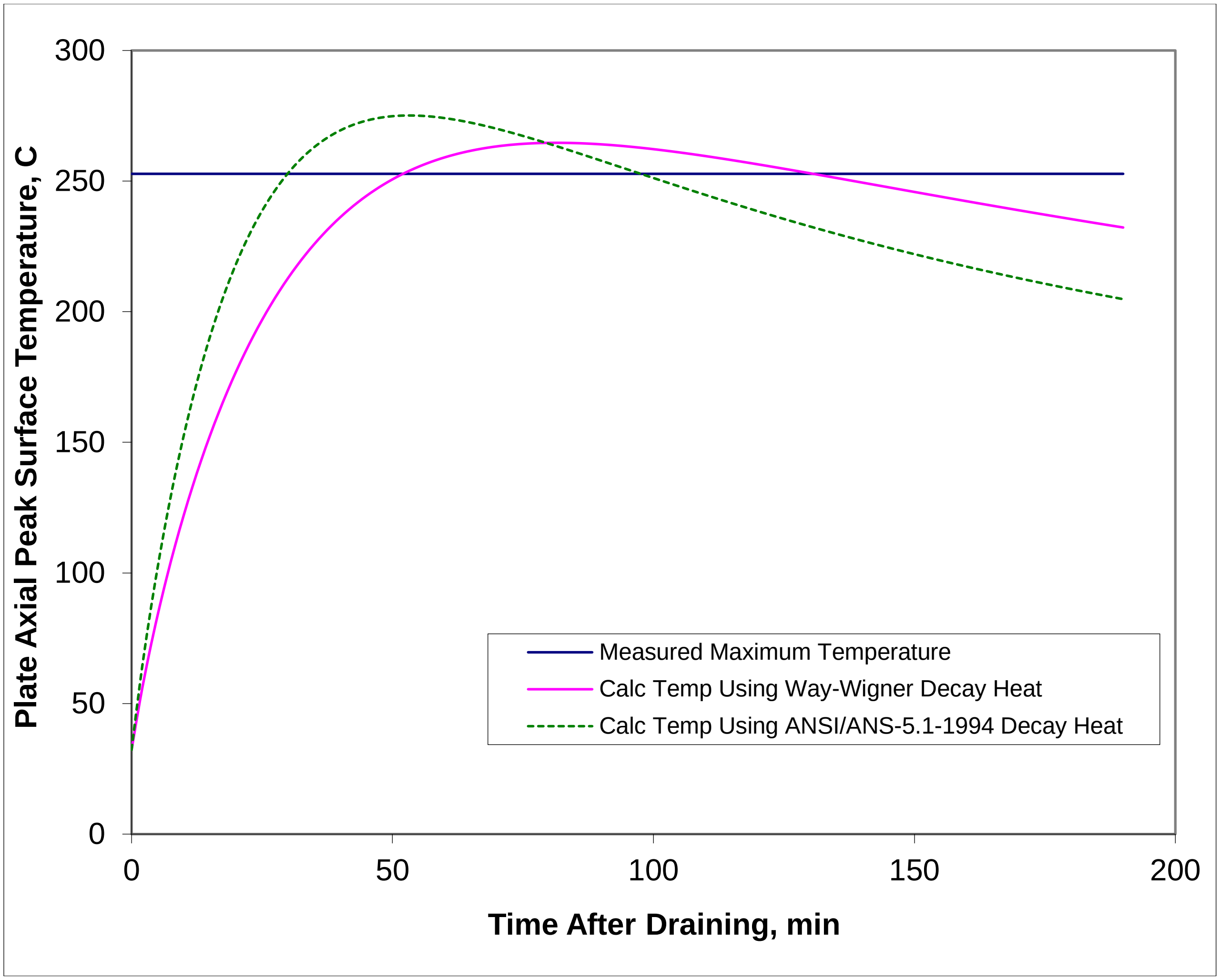


Figure 2. Plate Peak Surface Temperature in the Low Intensity Testing Reactor (LITR) Test 18 (Absorption correction applied using factor G(t) to the ANSI/ANS-5.1 decay heat)

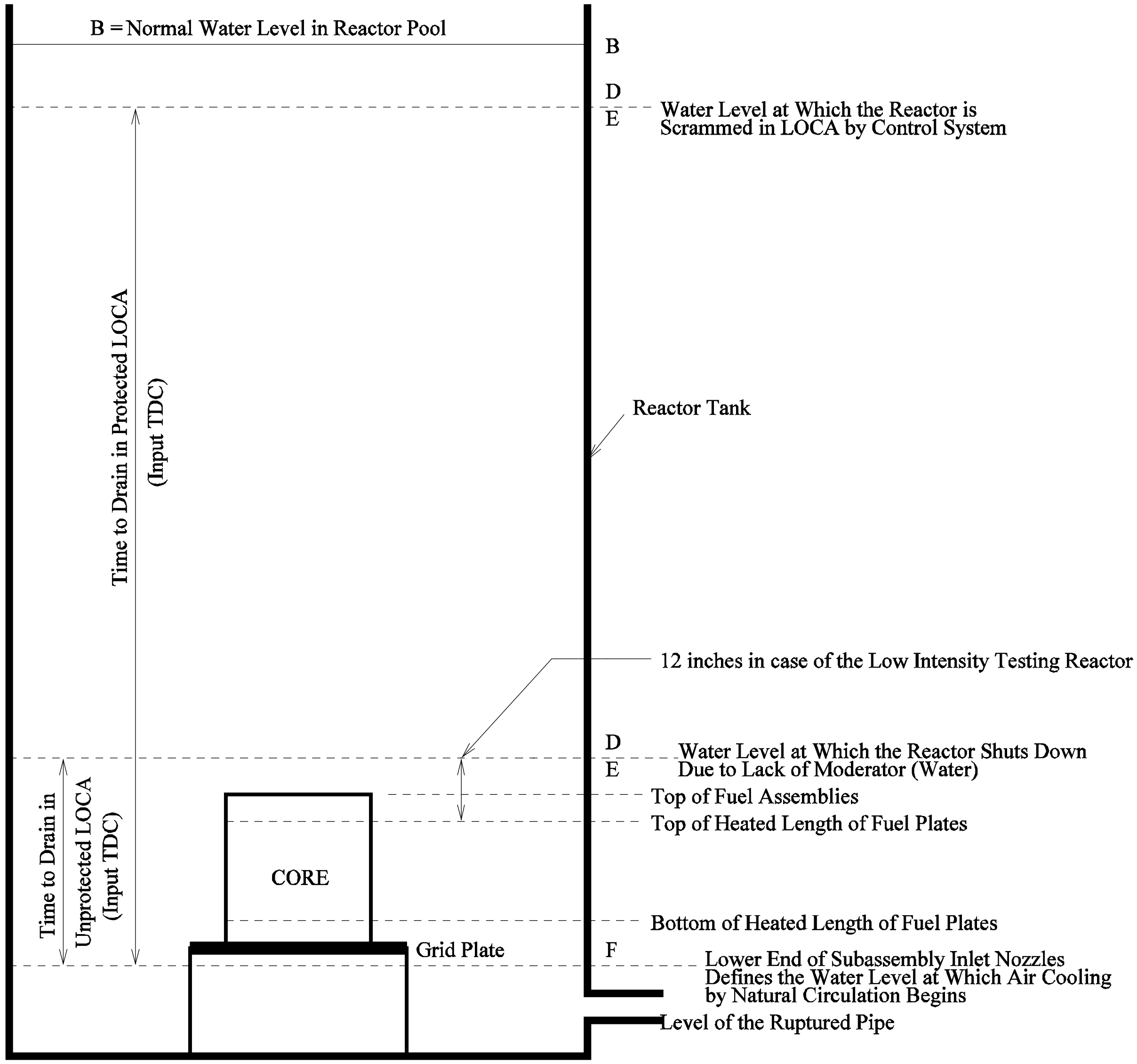
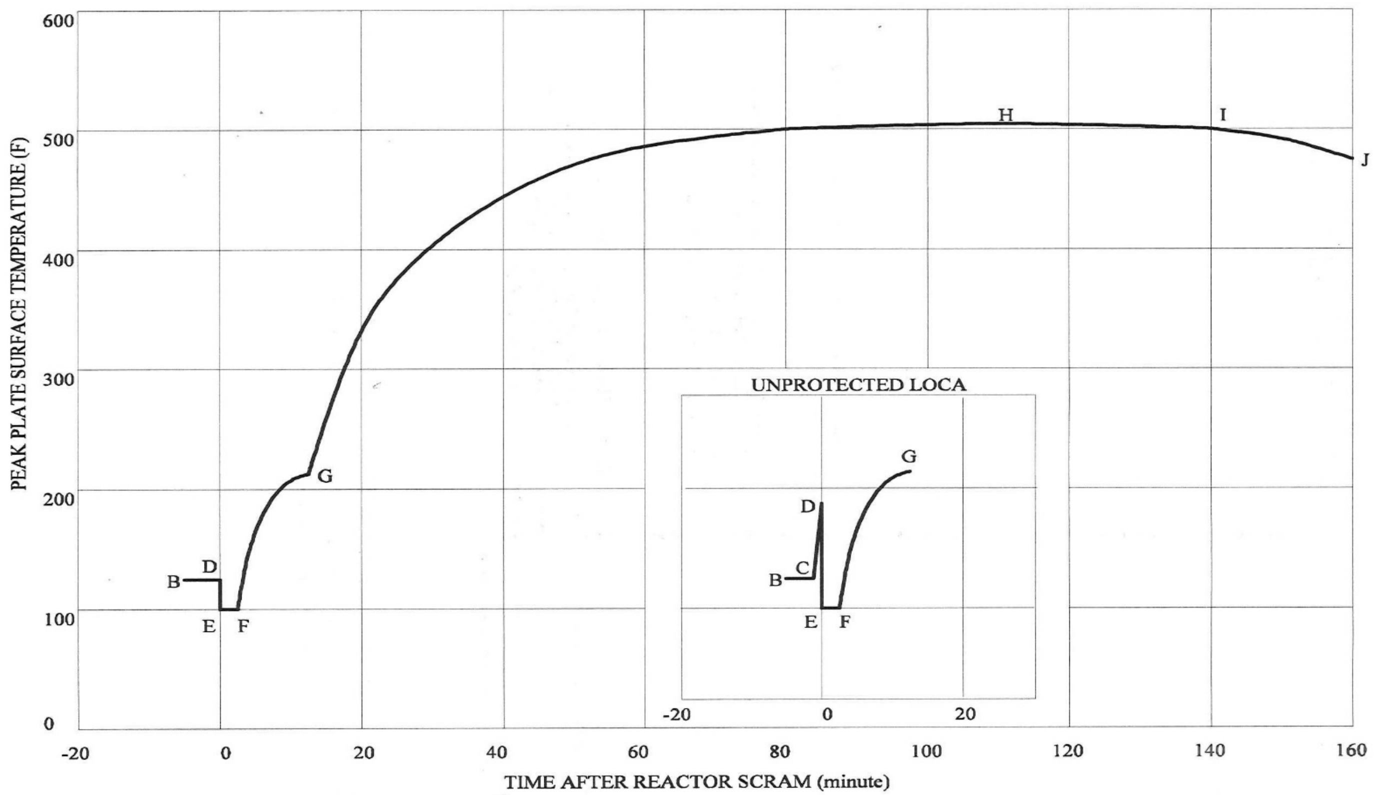


Figure 3. Diagram to Define the Time (Program Input TDC) After Shutdown to Drain the Reactor Tank to Fully Uncover the Fuel in LOCA (Symbols B to F are Also Marked in the Fuel Plate Temperature Variation Shown in Fig. 4)



B = Pipe Rupture With the Reactor Operating at Full Power
C = Start of Temperature Spike Due to Reduced Water Flow Through Core While the Reactor is Operating at Full Power
D = Reactor Shutdown by Moderator Loss in Unprotected LOCA, or Reactor Scrammed in Protected LOCA
E = Reactor at Decay Power and Water Draining Out of Core Which Cools the Fuel Plate to the Pool Water Temperature
F = Water Drained Out of Core Completely, Leaving the Fuel Plate at at the Pool Water Temperature
G = Evaporation of the Water Film Left on the Fuel Plate is Complete
H = Maximum Peak Plate Surface Temperature
I = Time of Starting a Chimney Effect by Simultaneously Opening the 6-inch Valve at the Bottom and the Manhole at the Top of the LITR Tank
J = Plate Temperature Drop Due to Additional Cooling by the Chimney Effect

Figure 4. Fuel Plate Surface Temperature in a Typical Protected Loss-of-Coolant Test in LITR

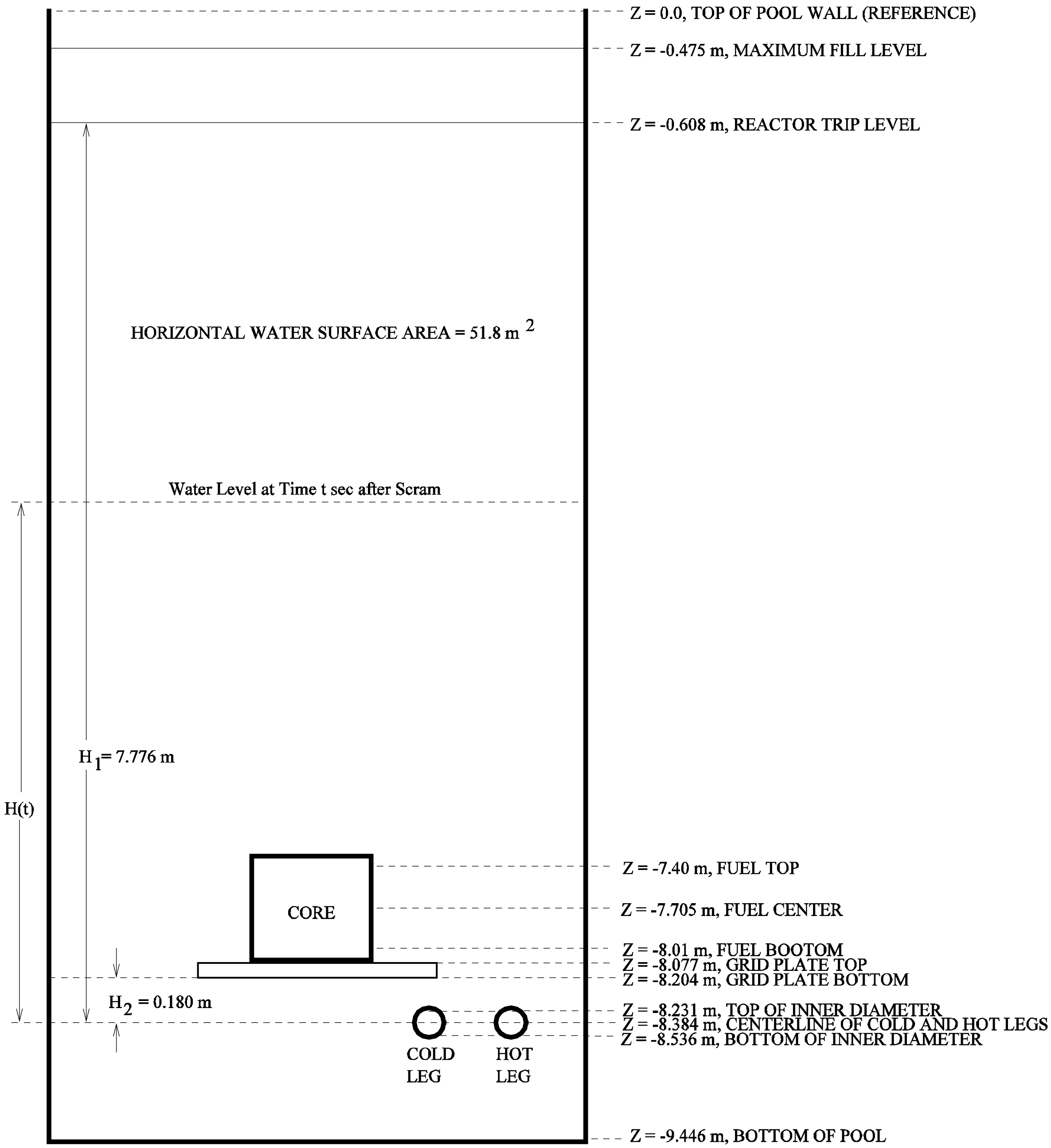
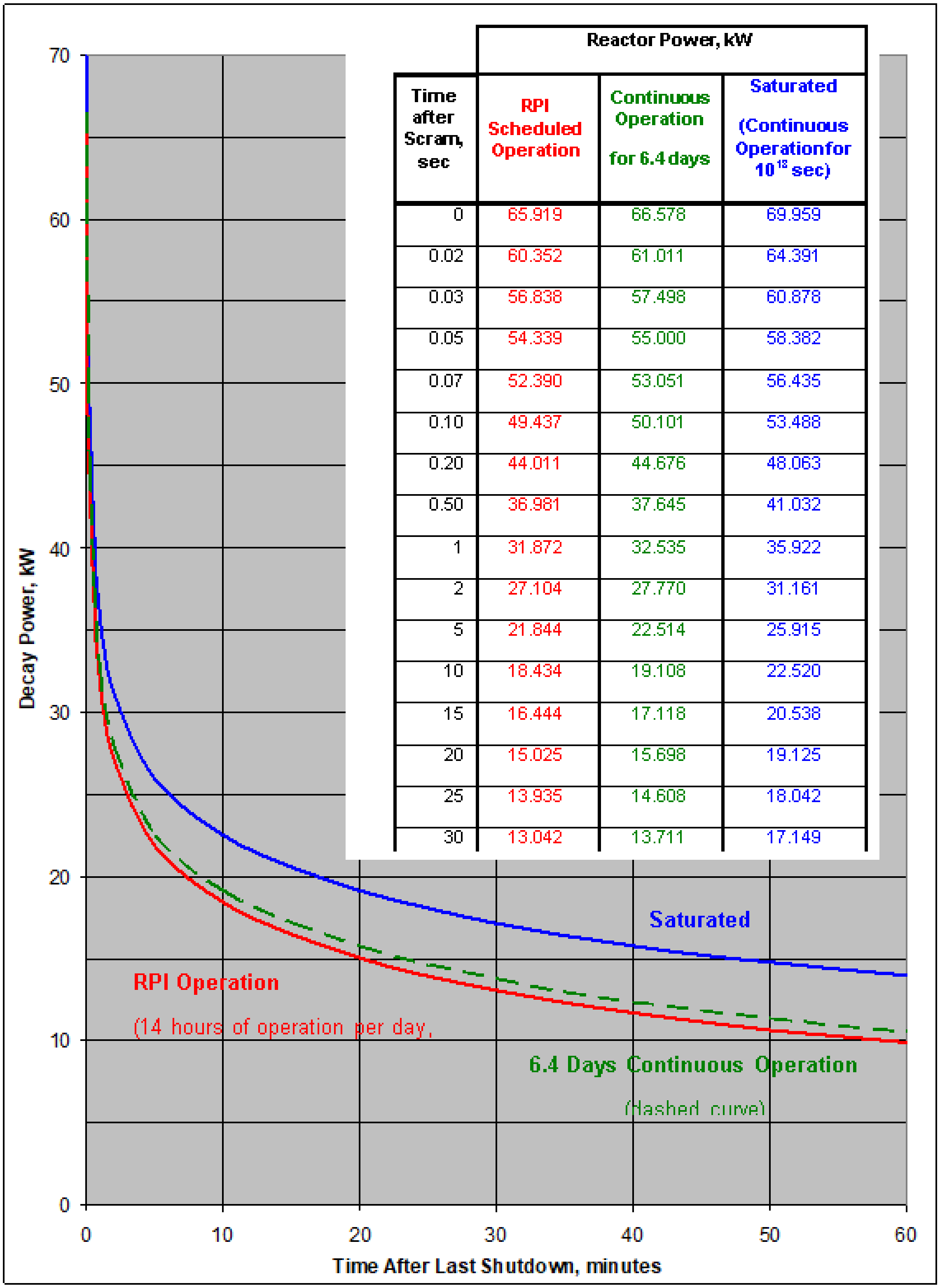


Figure 5. Diagram Showing the Vertical Positions of Reactor Core and Pipe Rupture Location in the RPI Pool (Not Drawn to Scale)



Time after Scram, sec	Reactor Power, kW: RPI Scheduled Operation	Continuous Operation for 6.4 days	Saturated (Continuous Operation for 10^{13} sec)
0	65.919	66.578	69.959
0.02	60.352	61.011	64.391
0.03	56.838	57.498	60.878
0.05	54.339	55.000	58.382
0.07	52.390	53.051	56.435
0.10	49.437	50.101	53.488
0.20	44.011	44.676	48.063
0.50	36.981	37.645	41.032
1	31.872	32.535	35.922
2	27.104	27.770	31.161
5	21.844	22.514	25.915
10	18.434	19.108	22.520
15	16.444	17.118	20.538
20	15.025	15.698	19.125
25	13.935	14.608	18.042
30	13.042	13.711	17.149

Figure 6. Decay Heat Power of RPI (ANSI/ANS-5.1 of 1994, Including Absorption Correction and One-Sigma Uncertainty

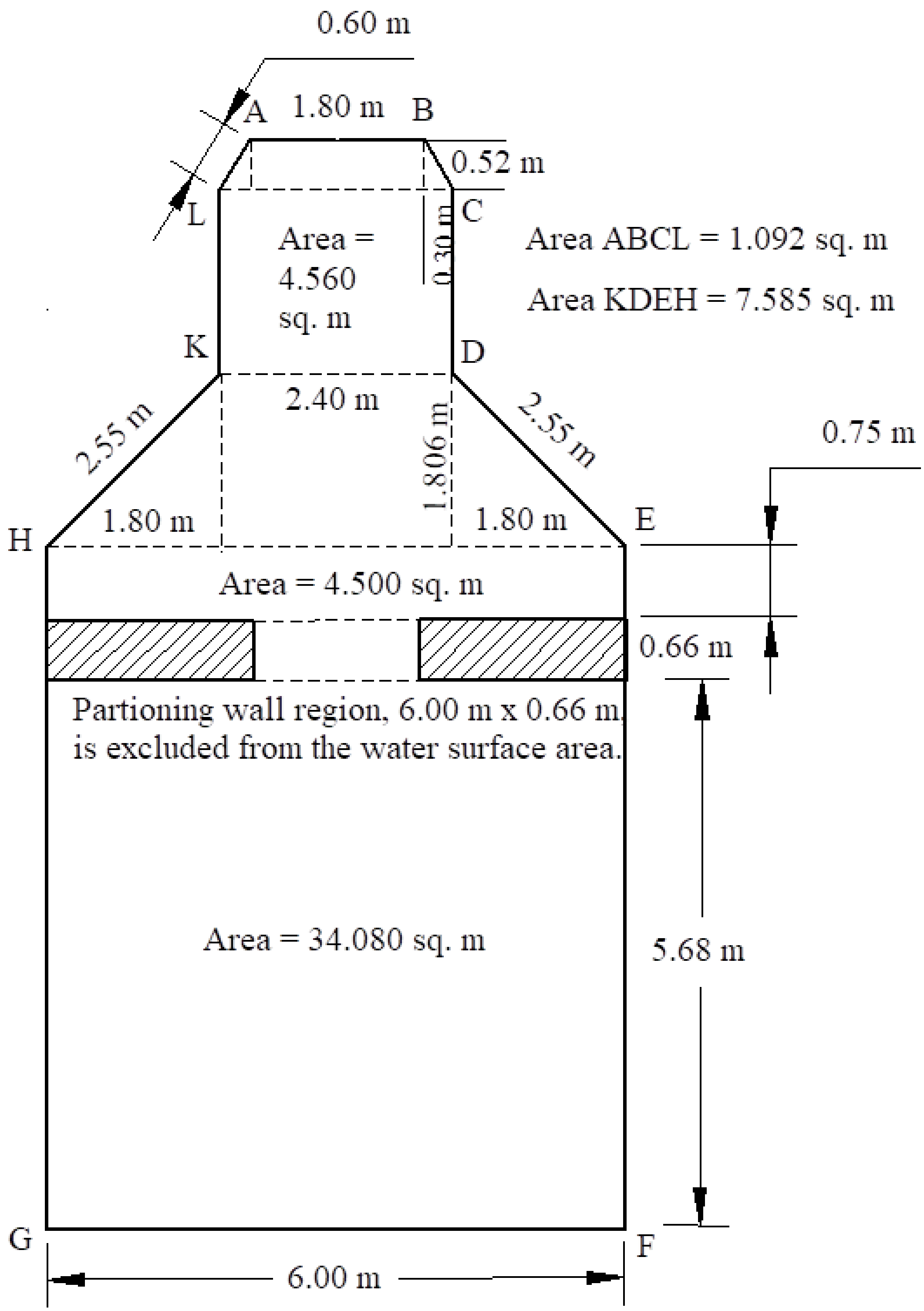


Figure 7. Diagram Showing the Cross Sectional Area of Water in the RPI Pool

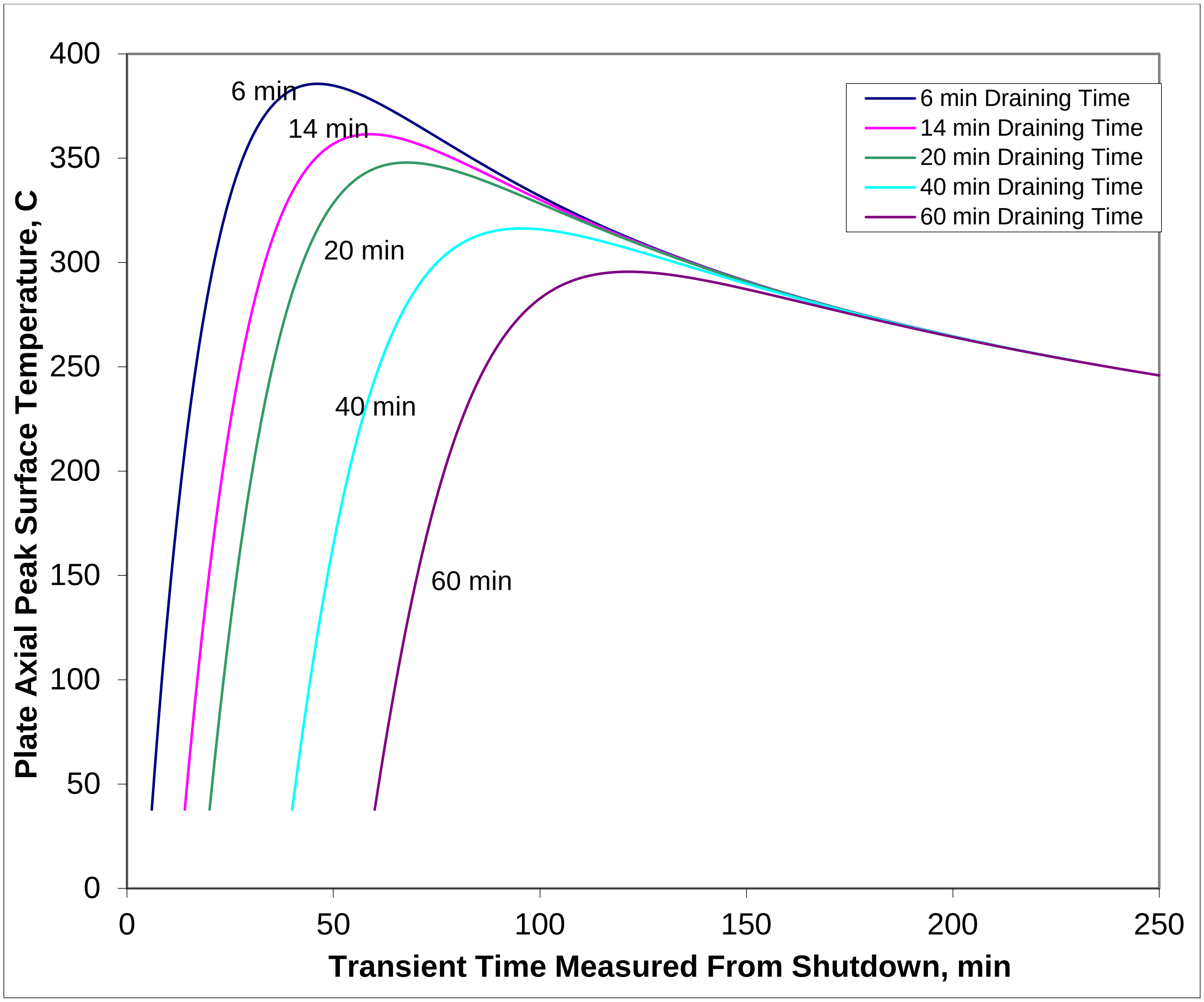


Figure 8. Plate Surface Temperature during LOCA Calculated Using the One-Node Model in the Highest Power Standard Fuel Assembly N9 of the RPI HEU Core (pre-LOCA reactor operation at 1.0 MW for 10 weeks, 5 days a week, 14 hours/day)

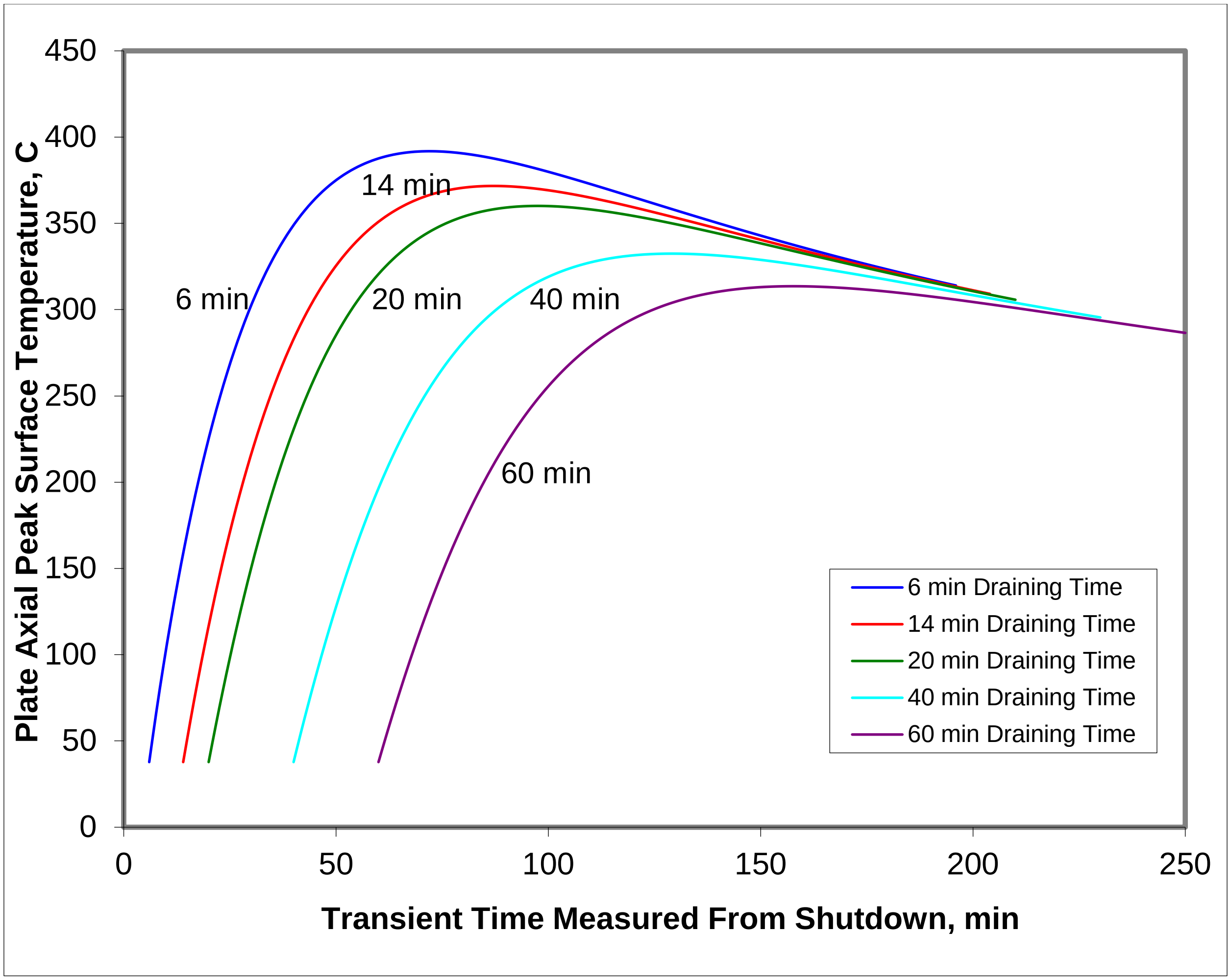


Figure 9. Plate Surface Temperature during LOCA Calculated Using the One-Node Model in the Highest Power Control Fuel Assembly C3 of the RPI HEU Core (pre-LOCA reactor operation at 1.0 MW for 10 weeks, 5 days a week, 14 hours/day)

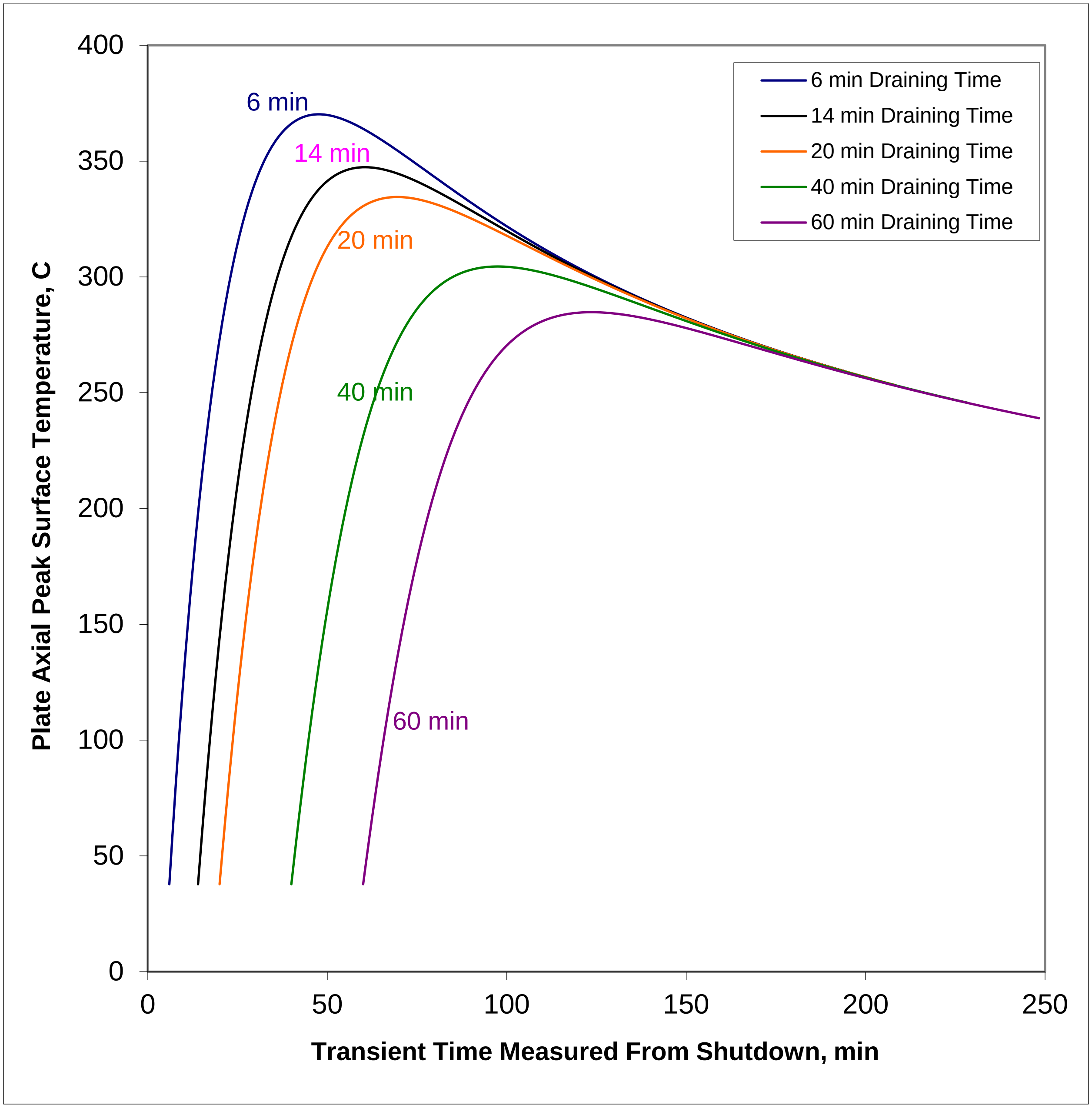


Figure 10. Plate Surface Temperature during LOCA Calculated Using the One-Node Model in the Highest Power Standard Fuel Assembly N9 of the RPI LEU Core (pre-LOCA reactor operation at 1.0 MW for 10 weeks, 5 days a week, 14 hours/day)

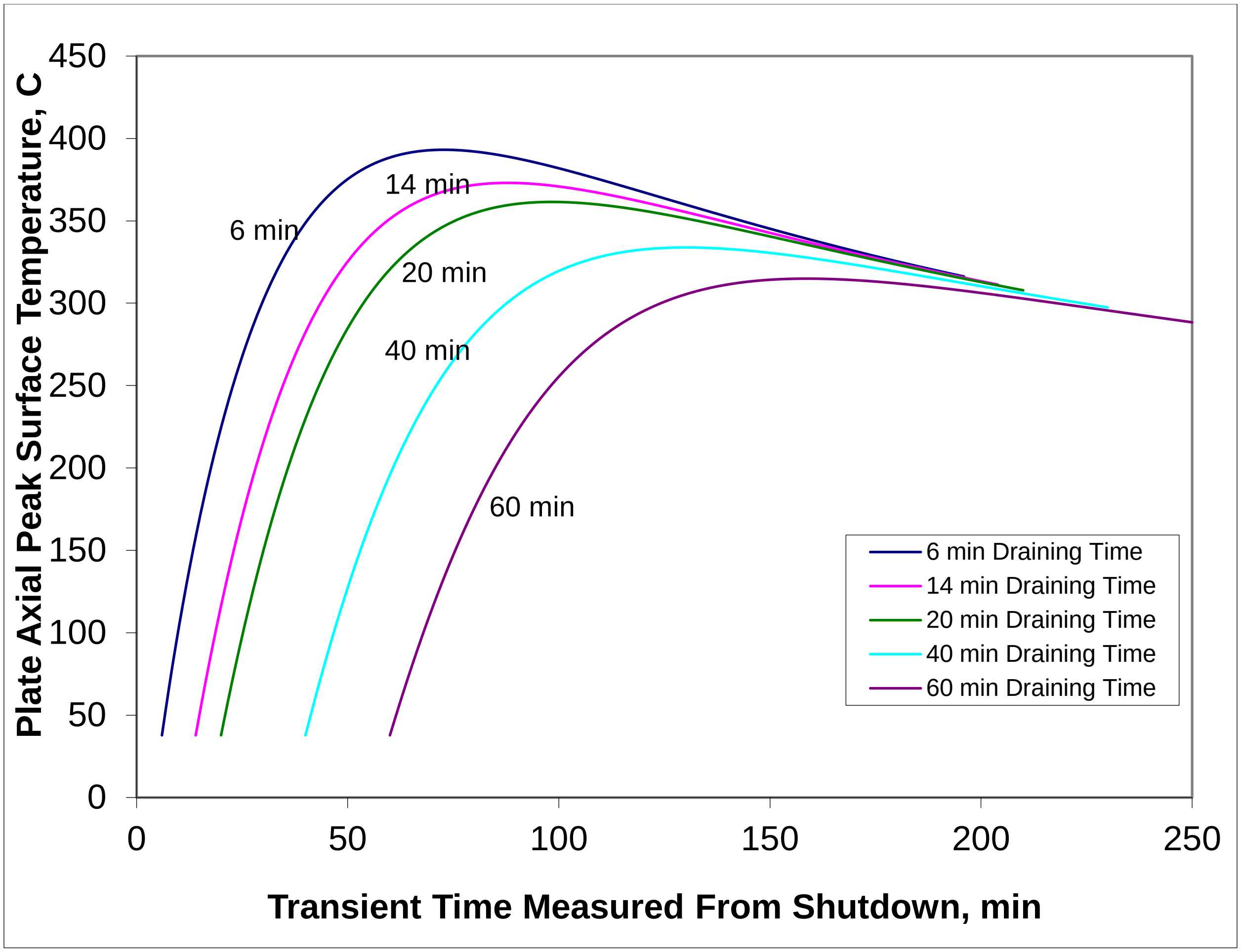


Figure 11. Plate Surface Temperature during LOCA Calculated Using the One-Node Model in the Highest Power Control Fuel Assembly C3 of RPI LEU Core (pre-LOCA reactor operation at 1.0 MW for 10 weeks, 5 days a week, 14 hours/day)

Table 1. Fuel Assembly Design Features Important in Deciding if the One-Node LOCA Model Cold be Used for a Reactor

Fuel Assembly Design Features	Oak Ridge Research Reactor (ORR), HEU Core	Low Intensity Testing Reactor (LITR) in 1952	Omega West Reactor (OWR)	University of Virginia Reactor (UVAR)			Portuguese Research Reactor (RPI) in 2006	
				HEU Core in 1970	HEU Core in 1984	LEU Core in 1994	HEU Core	LEU Core
Reactor power, MW	30.0	1.0 for Test 17	8.0 after August 1967	2.0	2.0	2.0	1.0	1.0
Reactor flow rate, US gpm	18000	1200	3500	900	920	> 1000	950 [d]	950 [d]
Grid spacing, mm Grid plate thickness, mm	77.1 x 81.0	77.0 x 81.0 152.4	77.0 x 81.0 127.0	77.0 x 81.0 127.0	77.0 x 81.0 127.0	77.0 x 81.0 127.0	77.1 x 81.0 127.0	77.1 x 81.0 127.0
Fuel assembly operating power, MW	1.0 average	0.0635 for location C-25	0.335 for location 4-E	0.196 maximum	0.196 (assumed)	0.209 maximum	0.118 [e]	0.118 [e]
Fuel assembly type	MTR-type curved plate	MTR-type curved plate	MTR-type curved plate	MTR-type flat plate	MTR-type curved plate	MTR-type flat plate	MTR-type flat plate	MTR-type flat plate
Fuel meat	U_3O_8–Al dispersion	U-Al alloy	U-Al alloy	U-Al alloy	U-Al alloy	U_3Si_2-Al dispersion	U-Al alloy	U_3Si_2-Al dispersion
Cladding material	Al	1100 Al	Al	Al	1100 Al	Al	1100 Al	AG3NE
Structural material	Al	1100 Al	Al	Al	6061 Al	Al	1100 Al	AG3NE
Number of plates per standard fuel assembly	19	18	18	12	18	22	18	18
Plate thickness, mm	1.27 (first & last 1.65)	1.27 (first & last 1.65)	1.524	1.270	1.270	1.270	1.270	1.370
Channel thickness, mm	2.95	2.946	2.972	5.359	3.160	2.337	3.150	3.050
Meat thickness, mm	0.508	0.508	0.508	0.508	0.508	0.508	0.508	0.608
Cladding thickness, mm	0.380	0.381	0.508	0.381	0.381	0.381	0.381	0.381
Plate length, mm Meat length, mm	625.5 597.7	638.2 596.9	638.2 609.6	625.5 596.9	625.5 597.0	624.8 591.8	625.5 596.9	625.5 596.9
Plate width, mm Meat width, mm	71.04 62.8	71.12 63.5	71.12 63.5	73.3 63.5	68.3 60.3	71.12 60.96	71.02 63.35	71.02 63.35
Number of assemblies in the reactor	30 in 7 x 9 array	23 in 5 x 9 array	31 in 6 x 9 array	12+4 half in 4 x 5 array	16+4 control in 4 x 5 array	12+4 half in 4 x 4 array	7 + 5 control, 176 plates	7 + 5 control, 176 plates
U-235 mass in a standard fuel assembly, g	285	130 to 140 [c]	220	165	190	275	265	376

Table 1. Continued

Fuel Assembly Design Features	Oak Ridge Research Reactor (ORR), HEU Core	Low Intensity Testing Reactor (LITR) in 1952	Omega West Reactor (OWR)	University of Virginia Reactor (UVAR)			Portuguese Research Reactor (RPI) in 2006	
				HEU Core in 1970	HEU Core in 1984	LEU Core in 1994	HEU Core	LEU Core
Derived Quantities								
Mass in a standard fuel assembly, kg								
Al in fuel plates	3.068	2.842	3.418	1.915	2.611	3.031	2.510	2.476
Al in side plates	1.077	1.156	1.125	1.275	1.189	1.277	1.162	1.138
Al in nozzle(s)	1.425	1.425	1.565	0.442	0.442	0.486	0.486	0.486
Al in grid plate/pitch	[a]	1.731[f]	0.905	1.360	1.359	1.159	1.162	1.162
Total Aluminum	5.063	7.155	7.013	4.992	5.601	5.953	5.320	5.262
UAl_3/UAl_4/U_3Si_2 in meat		0.226			0.318	1.502	0.443	2.032
Heat capacitance of a fuel assembly, MJ / °F [b]	2.81x10^{-3}	3.98x10^{-3}	3.53x10^{-3} 4.20x10^{-3} [4]	2.52x10^{-3} 3.50x10^{-3} [5]	3.10x10^{-3}	3.44x10^{-3}	3.04x10^{-3}	3.12x10^{-3}
Numerical factor in heat loss rate, MW/ °F	4.54x10^{-6}	1.30x10^{-6}	1.30x10^{-6}	0.87x10^{-6}	1.30x10^{-6} 1.80x10^{-6} [g]	1.59x10^{-6} 2.20x10^{-6} [h]	1.30x10^{-6}	1.30x10^{-6}

Note a. Exclude this from fuel assembly heat capacitance because the fuel assembly was hung out of the reactor. It was not in contact with the grid plate.

Note b. Specific heat of Al = 903 J/kg-°C, Specific heat of U = 116 J/kg-°C, Specific heat of U_3Si_2 at 200 °C = 220 J/kg-°C, Specific heat of UAl_3 at 200 °C = 371 J/kg-°C, Specific heat of UAl_4 at 200 °C = 521 J/kg-°C

Note c. Total 3100 g U-235 in the LITR core

Note d. 950 US gallons/minute = 0.06 m^3/sec = 216 m^3/hour

Note e. Fuel assembly power = 1.0 MW/(176 plates)×(18 plates in fuel assembly)×(1.15 radial power peaking factor)

Note f. The LITR has two grid plates (lower and upper) [10]. The upper grid was *assumed* to be 3 inch thick.

Note g. The numerical factor is 1.80x10^{-6} for use with the ANSI/ANS-5.1 decay heat, and 1.30x10^{-6} MW/°F for use with the Way-Wigner decay heat.

Note h. The numerical factor is 1.80x10^{-6}x 22/18 = 2.20x10^{-6} for use with the ANSI/ANS-5.1 decay heat, and 1.30x10^{-6}x22/18 = 1.59x10^{-6} MW/°F for use with the Way-Wigner decay heat.

Table 2. Equilibrium Temperature of the ORR-Irradiated Fuel Assemblies Cooled in Stagnant Air

No	ORR Subass-embly	U-235 Mass at the Beginning of Last Cycle, g	Average Neutron Flux, 10^{14}	Irradiation Time in the Last Cycle Prior to Measure-ment, hours	Decay Time at Measure-ment, hours	Thermo-Couple Distance From Top of Fuel, inch	Measured Temper-atures, °F	Measured Peak Temper-ature, °F	Subass-embly Power, MW [b]	Calculated Peak Temper-ature, °F
1	103	194.7	0.6	321	85	4 16	245 285	287 [a]	0.578	302
2					131	4 16	201 256	261 [a]	0.578	258
3					154	4 16	209 245	247 [a]	0.578	243
4					180	4 16	203 230	232 [a]	0.578	229
5					203	4 16	195 222	224 [a]	0.578	219
6					219	4 16	191 218	220 [a]	0.578	213
7	87	193.7	1.2	321	104	4 16	312 352	354 [a]	1.151	416
8					176	4 16	249 302	305 [a]	1.151	335
9	97	143.2	1.1	321	108	4 16	298 341	343 [a]	0.780	327
10	94	150.7	1.04	144	780	4 16	153 175	176 [a]	0.776	122
11	82	173.5	0.91	200	34	4 16	395 473	478 [a]	0.782	442
12	100	146.3	1.18	200	31	4 16	385 440	443 [a]	0.855	481
13	151	199.6	1.02	200	28	4 16	366 496	504 [a]	1.008	549
14	158	200.0	0.75	417	723	5.8 9.3 15.7	155 160 159	161	0.743	162
15	87*	176.5	0.87	417	723	5.8 9.3 15.7	196 201 193	201	0.760	164
16	164	200.0	1.01	536	19.25	9.3 15.7 19.4	634 641 620	645	1.0	713
17					40.25	6.0 14.5 17.8	465 518 505	518	1.0	586
18					61	11.5 13.3 17.3	438 450 450	455	1.0	518

Note a: Estimated using the axial temperature profile of fuel assembly ORR-164,
Tpeak = T(4 inch)+1.058[T(16 inch) – T(4 inch)]

Note b: Fuel assembly power was obtained from U-235 mass and neutron flux in the fuel assembly, assuming a power of 1.0 MW in fuel assembly ORR-164.

Table 3. Loss-of-Coolant Tests Performed in the Low Intensity Testing Reactor (LITR) During 1951-1953

Test Number	Reactor Operating Power, MW	Time at Power, hour	Location of the Fuel Assembly in Core	Maximum Rise of Fuel Plate Surface Temperature Above the Ambient Air, °F	Maximum Fuel Plate Surface Temperature, °F	Time After Reactor Shutdown to Reach the Maximum Surface Temperature, minute
3	0.0225	2.13		7.5		35
4	0.060	2.5		16.5		35
5	0.090	2.5		22.0		40
6	0.112	2.25		26.0		40
7	0.112	2.17		28.5		
8	0.135	2.08		31.0		40
9	0.150	2.2		33.5		45
10	0.150	6.5		40.0		40
11	0.150	24.5		53.0		100
12	0.300	21.0		62.5		51.7
13	0.150	24.5		47.0		150
14	0.150	117.0		60.0		150
15	0.350	129.0 [b]		126		150
16	0.770	131.6 [c]		180		100
17	1.000	142	C-25		478	107
18	1.250	138	C-25		487 [d]	135
19	1.250	115			399	100
20[a]	1.250	141			186	22
21[a]	1.500	152			186	17
22[a]	1.500	143			183	36
23[a]	1.900	134			174	26.7
24*	2.300	114	C-36		198	18

Note a. Tests performed using an auxiliary spray of about 3 gallons/minute
Note b. This time is written to be 115 hours in a memorandum dated February 21, 1952 from S. E. Beall to J. A. Cox, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.
Note c. This time is written to be 138 hours in the above memorandum.
Note d. A maximum temperature of 489 °F (254 °C) is also given for test 18 in the same report [3].

Table 4. Calculated Fuel Plate Peak Surface Temperature in Fuel Assembly C-25 in the LOCA Test of May 12, 1952 (Test 17) in the LITR (Using the Way-Wigner Decay Heat Relation of 1958)

```
INPUT DATA EDIT
Fully Uncovered LOCA Test of LITR on 5/12/1952, operating at 1 MW for
142 hr, Subas C-25 power=1.0 MW/(23 #subas)*(1.46 radial power factor)
COEF        CPM         TTA         PA          TOP         TDC
1.30E-06    3.98E-03    111.0       0.0635      8520.0      1.2
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       0     0     1.0
NWEEK NDAYS KPRINT
1     1     0
```

Time After Drain, min	Max Plate Temp, F	Decay Power in Subass, kW	Time After Drain, min	Max Plate Temp, F	Decay Power in Subass, kW
0.000	111.000	1.3942E+00	71.667	461.418	4.5412E-01
1.667	141.788	1.1258E+00	73.333	462.073	4.5079E-01
3.333	167.520	1.0022E+00	75.000	462.621	4.4756E-01
5.000	190.248	9.2412E-01	76.667	463.069	4.4441E-01
6.667	210.784	8.6791E-01	78.333	463.422	4.4134E-01
8.333	229.567	8.2445E-01	80.000	463.686	4.3835E-01
10.000	246.873	7.8929E-01	81.667	463.867	4.3543E-01
11.667	262.895	7.5990E-01	83.333	463.969	4.3258E-01
13.333	277.776	7.3477E-01	**85.000**	**463.999**	**4.2979E-01**
15.000	291.628	7.1288E-01	86.667	463.959	4.2707E-01
16.667	304.543	6.9354E-01	88.333	463.855	4.2442E-01
18.333	316.596	6.7625E-01	90.000	463.690	4.2182E-01
20.000	327.852	6.6065E-01	91.667	463.468	4.1927E-01
21.667	338.369	6.4646E-01	93.333	463.194	4.1679E-01
23.333	348.197	6.3346E-01	95.000	462.870	4.1435E-01
25.000	357.381	6.2148E-01	96.667	462.499	4.1197E-01
26.667	365.962	6.1038E-01	98.333	462.085	4.0963E-01
28.333	373.978	6.0005E-01	100.000	461.631	4.0734E-01
30.000	381.462	5.9040E-01	101.667	461.139	4.0509E-01
31.667	388.447	5.8135E-01	103.333	460.612	4.0289E-01
33.333	394.961	5.7283E-01	105.000	460.053	4.0073E-01
35.000	401.034	5.6480E-01	106.667	459.463	3.9861E-01
36.667	406.689	5.5719E-01	108.333	458.845	3.9653E-01
38.333	411.951	5.4998E-01	110.000	458.200	3.9449E-01
40.000	416.842	5.4313E-01	111.667	457.532	3.9249E-01
41.667	421.384	5.3660E-01	113.333	456.841	3.9052E-01
43.333	425.597	5.3037E-01	115.000	456.129	3.8858E-01
45.000	429.498	5.2441E-01	116.667	455.399	3.8668E-01
46.667	433.106	5.1871E-01	118.333	454.651	3.8481E-01
48.333	436.438	5.1324E-01	120.000	453.887	3.8297E-01
50.000	439.508	5.0799E-01	121.667	453.108	3.8116E-01
51.667	442.333	5.0294E-01	123.333	452.316	3.7938E-01
53.333	444.925	4.9807E-01	125.000	451.512	3.7763E-01
55.000	447.298	4.9339E-01	126.667	450.696	3.7591E-01
56.667	449.464	4.8886E-01	128.333	449.871	3.7421E-01
58.333	451.436	4.8449E-01	130.000	449.037	3.7254E-01
60.000	453.224	4.8027E-01	131.667	448.194	3.7089E-01
61.667	454.839	4.7618E-01	133.333	447.345	3.6927E-01
63.333	456.291	4.7222E-01	135.000	446.489	3.6768E-01
65.000	457.589	4.6838E-01	136.667	445.628	3.6611E-01
66.667	458.743	4.6466E-01	138.333	444.763	3.6456E-01
68.333	459.761	4.6104E-01	140.000	443.893	3.6303E-01
70.000	460.650	4.5753E-01			

Table 5. Calculated Fuel Plate Peak Surface Temperature in Fuel Assembly C-25 in the LOCA Test of May 12, 1952 (Test 17) in the LITR (Using the ANSI/ANS-51 Decay Heat of 1994 without Absorption Correction and One Sigma Uncertainty, Recoverable Energy = 202.2 MeV/Fission)

INPUT DATA EDIT

```
Fully Uncovered LOCA Test of LITR on 5/12/1952, operating at 1 MW for
142 hr, Subas C-25 power=1.0 MW/(23 #subas)*(1.46 radial power factor)
COEF        CPM         TTA         PA          TOP         TDC
1.80E-06    3.98E-03    111.0       0.0635      8520.0      1.2
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       2     0     1.0
NWEEK NDAYS KPRINT
1     1     0
```

Time After Drain, min	Max Plate Temp, F	Decay Power in Subass, kW
0.000	111.000	1.8773E+00
1.667	152.523	1.5322E+00
3.333	187.220	1.3775E+00
5.000	217.774	1.2808E+00
6.667	245.189	1.2097E+00
8.333	269.980	1.1526E+00
10.000	292.472	1.1046E+00
11.667	312.908	1.0631E+00
13.333	331.481	1.0265E+00
15.000	348.358	9.9382E-01
16.667	363.680	9.6435E-01
18.333	377.577	9.3751E-01
20.000	390.161	9.1290E-01
21.667	401.538	8.9019E-01
23.333	411.801	8.6913E-01
25.000	421.038	8.4951E-01
26.667	429.330	8.3116E-01
28.333	436.749	8.1396E-01
30.000	443.367	7.9778E-01
31.667	449.245	7.8252E-01
33.333	454.443	7.6811E-01
35.000	459.015	7.5447E-01
36.667	463.013	7.4153E-01
38.333	466.484	7.2924E-01
40.000	469.469	7.1754E-01
41.667	472.011	7.0640E-01
43.333	474.146	6.9577E-01
45.000	475.908	6.8562E-01
46.667	477.330	6.7590E-01
48.333	478.440	6.6660E-01
50.000	479.266	6.5769E-01
51.667	479.832	6.4913E-01
53.333	480.162	6.4091E-01
55.000	**480.276**	**6.3301E-01**
56.667	480.195	6.2541E-01
58.333	479.936	6.1808E-01
60.000	479.517	6.1101E-01
61.667	478.951	6.0420E-01
63.333	478.253	5.9761E-01
65.000	477.437	5.9125E-01
66.667	476.513	5.8510E-01
68.333	475.493	5.7914E-01
70.000	474.387	5.7337E-01
71.667	473.204	5.6777E-01
73.333	471.952	5.6235E-01
75.000	470.639	5.5708E-01
76.667	469.272	5.5197E-01
78.333	467.858	5.4700E-01
80.000	466.402	5.4216E-01
81.667	464.910	5.3746E-01
83.333	463.388	5.3289E-01
85.000	461.838	5.2843E-01
86.667	460.266	5.2408E-01
88.333	458.676	5.1985E-01
90.000	457.070	5.1572E-01
91.667	455.453	5.1169E-01
93.333	453.826	5.0775E-01
95.000	452.192	5.0391E-01
96.667	450.555	5.0015E-01
98.333	448.915	4.9648E-01
100.000	447.275	4.9289E-01
101.667	445.637	4.8938E-01
103.333	444.002	4.8594E-01
105.000	442.372	4.8257E-01
106.667	440.748	4.7928E-01
108.333	439.130	4.7605E-01
110.000	437.522	4.7288E-01
111.667	435.922	4.6978E-01
113.333	434.332	4.6674E-01
115.000	432.753	4.6375E-01
116.667	431.185	4.6082E-01
118.333	429.629	4.5795E-01
120.000	428.085	4.5512E-01
121.667	426.554	4.5235E-01
123.333	425.037	4.4963E-01
125.000	423.533	4.4695E-01
126.667	422.043	4.4432E-01
128.333	420.567	4.4173E-01
130.000	419.105	4.3919E-01
131.667	417.657	4.3669E-01
133.333	416.224	4.3423E-01
135.000	414.806	4.3181E-01
136.667	413.402	4.2943E-01
138.333	412.013	4.2708E-01
140.000	410.639	4.2478E-01

Table 6. Calculated Fuel Plate Peak Surface Temperature in Fuel Assembly C-25 in the LOCA Test of May 19, 1952 (Test 18) in the LITR (Using the Way-Wigner Decay Heat Relation of 1958)

INPUT DATA EDIT

```
Fully Uncovered LOCA Test of LITR on 5/19/1952, operating at 1.25 MW for
138 hr, Subas C-25 power=1.25 MW/(23 #subas)*(1.46 radial power factor)
COEF        CPM         TTA         PA          TOP         TDC
1.30E-06    3.98E-03    90.0        0.0793      8280.0      2.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       0     0     1.0
NWEEK NDAYS KPRINT
1     1     0
```

Time After Drain, min	Max Plate Temp, F	Decay Power in Subass, kW
0.000	90.000	1.5354E+00
1.667	125.203	1.3193E+00
3.333	155.704	1.1982E+00
5.000	183.027	1.1158E+00
6.667	207.896	1.0542E+00
8.333	230.735	1.0054E+00
10.000	251.828	9.6526E-01
11.667	271.378	9.3131E-01
13.333	289.542	9.0199E-01
15.000	306.446	8.7627E-01
16.667	322.192	8.5342E-01
18.333	336.871	8.3289E-01
20.000	350.558	8.1429E-01
21.667	363.322	7.9731E-01
23.333	375.224	7.8171E-01
25.000	386.320	7.6730E-01
26.667	396.660	7.5392E-01
28.333	406.291	7.4144E-01
30.000	415.256	7.2976E-01
31.667	423.595	7.1878E-01
33.333	431.346	7.0845E-01
35.000	438.543	6.9868E-01
36.667	445.220	6.8943E-01
38.333	451.406	6.8064E-01
40.000	457.131	6.7228E-01
41.667	462.422	6.6431E-01
43.333	467.305	6.5670E-01
45.000	471.803	6.4941E-01
46.667	475.940	6.4244E-01
48.333	479.736	6.3574E-01
50.000	483.212	6.2930E-01
51.667	486.387	6.2311E-01
53.333	489.279	6.1714E-01
55.000	491.905	6.1139E-01
56.667	494.280	6.0584E-01
58.333	496.420	6.0047E-01
60.000	498.340	5.9528E-01
61.667	500.052	5.9025E-01
63.333	501.569	5.8538E-01
65.000	502.903	5.8066E-01
66.667	504.066	5.7607E-01
68.333	505.068	5.7162E-01
70.000	505.918	5.6729E-01
71.667	506.628	5.6308E-01
73.333	507.204	5.5899E-01
75.000	507.657	5.5500E-01
76.667	507.993	5.5112E-01
78.333	508.221	5.4733E-01
80.000	508.347	5.4364E-01
81.667	**508.378**	**5.4003E-01**
83.333	508.320	5.3652E-01
85.000	508.179	5.3308E-01
86.667	507.960	5.2972E-01
88.333	507.670	5.2644E-01
90.000	507.312	5.2323E-01
91.667	506.891	5.2009E-01
93.333	506.412	5.1701E-01
95.000	505.879	5.1400E-01
96.667	505.296	5.1105E-01
98.333	504.666	5.0816E-01
100.000	503.993	5.0533E-01
101.667	503.280	5.0255E-01
103.333	502.529	4.9983E-01
105.000	501.745	4.9716E-01
106.667	500.929	4.9454E-01
108.333	500.084	4.9196E-01
110.000	499.213	4.8943E-01
111.667	498.317	4.8695E-01
113.333	497.399	4.8451E-01
115.000	496.460	4.8212E-01
116.667	495.504	4.7976E-01
118.333	494.530	4.7744E-01
120.000	493.541	4.7516E-01
121.667	492.539	4.7292E-01
123.333	491.524	4.7072E-01
125.000	490.499	4.6855E-01
126.667	489.464	4.6641E-01
128.333	488.421	4.6431E-01
130.000	487.371	4.6224E-01
131.667	486.314	4.6020E-01
133.333	485.252	4.5819E-01
135.000	484.186	4.5622E-01
136.667	483.116	4.5427E-01
138.333	482.043	4.5235E-01
140.000	480.969	4.5045E-01

Table 7. Calculated Fuel Plate Peak Surface Temperature in Fuel Assembly C-25 in the LOCA Test of May 19, 1952 (Test 18) in the LITR (Using the ANSI/ANS-5.1 Decay Heat of 1994 without Absorption Correction and One Sigma Uncertainty, Recoverable Energy = 202.2 MeV/Fission)

INPUT DATA EDIT

```
Fully Uncovered LOCA Test of LITR on 5/19/1952, operating at 1.25 MW for
138 hr, Subas C-25 power=1.25 MW/(23 #subas)*(1.46 radial power factor)
COEF        CPM         TTA         PA          TOP         TDC
1.80E-06    3.98E-03    90.0        0.0793      8280.0      2.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       2     0     1.0
NWEEK NDAYS KPRINT
1     1     0
```

Time After Drain, min	Max Plate Temp, F	Decay Power in Subass, kW	Time After Drain, min	Max Plate Temp, F	Decay Power in Subass, kW
0.000	90.000	2.0800E+00	71.667	516.453	7.0400E-01
1.667	137.733	1.8051E+00	73.333	514.805	6.9733E-01
3.333	179.072	1.6550E+00	75.000	513.095	6.9084E-01
5.000	215.947	1.5523E+00	76.667	511.330	6.8454E-01
6.667	249.211	1.4730E+00	78.333	509.520	6.7842E-01
8.333	279.350	1.4077E+00	80.000	507.669	6.7246E-01
10.000	306.703	1.3519E+00	81.667	505.785	6.6667E-01
11.667	331.534	1.3032E+00	83.333	503.872	6.6103E-01
13.333	354.068	1.2600E+00	85.000	501.937	6.5553E-01
15.000	374.497	1.2212E+00	86.667	499.983	6.5017E-01
16.667	392.993	1.1861E+00	88.333	498.015	6.4495E-01
18.333	409.712	1.1539E+00	90.000	496.036	6.3985E-01
20.000	424.795	1.1244E+00	91.667	494.050	6.3487E-01
21.667	438.373	1.0970E+00	93.333	492.060	6.3001E-01
23.333	450.563	1.0716E+00	95.000	490.069	6.2527E-01
25.000	461.478	1.0479E+00	96.667	488.079	6.2063E-01
26.667	471.219	1.0257E+00	98.333	486.092	6.1609E-01
28.333	479.881	1.0049E+00	100.000	484.111	6.1166E-01
30.000	487.552	9.8523E-01	101.667	482.137	6.0732E-01
31.667	494.314	9.6669E-01	103.333	480.172	6.0307E-01
33.333	500.242	9.4917E-01	105.000	478.218	5.9890E-01
35.000	505.406	9.3256E-01	106.667	476.274	5.9483E-01
36.667	509.872	9.1680E-01	108.333	474.344	5.9083E-01
38.333	513.698	9.0181E-01	110.000	472.427	5.8692E-01
40.000	516.940	8.8755E-01	111.667	470.525	5.8308E-01
41.667	519.649	8.7395E-01	113.333	468.638	5.7932E-01
43.333	521.872	8.6096E-01	115.000	466.767	5.7562E-01
45.000	523.653	8.4855E-01	116.667	464.912	5.7200E-01
46.667	525.030	8.3667E-01	118.333	463.075	5.6844E-01
48.333	526.042	8.2530E-01	120.000	461.255	5.6494E-01
50.000	526.721	8.1438E-01	121.667	459.453	5.6151E-01
51.667	527.098	8.0390E-01	123.333	457.669	5.5814E-01
53.333	**527.203**	**7.9383E-01**	125.000	455.903	5.5482E-01
55.000	527.061	7.8415E-01	126.667	454.156	5.5156E-01
56.667	526.696	7.7482E-01	128.333	452.427	5.4836E-01
58.333	526.130	7.6583E-01	130.000	450.717	5.4521E-01
60.000	525.383	7.5716E-01	131.667	449.026	5.4211E-01
61.667	524.473	7.4879E-01	133.333	447.353	5.3907E-01
63.333	523.418	7.4070E-01	135.000	445.699	5.3607E-01
65.000	522.233	7.3288E-01	136.667	444.064	5.3312E-01
66.667	520.931	7.2531E-01	138.333	442.447	5.3021E-01
68.333	519.526	7.1799E-01	140.000	440.849	5.2735E-01
70.000	518.030	7.1089E-01			

Table 8. Maximum Plate Surface Temperature in LOCA Calculated Using the One-Node Model in the Omega West Reactor (OWR) (Reactor Shutdown after a 120-Hour Operation at 8.0 MW, Way-Wigner Decay Heat)

Location of the Fuel Assembly in Core	Operating Power of the Fuel Assembly, MW	Time (After Reactor Shutdown) to Uncover the Fuel, minutes	ANL Calculation Using LANL Input Parameters		Calculated Maximum Fuel Temperature Reported in Ref. [4], °F
			Maximum Fuel Temperature, °F	Time (After Uncovering) to Max Temp, minutes	
4-E	0.335	6	1316	60.0	1316
		30	1196	75.0	1191
		60	1113	85.0	1109
		90	1057	91.7	1055
		120	1013	98.3	1008
5-D or 5-F	0.317	6	1268	60.0	1268
4-C or 4-G	0.306	6	1238	61.7	1239
5-E	0.300	6	1222	61.7	1223
			Calculation Using ANL Estimate of Heat Capacitance		
4-E	0.335	6	1355	50.0	1316

INPUT DATA FOR FUEL ASSEMBLY LOCATION 4-E, USING HEAT CAPACITANCE FOUND BY LANL

```
Fully Uncovered LOCA Analysis of OWR operating at 8 MW for 120 hours
Power of subass in core position 4-E = 4.19% of 8 MW = 0.335 MW
COEF        CPM         TTA         PA          TOP         TDC
1.30E-06    4.20E-03    115.0       0.335       7200.0      6.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       0     0     1.0
NWEEK NDAYS KPRINT
1     1     0
```

INPUT DATA FOR FUEL ASSEMBLY LOCATION 4-E, USING HEAT CAPACITANCE FOUND BY ANL

```
Fully Uncovered LOCA Analysis of OWR operating at 8 MW for 120 hours
Power of subass in core position 4-E = 4.19% of 8 MW = 0.335 MW
COEF        CPM         TTA         PA          TOP         TDC
1.30E-06    3.53E-03    115.0       0.335       7200.0      6.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       0     0     1.0
NWEEK NDAYS KPRINT
1     1     0
```

Table 9. Maximum Plate Surface Temperature in LOCA Calculated Using the One-Node Model in the Hottest 12-Plate HEU Fuel Assembly of the UVAR (Reactor Shutdown after a 120-Hour Operation at 2.0 MW, Way-Wigner Decay Heat)

Time (After Reactor Shutdown) to Uncover the Fuel, minutes	ANL Calculation Using ANL Input Parameters		ANL Calculation Using the Input Parameters in Ref. [5]		Calculated Maximum Fuel Temperature Reported in Ref. [5], °F
	Maximum Fuel Temperature, °F	Time (After Uncovering) to Max Temp, minutes	Maximum Temperature, °F	Time (After Uncovering) to Maximum Temp, minutes	
10	1183	60.0	1120	80.0	1122
15	1156	63.3	1097	85	1100
30	1096	70.0	1047	93.3	1049
60	1018	80.0	980	106.7	982
120	924	93.3	895	121.7	897

INPUT DATA USING HEAT CAPACITANCE FOUND BY ANL

```
Fully Uncovered LOCA Analysis of UVAR operating at 2 MW for 120 hours
Subass power = 2.0MW/(14 #subass)*(1.37 radial peaking factor) = 0.196 MW
COEF        CPM         TTA         PA          TOP         TDC
0.87E-06    2.52E-03    100.0       0.196       7200.0      10.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       0     0     1.0
NWEEK NDAYS KPRINT
1     1     0
```

INPUT DATA USING HEAT CAPACITANCE FOUND BY
THE UNIVERSITY OF VIRGINIA

```
Fully Uncovered LOCA Analysis of UVAR operating at 2 MW for 120 hours
Subass power = 2.0MW/(14 #subass)*(1.37 radial peaking factor) = 0.196 MW
COEF        CPM         TTA         PA          TOP         TDC
0.87E-06    3.50E-03    100.0       0.196       7200.0      10.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       0     0     1.0
NWEEK NDAYS KPRINT
1     1     0
```

Table 10. Comparison of Maximum Fuel Plate Surface Temperatures in LOCA between the UVAR 18-Plate and 12-Plate HEU Fuel Assemblies Operating at 0.196 MW Reactor Shutdown after a 120-Hour Operation at 2.0 MW, Way-Wigner Decay Heat)

Time (After Reactor Shutdown) to Uncover the Fuel, minutes	ANL Calculation for the 18-Plate HEU Fuel Assembly		Maximum Fuel Temperature for the 12-Plate HEU Fuel Assembly, °F
	Maximum Fuel Temperature, °F	Time (After Uncovering) to Max Temp, minutes	
10	931	56.7	1183
15	909	60.0	1156
30	861	66.7	1096
60	800	76.7	1018
120	725	88.3	924

INPUT DTA USING HEAT CAPACITANCE FOUND BY ANL

```
Fully Uncovered LOCA of UVAR 18-Plate HEU Core of 1984, ANL input data
Operating at 2 MW for 120 hr, Fuel Assembly Power = 0.196 MW
COEF        CPM         TTA         PA          TOP         TDC
1.30E-06    3.10E-03    100.0       0.196       7200.0      10.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       0     0     1.0
NWEEK NDAYS KPRINT
1     1     0
```

Table 11. Maximum Plate Surface Temperature in LOCA Calculated Using the One-Node Model in the Hottest 22-Plate LEU Fuel Assembly of the UVAR (For Reactor Shutdown after a 120-Hour Operation at 2.0 MW)

Time (After Reactor Shutdown) to Uncover the Fuel, minutes	ANL Calculation Using ANL Input Parameters		ANL Calculation Using the Input Parameters in Ref. [16]		Calculated Maximum Fuel Temperature Reported in Ref. [16], °F
	Maximum Fuel Temperature, °F	Time (After Uncovering) to Max Temp, minutes	Maximum Temperature, °F	Time (After Uncovering) to Maximum Temp, minutes	
18 (0.3 hr)	874	41.7	949	38.3	975
60	740	53.3	799	48.3	835
90	688	60.0	741	53.3	764
120	649	63.3	699	56.7	727

INPUT DATA USING HEAT CAPACITANCE AND HEAT LOSS TERM FOUND BY ANL

```
Fully Uncovered LOCA of UVAR 22-plate LEU Core of 1994, ANL input data
Operating at 2 MW for 120 hr, Maximum Fuel Assembly Power = 0.209 MW
COEF         CPM          TTA          PA           TOP          TDC
2.20E-06     3.437E-03    100.0        0.209        7200.0       18.0
TDCEND       IOPT   IOPTG SIGMA        CPM1         CPM2         TFIN
190.0        1      1     1.02         3.087E-03    0.892E-06
NWEEK NDAYS KPRINT
1     1     0
```

INPUT DATA USING HEAT CAPACITANCE AND HEAT LOSS TERM FOUND BY THE UNIVERSITY OF VIRGINIA

```
Fully Uncovered LOCA of UVAR 22-plate LEU Core of 1994, UV input data
Operating at 2 MW for 120 hr, Maximum Fuel Assembly Power = 0.209 MW
COEF         CPM          TTA          PA           TOP          TDC
1.98E-06     3.022E-03    100.0        0.209        7200.0       18.0
TDCEND       IOPT   IOPTG SIGMA        CPM1         CPM2         TFIN
190.0        1      1     1.02         2.7155E-03   0.784E-06    212.0
NWEEK NDAYS KPRINT
1     1     0
```

Table 12. Decay Heat Power of the RPI after Scheduled Operation at 1.0 MW for 10 Weeks, 5 Days per Week, 14 Hours per Day (Total 68 Days) Based on ANSI/ANS-5.1 of 1994, Including Absorption Correction and One Sigma Uncertainty

Note: The first column was used in the LOCA analysis. The other two columns are shown only for comparison.

	DECAY HEAT OF REACTOR, kW		
Time after Scram, sec	RPI Scheduled Operation	Continuous for 6.4 days	Continuous for 10^{13} sec
0.0	65.919	66.578	69.959
1.0	60.352	61.011	64.391
2.0	56.838	57.498	60.878
3.0	54.339	55.000	58.382
4.0	52.390	53.051	56.435
6.0	49.437	50.101	53.488
12.0	44.011	44.676	48.063
30.0	36.981	37.645	41.032
60.0	31.872	32.535	35.922
120.0	27.104	27.770	31.161
300.0	21.844	22.514	25.915
600.0	18.434	19.108	22.520
900.0	16.444	17.118	20.538
1200.0	15.025	15.698	19.125
1500.0	13.935	14.608	18.042
1800.0	13.042	13.711	17.149
2100.0	12.300	12.966	16.408
2400.0	11.671	12.335	15.781
2700.0	11.131	11.792	15.242
3000.0	10.661	11.319	14.773
3300.0	10.247	10.903	14.361
3600.0	9.880	10.533	13.995
3900.0	9.551	10.202	13.668
4200.0	9.253	9.901	13.369
4500.0	8.981	9.625	13.097
4800.0	8.733	9.374	12.847
5100.0	8.505	9.143	12.619
5400.0	8.295	8.929	12.408
5700.0	8.101	8.731	12.213
6000.0	7.920	8.547	12.031
6300.0	7.751	8.375	11.861
6600.0	7.593	8.213	11.702
6900.0	7.444	8.061	11.553
7200.0	7.304	7.918	11.412
7500.0	7.172	7.782	11.279

Table 13. Calculation of Heat Capacitance of a Fuel Assembly in the RPI HEU and LEU Cores

	HEU Standard Fuel Assembly	HEU Control Fuel Assembly	LEU Standard Fuel Assembly	LEU Control Fuel Assembly
Highest Power Assembly Location	N9	C3	N9	C3
Operating Power of the Assembly, MW	0.1187	0.0816	0.1129	0.0823
Components of Assembly Heat Capacitance				
UAl_4 mass in 18/10 fuel plates, kg [a]	0.443	0.246		
Specific heat of UAl_4 at 200 °C, J/kg-°C	521.0	521.0		
Heat capacitance of UAl_4 , J/°C	**230.8**	**128.2**		
U_3Si_2 mass in 18/10 fuel plates, kg [a]			2.032	1.142
Specific heat of U_3Si_2 at 200 °C, J/kg-°C			220.0	220.0
Heat capacitance of U_3Si_2 , J/°C			**447.0**	**251.6**
Al mass in 18/10 fuel plates, kg [a]	2.510	1.414	2.476	1.392
Al mass in 2 side plates, kg	1.162	1.383	1.138	1.372
Al mass in lower nozzle, kg	0.486	0.486	0.486	0.486
Al mass in grid plate/pitch, kg	1.162	1.162	1.162	1.162
Al mass in 2 guide plates, kg		0.871		0.871
Al mass in the shock absorber, kg		0.308		0.308
Total Al mass in a fuel assembly, kg	5.320	5.624	5.262	5.591
Specific heat of Al at 200 °C, J/kg-°C	984.0	984.0	984.0	984.0
Heat Capacitance of Al, J/°C	**5234.9**	**5534.0**	**5177.8**	**5501.5**
Total Assembly Heat Capacitance, J/°C	**5465.7**	**5662.2**	**5624.8**	**5752.7**
Total Assembly Heat Capacitance, MJ/°F	**3.04×10^{-3}**	**3.15×10^{-3}**	**3.12×10^{-3}**	**3.20×10^{-3}**

Note a. Mass in18 fuel plates of a standard assembly, and 10 fuel plates of a control assembly.

Table 14. Maximum Plate Surface Temperature in LOCA Calculated Using the One-Node Model in the Portuguese Research Reactor (RPI) (pre-LOCA reactor operation at 1.0 MW for 10 weeks, 5 days/week, 14 /day)

Location of the Highest Power Fuel Assembly in Core	Radial Power Peaking Factor [a]	Operating Power of the Fuel Assembly, MW	Time (After Reactor Shutdown) to Uncover the Fuel, minutes	Time (After Uncovering) to Max Temp, minutes	Maximum Fuel Temperature	
					°F	°C
HEU Core						
Standard Assembly N9	1.279	0.1187	6	40.0	726	386
			11.8	43.3	693	367
			14	**45.0**	**683**	**362**
			20	48.3	658	348
			40	55.0	601	316
			60	61.7	564	296
Control Assembly C3	1.434	0.0815	6	66.7	737	392
			11.8	71.7	710	377
			14	**75.0**	**701**	**372**
			20	76.7	680	360
			40	88.7	630	332
			60	98.3	596	313
LEU Core						
Standard Assembly N9	1.217	0.1129	6	41.7	699	370
			11.8	45.0	667	353
			14	**46.7**	**658**	**348**
			20	50.0	634	334
			40	58.3	580	304
			60	63.3	545	285
Control Assembly C3	1.448	0.0823	6	66.7	740	393
			11.8	71.7	712	378
			14	**73.3**	**703**	**373**
			20	78.3	683	362
			40	90.0	633	334
			60	98.3	599	315

INPUT DATA FOR HEU STANDARD FUEL ASSEMBLY

```
Fully Uncovered LOCA of RPI HEU Core at 1 MW for 10 weeks, 5 days/week, 14 hrs/day
Power of subass in location N9 = 1.0MW/(194plates)*(18plates)*1.279 = 0.1187 MW
COEF        CPM         TTA         PA          TOP         TDC
1.80E-06    3.04E-03    100.0       0.1187      840.0       14.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       2     1     1.02
NWEEK NDAYS KPRINT
10    5     0
```

Table 14. Continued

INPUT DATA FOR HEU CONTROL FUEL ASSEMBLY

```
Fully Uncovered LOCA of RPI HEU Core at 1 MW for 10 weeks, 5 days/week, 14 hrs/day
Power of subass in location C3 = 1.0MW/(176plates)*(10plates)*1.434 = 0.0.0815 MW
COEF        CPM         TTA         PA          TOP         TDC
1.00E-06    3.15E-03    100.0       0.0815      840.0       14.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       2     1     1.02
NWEEK NDAYS KPRINT
10    5     0
```

INPUT DATA FOR LEU STANDARD FUEL ASSEMBLY

```
Fully Uncovered LOCA of RPI LEU Core at 1 MW for 10 weeks, 5 days/week, 14 hrs/day
Power of subass in location N9 = 1.0MW/(194plates)*(18plates)*1.217 = 0.1129 MW
COEF        CPM         TTA         PA          TOP         TDC
1.80E-06    3.12E-03    100.0       0.1129      840.0       14.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       2     1     1.02
NWEEK NDAYS KPRINT
10    5     0
```

INPUT DATA FOR LEU CONTROL FUEL ASSEMBLY

```
Fully Uncovered LOCA of RPI LEU Core at 1 MW for 10 weeks, 5 days/week, 14 hrs/day
Power of subass in location C3 = 1.0MW/(176plates)*(10 plates)*1.448 = 0.0823 MW
COEF        CPM         TTA         PA          TOP         TDC
1.00E-06    3.20E-03    100.0       0.08230     840.0       14.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       2     1     1.02
NWEEK NDAYS KPRINT
10    5     0
```

APPENDIX A - Input Data Description for Program *1NODE-LOCA*

The program looks for an input filename *1node-loca.inp* in the working directory.

Card 1 Problem title of up to 80 characters
FORMAT (20A4)

Card 2 Additional title card, of the same format as card 1, (required)

Card 3 Alphanumeric comment card, (required)
FORMAT (20A4)

Card 4 COEF, CPM, TTA, PA, TOP, TDC
FORMAT (6E12.4)

COEF Numerical factor in (heat transfer coefficient) × (heat transfer area in a fuel assembly) used in Eq. (8), Eq. (9) or Eq. (10) of the LOCA model, MW/°F. Its value calibrated to the LITR tests and the ORR tests for an 18-plate MTR-type standard fuel assembly depends on the option IOPT (input on card 6) as follows:
COEF = 1.30×10^{-6} MW/°F if IOPT = 0
COEF = 1.80×10^{-6} MW/°F if IOPT = 1 or 2
COEF = 4.54×10^{-6} MW/°F if IOPT = 0 if the fuel assembly is moved out of core and hung in air outside.

CPM Fuel assembly heat capacitance (mass × specific heat), MJ/°F
The fuel assembly heat capacitance includes that of all fuel plates (meat and aluminum) in the fuel assembly, the two side plates holding the fuel plates, lower and upper nozzles attached to the fuel assembly, a rectangular pitch of the grid plate and other structural material in good thermal contact with the fuel assembly.

TTA Ambient air temperature, °F
The temperatures of ambient air and tank water are assumed to be equal. The temperature of water in the reactor tank (specially the water at the upper surface of the tank) passes over the fuel plates last and sets the initial temperature of the plates from which it rises due to decay power.

PA Operating power of the hottest fuel assembly including its radial power peaking factor, MW

TOP Reactor operating time before shutdown, minutes

TDC Time (after reactor shutdown) to drain the tank to fully uncover the fuel plate and the grid plate (see Fig. 3), minutes

Card 5 Alphanumeric comment card, (required)
FORMAT (20A4)

Card 6 TDCEND, IOPT, IOPTG, SIGMA, CPM1, CPM2, TFIN
FORMAT (E12.4, 2I6,4E12.4)

TDCEND Time (after draining) up to which the transient solution is desired, minutes

IOPT Option to choose the equation to calculate the decay heat power
= 0, Way-Wigner decay heat equation used in the original model

by the experimenters of the ORR and the LITR.
= 1, ANSI/ANS-5.1 decay heat equation of 1979
= 2, ANSI/ANS-5.1 decay heat equation of 1994

IOPTG Option for making absorption correction to decay heat calculated using the ANSI/ANS-5.1 standard of 1979 or 1994. It is not applied to the Way-Wigner decay heat equation.
= 0, No absorption correction.
= 1, Use G_{max} given in the ANSI/ANS-5.1-1979, and reproduced here in Appendix D.
Options 1 and 2 are conservative for all reactors, and especially so for research reactors. G_{max} is the maximum absorption correction, and amounts to an increase of about 3%.
= 2, Use G_{max} given in the ANSI/ANS-5.1-1994, and reproduced here in Appendix D.
= 3, Use the analytical function G(t) given as Eq. (11) in both standards ANSI/ANS-5.1-1979 and ANSI/ANS-5.1-1994.
It is suitable for shutdown time $t \leq 10^4$ sec.

SIGMA A factor used to apply one-sigma statistical uncertainty to the ANSI/ANS-5.1 decay heat of 1979 or 1994. It is not applied to the Way-Wigner decay heat equation.
Recommended value: 1.02

CPM1 Instead of the *constant* assembly heat capacitance (MJ/°F) input on card 4, use the temperature-dependent value *CPM1 + CPM2*T* where T (°F) is the temperature of the fuel assembly. It is used only if CPM2 is non-zero.

CPM2 Coefficient of temperature in assembly heat capacitance. See the input CPM1 above.

TFIN Fuel plate temperature when they are initially uncovered, °F
Recommended value is the ambient air temperature, or the pool water temperature, i.e., TTA (input on card 4).

Card 7 Alphanumeric comment card, (required)
FORMAT (20A4)

Card 8 NWEEKS, NDAYS, KPRINT
FORMAT (3I6)

NWEEKS Number of weeks of pre-LOCA reactor operation cycles of time TOP minutes at the assembly power PA. (TOP and PA are input on card 4.) The decay heat used in the LOCA analysis is calculated assuming that the reactor has operated for NWEEKS weeks, NDAYS per week, for time TOP minutes per day. The reactor is assumed to be shutdown every week on the remaining days of the week, i.e., 7-NDAYS days. Also, the reactor is assumed to be shutdown every day for the remaining part of the day, i.e.,
24x60 – TOP minutes per day. (Default: NWEEKS = 1)

NDAYS Number of days per week on which the reactor is operated.
(Default: NDAYS = 1)
For example, if a reactor has operated prior to LOCA for 10 weeks, 5 days per week, 14 hours per day, then use the input data
NWEEKS = 10, NDAYS = 5, and TOP = 14x60 minutes.

Note: If NDAYS = 1, then the reactor operating schedule is to operate TOP minutes per week, for NWEEKS weeks. For example, if a reactor has operated for 10 weeks, 120 hours per week,
then use the input data NWEEKS = 10, NDAYS = 1, and
TOP = 120x60 minutes.

KPRINT 0, Standard output without debug prints

A Typical Input Data File

```
Fully Uncovered LOCA of UVAR 18-Plate HEU Core of 1984, ANL input data
Operating at 2 MW for 120 hr, Fuel Assembly Power = 0.196 MW
COEF        CPM         TTA         PA          TOP         TDC
1.30E-06    3.10E-03    100.0       0.196       7200.0      10.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
190.0       0     0     1.0
NWEEK NDAYS KPRINT
1     1     0
```

APPENDIX B – Input Data Files Used in the One-Node Model for All 18 LOCA Tests in Which Irradiated Oak Ridge Research Reactor Assemblies Were Hung in Air (Table 2 lists these tests)

Test 1

```
Fully Uncovered LOCA Analysis of Fuel Assembly ORR-103 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.578       19260.0     5030.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0
```

Test 2

```
Fully Uncovered LOCA Analysis of Fuel Assembly ORR-103 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.578       19260.0     7780.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0
```

Test 3

```
Fully Uncovered LOCA Analysis of Fuel Assembly ORR-103 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.578       19260.0     9155.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0
```

Test 4

```
Fully Uncovered LOCA Analysis of Fuel Assembly ORR-103 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.578       19260.0     10710.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0
```

Test 5

```
Fully Uncovered LOCA Analysis of Fuel Assembly ORR-103 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.578       19260.0     12090.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0
```

Test 6

```
Fully Uncovered LOCA Analysis of Fuel Assembly ORR-103 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.578       19260.0     13050.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
```

```
NWEEK NDAYS KPRINT
1     1     0
Test 7

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-87 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        1.151       19260.0     6165.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0

Test 8

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-87 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        1.151       19260.0     10485.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0


Test 9

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-97 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.780       19260.0     6410.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0

Test 10

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-94 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.776       8640.0      46675.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0

Test 11

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-82 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.782       12000.0     1985.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0

Test 12

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-100 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.855       12000.0     1810.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0
```

```
Test 13

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-151 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        1.008       12000.0     1630.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0

Test 14

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-158 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.743       25020.0     43265.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0

Test 15

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-87* hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        0.760       25020.0     43265.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0

Test 16

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-164 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        1.000       32160.0     1112.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0

Test 17

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-164 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        1.000       32160.0     2367.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0

Test 18

Fully Uncovered LOCA Analysis of Fuel Assembly ORR-164 hanging in air
assuming ORR-164 operating power = 1.0 MW
COEF        CPM         TTA         PA          TOP         TDC
4.54E-06    2.81E-03    90.0        1.000       32160.0     3607.0
TDCEND      IOPT  IOPTG SIGMA       CPM1        CPM2        TFIN
160.0       0     0
NWEEK NDAYS KPRINT
1     1     0
```

APPENDIX C – FORTRAN Program to Find the Aluminum and UAl_4 Masses, and the Heat Capacitance of a Fuel Assembly of the Low Intensity Testing Reactor

```
C     Calculate Al mass per fuel assembly, UAl4 mass per fuel assembly,
C     M*Cp per fuel assembly for use in the one-node LOCA analysis code.
C
C     Low Intensity Testing Reactor (LITR) data from report ORNL-4169
C     It has 2 grid plates, one at bottom and the other at top of fuel assembly.
C     U-Al alloy fuel, assuming the alloy to be aluminum and UAl4
C
      DATA CP_U/116.0/, CP_AL/984.0/, CP_U3SI2/220.0/
      DATA CP_UAL3/371.0/, CP_UAL4/521.0/
      DATA RHO_U/19070.0/, RHO_AL/2702.0/, RHO_U3SI2/12200.0/
      DATA RHO_UAL3/6800.0/, RHO_UAL4/5700.0/
C     CP_U, CP_AL, CP_U3SI2 = Sp heat of U, Al, U3SI2 at 200C, J/kg-C
C     RHO_U, RHO_AL, RHO_U3SI2 = Density of U, Al, U3SI2, kg/m**3
      PI=3.14159265
C     Fuel meat data
      NPLATE=18
      H_MEAT=0.5969
      T_MEAT=0.508E-3
      W_MEAT=0.0635
      AM_U235=0.135
C     AM_U235 = Mass of U-235 per fuel assembly, kg
      AM_U=AM_U235/0.934
C     U enrichment of LEU core = (U-235 mass)/(U mass) = 0.1975
C     U enrichment of HEU core = (U-235 mass)/(U mass) = 0.934
C
C     Find UAl4 mass in meat per subass, Al mass in meat per subass, and
C     Al mass in rest of plate per subass.
      AM_UAL4=AM_U/0.640
      V_UAL4=AM_UAL4/RHO_UAL4
      V_MEAT=H_MEAT *T_MEAT *W_MEAT *FLOAT(NPLATE)
      VFUAL4=V_UAL4/V_MEAT
      VFP=0.0
C     See IAEA-TECDOC-463, Vol. 4, Porosity in UAlx dispersion fuel varies
C     from 0.03 to 0.12; zero porosity in alloy.
      VF_AL=1.0-VFUAL4-VFP
      WF_U=AM_U/(AM_UAL4 + VF_AL*V_MEAT*RHO_AL)
C     VFUAL4= Volume fraction of UAL4 in meat
C     VFP = Porosity volume fraction in meat
C     VF_AL = Volume fraction of Aluminum in meat
C
C     Fuel plate data
      H_PLATE=0.6382
      H_PLATE2=0.7271
C     H_PLATE2 = Height of first and last plates in a fuel assembly
      T_PLATE=1.270E-3
      T_PLATE2=1.650E-3
C     T_PLATE2 = Thickness of first and last plates in a fuel assembly
      W_PLATE=0.07102
      T_CLAD=0.381E-3
C     Side plates with grooves
      H_SIDEP=0.7271
      T_SIDEP=4.75E-3
      W_SIDEP=0.0805
      D_GROOV=0.138*0.0254
      T_GROOV=0.055*0.0254
C
C     V_AL1 = Volume of Al in all plates of a fuel assembly, m**3
      V_PLATE =H_PLATE * T_PLATE * W_PLATE
      V_PLATE2=H_PLATE2* T_PLATE2* W_PLATE
      V_AL1=V_PLATE*FLOAT(NPLATE-2) +V_PLATE2*2.0 +(VF_AL -1.0)*V_MEAT
      AM_AL1=V_AL1*RHO_AL
C
C     Get volume of two side plates
```

```
      V_SIDEP=H_SIDEP*T_SIDEP*W_SIDEP-
     1 FLOAT(NPLATE)*H_SIDEP*D_GROOV*T_GROOV
      V_SIDEP=V_SIDEP*2.0
      AM_AL2=V_SIDEP*RHO_AL
C
C     AM_AL3 = Mass of lower plus upper end boxes in a fuel assembly, kg
C              Rectangular cross section, 7.144 by 7.223 cm on the outside,
C              5.715 by 5.794 cm on the inside, combined length 28.53 cm
      VOL_AL3=28.53*(7.144*7.223 - 5.715*5.794)*1.0E-06
      AM_AL3=RHO_AL*VOL_AL3
C
C     AM_AL4 = Mass of grid plate per pitch, kg
C              The rectangular area per fuel assembly, 7.7 by 8.1 cm,
C              is determined by grid spacing, in which there is a hole,
C              5.86 by 5.86 cm, for nozzle.  The lower grid is 15.24 cm thick.
C              The upper grid plate thickness is assumed 50% of the lower.
      VOL_AL4=(7.7*8.1-5.86*5.86)*15.24*1.0E-06 *1.5
      AM_AL4=VOL_AL4*RHO_AL
C
C     CPM= Fuel assembly mass * specific heat (MJ/F)
      AM_AL=AM_AL1+AM_AL2+AM_AL3+AM_AL4
      CPM=AM_AL*CP_AL + AM_UAL4*CP_UAL4
C     Convert the units of CPM from J/C to MJ/F
      CPM1=CPM/(1.8E+06)
      WRITE(6,1) WF_U
   1  FORMAT(/,'U wt fraction in U-Al alloy meat =',F6.3,/,
     1 'It should be < 0.25 for this calculation to be good.')
      WRITE(6,2) AM_AL1,AM_AL2,AM_AL3,AM_AL4,AM_AL,AM_UAL4,CPM,CPM1
   2  FORMAT(/,'Mass of Alumunum per fuel assembly:',/,
     2 '     in fuel meat and cladding, kg            =',1P,E12.4,/,
     3 '     in the pair of side plates, kg           =',E12.4,/,
     4 '     in the nozzles, kg                       =',E12.4,/,
     5 '     in grid plate, kg                        =',E12.4,/,
     6 '     Total Aluminum, kg                       =',E12.4,/,
     7 'Mass of UAl4 (fuel) per fuel assembly, kg     =',E12.4,/,
     8 'Fuel assembly mass * specific heat, J/deg C   =',E12.4,/,
     9 'Fuel assembly mass * specific heat, MJ/deg F  =',E12.4)
      END
```

APPENDIX D – ANSI/ANS-5.1 Decay Heat Power Due to a Single or Multiple Cycles of Reactor Operation

As defined by the ANSI/ANS-5.1 standard [11, 12], the decay heat power due to a single fission at time zero is f(t) MeV/sec. The function f(t) is empirically written as a sum of 23 exponentials as follows. The parameters α_i and λ_i in the empirical Eq. (D.1) depend upon the fissile isotope, and are reproduced here in Table D.1 for convenience.

$$f(t) = \sum_{i=1}^{23} \alpha_i \, exp(-\lambda_i t) \qquad \text{(D.1)}$$

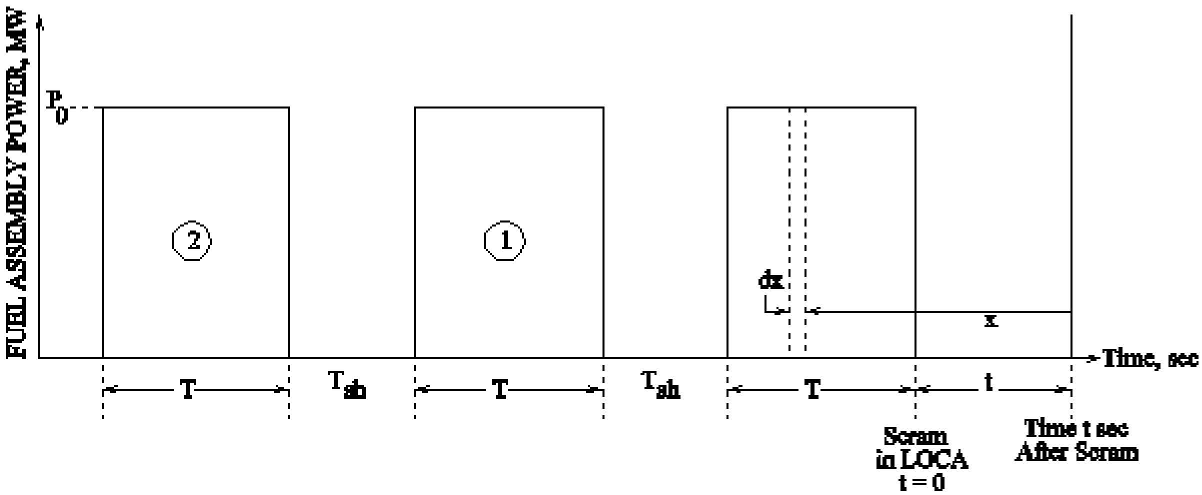


Figure D.1. Diagram Showing Cycles of a Fuel Assembly Operation at Power P_0 (MW) for Time T (sec) with a Shutdown Time of T_{sh} (sec) Between Two Consecutive Reactor Operations

The fuel assembly operating power P_0 (MW) is converted into fission rate as follows.

Operating power = P_0 MW = $P_0 C_1$ MeV/sec where $C_1 = 6.241496\times10^{18}$ MeV per MJ
= $P_0 C_1/E_r$ fissions/sec where E_r = 202.2 MeV per fission

The number of fissions in the differential time interval dx = $\frac{P_0 C_1}{E_r} dx$ (D.2)

Decay power (MeV/sec) due to the fissions in Eq. (D.2), at time t sec after shutdown

$$= \frac{P_0 C_1}{E_r} dx \, f(x) \qquad \text{(D.3)}$$

If a U^{235}-fueled fuel assembly has operated for time T (sec) at a constant power P_0 (MW) after which the reactor is shutdown at time t = 0, the decay power (MeV/sec) at time t (sec) after shutdown is obtained by integrating Eq. (D.3) over the time of reactor operation.

Decay power (MeV/sec) due to reactor operation over the time T sec just before the scram in the above diagram = $\frac{P_0 C_1}{E_r} \int_{x=t}^{T+t} dx \, f(x)$ (D.4)

The decay power given by Eq. (D.4) can be converted into MW by dividing by C_1, and this gives the decay power (MW) at time t sec after scram, due to the reactor operation for T sec just before the scram. This gives Eq. (D.5) for the decay power P'(t) (MW) due to a single constant power operation. Putting f(x) from Eq. (D.1) into Eq. (D.5) and integrating, one obtains Eq. (D.6).

$$P'(t) = \frac{P_0}{E_r} \int_{x=t}^{T+t} dx\, f(x) \tag{D.5}$$

$$P'(t) = \frac{P_0}{E_r} \sum_{i=1}^{23} \frac{\alpha_i}{\lambda_i}\, exp(-\lambda_i t)\,[1 - exp(-\lambda_i T)] \tag{D.6}$$

Equation (D.6) gives the decay power without the absorption correction and without accounting for the statistical uncertainties in the decay heat data used to develop the standard ANSI/ANS-5.1. To apply the absorption correction, the decay power of Eq. (D.6) is multiplied by a factor $G_{max}(t)$, a function of the time after shutdown, given in the ANSI/ANS-5.1 standard of 1979 and 1994 [11, 12]. These data are reproduced here in Table D.2 for convenience. The one sigma uncertainty of the decay power due to U^{235} fissions varies from 1.7% to 2.0% depending upon the time after shutdown in the range 8 sec ≤ t ≥ 6.0×10^7 sec in the 1979 standard, and it varies from 1.7% to 2.1% for the same range of the time after shutdown in the 1994 standard. In the LOCA analyses of research and test reactors, the decay time after shutdown is limited to some months which is well within the above range, and the decay power is therefore multiplied by a fixed factor of 1.02 to add the one sigma uncertainty. The fuel assembly decay power including the absorption correction and one sigma uncertainty is given by

$$P(t) = 1.02\, G_{max}(t) \frac{P_0}{E_r} \sum_{i=1}^{23} \frac{\alpha_i}{\lambda_i}\, exp(-\lambda_i t)\,[1 - exp(-\lambda_i T)] \tag{D.7}$$

The fuel assembly decay power P_N (MW) after N cycles of the assembly operation at power P_0 for T (sec) with a shutdown time T_{sh} (sec) between two consecutive operations (as shown in the above diagram) can be found by adding the decay heat contribution of the earlier (N-1) cycles to Eq. (D.7). The contribution of the just previous operation cycle (marked as 1 in the diagram) is found by simply replacing t in Eq. (D.7) by $t+(T+T_{sh})$. The contribution of the cycle marked as 2 in the diagram is found by replacing t in Eq. (D.7) by $t+2(T+T_{sh})$, and so on.

$$P_N(t) = P(t) + \sum_{i=1}^{N-1} P(t + i\{T + T_{sh}\}) \tag{D.8}$$

Table D.1. Parameters for U^{235} Thermal Fission in Decay Heat Functions f(t) and F(t,T)[a] of ANSI/ANS-5.1 Standards of 1979 and 1994

ANSI/ANS-5.1 Standard of 1979			ANSI/ANS-5.1 Standard of 1994		
Index i	α_i	λ_i	Index i	α_i	λ_i
1	0.65057	22.138	1	5.2800×10^{-4}	2.7216
2	0.51264	0.51587	2	0.68588	1.0256
3	0.24384	0.19594	3	0.40752	0.31419
4	0.13850	0.10314	4	0.21937	0.11788
5	5.5440×10^{-2}	3.3656×10^{-2}	5	5.7701×10^{-2}	3.4365×10^{-2}
6	2.2225×10^{-2}	1.1681×10^{-2}	6	2.2530×10^{-2}	1.1762×10^{-2}
7	3.3088×10^{-3}	3.5870×10^{-3}	7	3.3392×10^{-3}	3.6065×10^{-3}
8	9.3015×10^{-4}	1.3930×10^{-3}	8	9.3667×10^{-4}	1.3963×10^{-3}
9	8.0943×10^{-4}	6.2630×10^{-4}	9	8.0899×10^{-4}	6.2608×10^{-4}
10	1.9567×10^{-4}	1.8906×10^{-4}	10	1.9572×10^{-4}	1.8924×10^{-4}
11	3.2535×10^{-5}	5.4988×10^{-5}	11	3.2609×10^{-5}	5.5074×10^{-5}
12	7.5595×10^{-6}	2.0958×10^{-5}	12	7.5827×10^{-6}	2.0971×10^{-5}
13	2.5232×10^{-6}	1.0010×10^{-5}	13	2.5189×10^{-6}	9.9940×10^{-6}
14	4.9948×10^{-7}	2.5438×10^{-6}	14	4.9836×10^{-7}	2.5401×10^{-6}
15	1.8531×10^{-7}	6.6361×10^{-7}	15	1.8523×10^{-7}	6.6332×10^{-7}
16	2.6608×10^{-8}	1.2290×10^{-7}	16	2.6592×10^{-8}	1.2281×10^{-7}
17	2.2398×10^{-9}	2.7213×10^{-8}	17	2.2356×10^{-9}	2.7163×10^{-8}
18	8.1641×10^{-12}	4.3714×10^{-9}	18	8.9582×10^{-12}	3.2956×10^{-9}
19	8.7797×10^{-11}	7.5780×10^{-10}	19	8.5968×10^{-11}	7.4225×10^{-10}
20	2.5131×10^{-14}	2.4786×10^{-10}	20	2.1072×10^{-14}	2.4681×10^{-10}
21	3.2176×10^{-16}	2.2384×10^{-13}	21	7.1219×10^{-16}	1.5596×10^{-13}
22	4.5038×10^{-17}	2.4600×10^{-14}	22	8.1126×10^{-17}	2.2573×10^{-14}
23	7.4791×10^{-17}	1.5699×10^{-14}	23	9.4678×10^{-17}	2.0503×10^{-14}

Note a. $f(t) = \sum_{i=1}^{23} \alpha_i \, exp(-\lambda_i t) \quad MeV \, / \sec per \, fission$

$$F(t,T) = \sum_{i=1}^{23} \frac{\alpha_i}{\lambda_i} \, exp(-\lambda_i t)[1 - exp(-\lambda_i T)] \, MeV \, / \, fission$$

T and t in seconds

Users are cautioned that double precision may be required to accurately calculate these sums of exponentials.

Table D.2. Ratio (G_{max}) of Decay with Absorption to Values without Absorption (Taken From ANSI/ANS-5.1 Standards of 1979 and 1994)

Time After Shutdown, t, sec	$G_{max}(t)$ of 1979 Standard	$G_{max}(t)$ of 1994 Standard	Time After Shutdown, t, sec	$G_{max}(t)$ of 1979 Standard	$G_{max}(t)$ of 1994 Standard
1.0	1.020	1.020	$1.5x10^5$	1.130	1.130
1.5	1.020	1.020	$2.0x10^5$	1.131	1.131
2.0	1.020	1.020	$4.0x10^5$	1.126	1.126
4.0	1.021	1.021	$6.0x10^5$	1.124	1.124
6.0	1.022	1.022	$8.0x10^5$	1.123	1.123
8.0	1.022	1.022	10^6	1.124	1.124
10.0	1.022	1.022	$1.5x10^6$	1.125	1.125
15.0	1.022	1.022	$2.0x10^6$	1.127	1.127
20.0	1.022	1.022	$4.0x10^6$	1.134	1.134
40.0	1.022	1.022	$6.0x10^6$	1.146	1.146
60.0	1.022	1.022	$8.0x10^6$	1.162	1.162
80.0	1.022	1.022	10^7	1.181	1.181
10^2	1.023	1.023	$1.5x10^7$	1.233	1.233
$1.5x10^2$	1.024	1.024	$2.0x10^7$	1.284	1.284
$2.0x10^2$	1.025	1.025	$4.0x10^7$	1.444	1.444
$4.0x10^2$	1.028	1.028	$6.0x10^7$	1.535	1.535
$6.0x10^2$	1.030	1.030	$8.0x10^7$	1.586	1.586
$8.0x10^2$	1.032	1.032	10^8	1.598	1.598
10^3	1.033	1.033	$1.5x10^8$	1.498	1.498
$1.5x10^3$	1.037	1.037	$2.0x10^8$	1.343	1.343
$2.0x10^3$	1.039	1.039	$3.0x10^8$	-	1.15
$4.0x10^3$	1.048	1.048	$4.0x10^8$	1.065	1.065
$6.0x10^3$	1.054	1.054	$6.0x10^8$	1.021	1.021
$8.0x10^3$	1.060	1.060	$8.0x10^8$	1.012	1.012
10^4	1.064	1.064	10^9	1.007	1.007
$1.5x10^4$	1.074	1.074	$1.5x10^9$		1.005
$2.0x10^4$	1.081	1.081	$2.0x10^9$		1.002
$4.0x10^4$	1.098	1.098	$4.0x10^9$		1.0
$6.0x10^4$	1.111	1.111	$6.0x10^9$		1.0
$8.0x10^4$	1.119	1.119	$8.0x10^9$		1.0
10^5	1.124	1.124	10^{10}		1.0

APPENDIX E – Draining Time of the RPI Pool from the Trip Level t the Grid Plate

Following the 1996 LOCA analysis for the HEU core, the 12-inch primary circuit pipe through which water normally returns to the pool is assumed to rupture just outside the pool wall. The gate between the two parts of the pool is assumed to be open (otherwise the water in the reactor-containing part of the pool will be drained very slowly and that will keep the reactor cool longer). The water in the pool begins to drain through both the cold leg pipe and the hot leg pipe. The draining in both pipes is driven by the same water head above the rupture location. To be conservative (smaller draining time), the hydraulic resistance of the cold leg is assumed to be zero, with the hot leg having the hydraulic resistance of the whole primary circuit. The primary pump is assumed to be stopped before the reactor scram. Performing a Bernoulli-type fluid flow energy balance between the pool water surface and the location of pipe rupture gives Eq. (E.1) for the water discharge velocity V_1 in the cold leg pipe at any time t second after the rupture. A similar energy balance gives Eq. (E.2) for the water discharge velocity V_2 in the hot leg pipe. Figure 5 shows the vertical positions of the reactor core, rupture location and trip level required for calculating the draining time, and Fig. 7 shows the horizontal surface area of water in the pool.

$$V_1 = \sqrt{2gH} \qquad \text{(E.1)}$$

$$V_2 = \frac{\sqrt{2gH}}{\sqrt{K_2+1}} \qquad \text{(E.2)}$$

where

A_1 = Flow area in the primary pipe, m² = 0.25π x (0.3048)² = 0.07297 m²

A_2 = Area of free surface of water in both parts of the pool, m² = 51.8 m² (see Fig. 7)

A_{2c} = Area of free surface of water in the core-containing part of the pool, m² = 17.7 m²

D = Diameter of the primary loop pipe, m

f = Moody friction factor = $0.184/Re^{0.2}$ for smooth pipe

g = acceleration due to gravity, m/s² = 9.8 m/s²

H(t) = Height of water level in the pool at any time t, above the pipe rupture location, m

H_1 = Height of the trip level above the pipe rupture location, m

H_2 = Height of the grid plate above the pipe rupture location, m

L = Length of pipe in the primary circuit, m

L_c = Length of pipe in the hot leg from the core to just outside the pool wall, m = 12.5 m

K_2 = Total head loss coefficient for the whole primary circuit = $2g\Delta h_p/(Q/A_1)^2$ = 191.5

K_c = Frictional pressure drop of the core expressed as a loss coefficient = $\frac{2g\Delta h_c}{(Q/A_1)^2}$ = 13.0

Q = Nominal volumetric flow rate in the primary circuit, m³/s
= 0.06 m³/s for the RPI

Re = Reynolds number

T_d = Time required to drain the pool from the trip level to the grid plate level, s

$V_1(t)$ = Discharge velocity of water in the cold leg pipe, m/s

$V_2(t)$ = Discharge velocity of water in the hot leg pipe, m/s

Δh_p = Pressure head generated by the primary pump during normal operation in the intact primary circuit at the nominal flow rate , m = 6.6 m of water for the RPI

The total head loss coefficient K_2 equals fL/D for the pipe length plus the sum of all major and minor loss coefficients for components in the primary circuit. Using the nominal operating coolant volumetric flow rate (Q = 0.06 m^3/s) and the corresponding frictional pressure drop (equal to the operating pump head, Δh_p = 6.6 m of water) in the intact primary circuit, K_2 is computed to be 191.5. The Moody friction factor f is a function of water velocity which changes with time, and hence fL/D is not constant. During the draining, the water velocity *decreases* with falling water level, the Reynolds number decreases, and the friction factor increases. It will be conservative to fix fL/D at *its initial value* (and keep K_2 fixed) during the draining of the pool because it will result in higher water velocities and a smaller draining time.

The sum of volumetric flow rates through both pipes is related to the rate of fall of water level in the pool as follows (all symbols are listed above).

$$-A_2\,\frac{dH}{dt} = A_1\left(\sqrt{2gH} + \frac{\sqrt{2gH}}{\sqrt{K_2+1}}\right) \qquad \text{(E.3)}$$

For constant K_2, Eq. (E.3) can be rewritten as Eq. (E.4) and integrated to find the time T_d taken to drain the pool from the reactor trip level to the grid plate level (see Fig. 5).

$$-C_1\frac{dH}{dt} = H^{1/2} \qquad \text{where } C_1 = \frac{A_2}{A_1\sqrt{2g}\,\left[1+\sqrt{1/(K_2+1)}\right]} \qquad \text{(E.4)}$$

$$T_d = \frac{A_2}{A_1}\sqrt{\frac{2}{g}}\;\frac{\left(\sqrt{H_1}-\sqrt{H_2}\right)}{\left[1+\sqrt{1/(K_2+1)}\right]} \qquad \text{(E.5)}$$

Using H_1 = 7.776 m, and H_2 = 0.180 m (see Fig. 5), the water velocities in the cold leg and hot leg pipes are found to be 12.35 m/s and 0.89 m/s when the water level is at the trip level. For the water level in the *combined pool* to fall from the trip level to the grid plate bottom, the draining time is found to be 707 sec. This draining time is an underestimate (conservative) because the flow resistance of the diffuser in the cold leg is not included in Eq. (E.1) for velocity V_1 which causes most of the draining. It is also shown below to be smaller than the draining time of *only the reactor-containing part* of the pool (with the partitioning gate closed) in the case of a hot leg pipe rupture near the pool wall.

If the hot leg is assumed to rupture just outside the pool wall, and to make the accident more severe the gate between the two parts of the pool is assumed to be closed, thus isolating the reactor-containing part of the pool from the other (bigger) part, the draining time T_{d1} for the water level in the *reactor-containing part* of the RPI pool to fall through the same heights is given Eq. (E.6) below.

$$T_{d1} = \frac{A_{2c}}{A_1}\sqrt{\frac{2}{g}}\;\frac{\left(\sqrt{H_1}-\sqrt{H_2}\right)}{\sqrt{1/(K_c+fL_c\,/D+1)}} \qquad \text{where } fL_c/D = 0.60 \qquad \text{(E.6)}$$

The frictional loss coefficient K_c of the core is found from the frictional pressure drop in the core (0.45 m of water) under normal operating conditions of the reactor. Using H_1 = 7.776 m, H_2 = 0.180 m, and the horizontal area of the core-containing part of the pool A_{2c} = 17.7 m^2, the draining time T_{d1} for the hot leg rupture is found to be 991 sec which is more than the draining time found above for the cold leg rupture.

APPENDIX F – FORTRAN Programs to Find the Heat Capacitance of an Assembly of the RPI Highly Enriched Uranium Core

Program for a HEU Standard Fuel Assembly

```
C     Calculate Al mass per subassembly, UAl4 mass per subassembly,
C     M*Cp per subassembly for use in the one-node LOCA analysis code.
C     Portuguese Research Reactor (RPI) HEU Core (Nov 14, 2006, ANL)
C     U-Al alloy fuel, assuming the alloy to be aluminum and UAl4
C
      DATA CP_U/116.0/, CP_AL/984.0/, CP_U3SI2/220.0/
      DATA CP_UAL3/371.0/, CP_UAL4/521.0/
      DATA RHO_U/19070.0/, RHO_AL/2700.0/, RHO_U3SI2/12200.0/
      DATA RHO_UAL3/6800.0/, RHO_UAL4/5700.0/
C     CP_U, CP_AL, CP_U3SI2 = Sp heat of U, Al, U3SI2 at 200C, J/kg-C
C     RHO_U, RHO_AL, RHO_U3SI2 = Density of U, Al, U3SI2, kg/m**3
      PI=3.14159265
C     Fuel meat data
      NPLATE=18
      H_MEAT=0.5969
      T_MEAT=0.508E-3
      W_MEAT=0.06335
      AM_U235=0.265
C     AM_U235 = Mass of U-235 per fuel subassembly, kg
      AM_U=AM_U235/0.934
C     U enrichment of LEU core = (U-235 mass)/(U mass) = 0.20
C     U enrichment of HEU core = (U-235 mass)/(U mass) = 0.934
C
C     Find UAl4 mass in meat per subass, Al mass in meat per subass, and
C     Al mass in rest of plate per subass.
      AM_UAL4=AM_U/0.640
      V_UAL4=AM_UAL4/RHO_UAL4
      V_MEAT=H_MEAT *T_MEAT *W_MEAT *FLOAT(NPLATE)
      VFUAL4=V_UAL4/V_MEAT
      VFP=0.07
C     See IAEA-TECDOC-463, Vol. 4, Porosity in UAlx varies from 0.03 to 0.12
C                                Average porosity = 0.07
      VF_AL=1.0-VFUAL4-VFP
      WF_U=AM_U/(AM_UAL4 + VF_AL*V_MEAT*RHO_AL)
C     VFUAL4= Volume fraction of UAL4 in meat
C     VFP = Porosity volume fraction in meat
C     VF_AL = Volume fraction of Aluminum in meat
C
C     Fuel plate data
      H_PLATE=0.6255
      H_PLATE2=0.7144
C     H_PLATE2 = Height of first and last plates in a subassembly
      T_PLATE=1.270E-3
      T_PLATE2=1.270E-3
C     T_PLATE2 = Thickness of first and last plates in a subassembly
      W_PLATE=0.07102
      T_CLAD=0.381E-3
C     Side plates with grooves
      H_SIDEP=0.7144
      T_SIDEP=4.78E-3
      W_SIDEP=0.0798
      D_GROOV=3.505E-3
      T_GROOV=T_PLATE
C
C     V_AL1 = Volume of Al in all plates of a subassembly, m**3
      V_PLATE =H_PLATE * T_PLATE * W_PLATE
      V_PLATE2=H_PLATE2* T_PLATE2* W_PLATE
      V_AL1=V_PLATE*FLOAT(NPLATE-2) +V_PLATE2*2.0 +(VF_AL -1.0)*V_MEAT
      AM_AL1=V_AL1*RHO_AL
C
C     Get volume of two side plates
      V_SIDEP=H_SIDEP*T_SIDEP*W_SIDEP-
     1 FLOAT(NPLATE)*H_SIDEP*D_GROOV*T_GROOV
      V_SIDEP=V_SIDEP*2.0
```

```
      AM_AL2=V_SIDEP*RHO_AL
C
C     AM_AL3 = Mass of lower plus upper end boxes in a fuel subassembly, kg
C              Circular cross section, 6.03 cm OD, 5.08 cm ID, 12.70 cm long &
C              Rectangular cross section, 6.57 by 7.37 cm on outside with
C              6.35 cm ID hole, 4.45 cm long, combined length 17.15 cm
      VOL_AL3=(12.70*PI*0.25*(6.03*6.03 - 5.08*5.08) +
     1         4.45*(6.57*7.37-PI*0.25*6.35*6.35))*1.0E-06
      AM_AL3=RHO_AL*VOL_AL3
C
C     AM_AL4 = Mass of grid plate per pitch, kg
C              The rectangular area per fuel subassembly, 7.71 by 8.1 cm,
C              is determined by grid spacing, in which there is a hole of
C              6.03 cm D for nozzle. The grid plate is 12.70 cm thick.
      VOL_AL4=(7.71*8.1-PI*0.25*6.03*6.03)*12.70*1.0E-06
      AM_AL4=VOL_AL4*RHO_AL
C
C     CPM= Fuel assembly mass * specific heat (MJ/F)
      AM_AL=AM_AL1+AM_AL2+AM_AL3+AM_AL4
      CPM=AM_AL*CP_AL + AM_UAL4*CP_UAL4
C     Convert the units of CPM from J/C to MJ/F
      CPM1=CPM/(1.8E+06)
      WRITE(6,1) WF_U
    1 FORMAT(/,'U wt fraction in U-Al alloy meat =',F6.3,/,
     1 'It should be < 0.25 for this calculation to be good.')
      WRITE(6,2) AM_AL1,AM_AL2,AM_AL3,AM_AL4,AM_AL,AM_UAL4,CPM,CPM1
    2 FORMAT(/,'Mass of Alumunum per subassembly:',/,
     2 '     in fuel meat and cladding, kg            =',1P,E12.4,/,
     3 '     in the pair of side plates, kg           =',E12.4,/,
     4 '     in the nozzles, kg                       =',E12.4,/,
     5 '     in grid plate, kg                        =',E12.4,/,
     6 '     Total Aluminum, kg                       =',E12.4,/,
     7 'Mass of UAl4 (fuel) per subassembly, kg       =',E12.4,/,
     8 'Fuel assembly mass * specific heat, J/deg C   =',E12.4,/,
     9 'Fuel assembly mass * specific heat, MJ/deg F  =',E12.4)
      END
```

Program for a HEU Control Fuel Assembly

```
C     Calculate Al mass per subassembly, UAl4 mass per subassembly,
C     M*Cp per subassembly for use in the one-node LOCA analysis code.
C     Portuguese Research Reactor HEU Control Assembly, Dec 14, 2006
C     U-Al alloy fuel, assuming the alloy to be aluminum and UAl4
C
      DATA CP_U/116.0/, CP_AL/984.0/, CP_U3SI2/220.0/
      DATA CP_UAL3/371.0/, CP_UAL4/521.0/
      DATA RHO_U/19070.0/, RHO_AL/2700.0/, RHO_U3SI2/12200.0/
      DATA RHO_UAL3/6800.0/, RHO_UAL4/5700.0/
C     CP_U, CP_AL, CP_U3SI2 = Sp heat of U, Al, U3SI2 at 200C, J/kg-C
C     RHO_U, RHO_AL, RHO_U3SI2 = Density of U, Al, U3SI2, kg/m**3
      PI=3.14159265
C     Fuel meat data
      NPLATE=10
      H_MEAT=0.5969
      T_MEAT=0.508E-3
      W_MEAT=0.06335
      AM_U235=0.147
C     AM_U235 = Mass of U-235 per fuel subassembly, kg
      AM_U=AM_U235/0.934
C     U enrichment of LEU core = (U-235 mass)/(U mass) = 0.1975
C     U enrichment of HEU core = (U-235 mass)/(U mass) = 0.934
C
C     Find UAl4 mass in meat per subass, Al mass in meat per subass, and
C     Al mass in rest of plate per subass.
      AM_UAL4=AM_U/0.640
      V_UAL4=AM_UAL4/RHO_UAL4
      V_MEAT=H_MEAT *T_MEAT *W_MEAT *FLOAT(NPLATE)
      VFUAL4=V_UAL4/V_MEAT
      VFP=0.07
C     See IAEA-TECDOC-463, Vol. 4, Porosity in UAlx varies from 0.03 to 0.12
```

```
C                                  Average porosity = 0.07
      VF_AL=1.0-VFUAL4-VFP
      WF_U=AM_U/(AM_UAL4 + VF_AL*V_MEAT*RHO_AL)
C     VFUAL4= Volume fraction of UAL4 in meat
C     VFP = Porosity volume fraction in meat
C     VF_AL = Volume fraction of Aluminum in meat
C
C     Fuel plate data
      H_PLATE=0.6255
      H_PLATE2=0.7144
C     H_PLATE2 = Height of first and last plates in a subassembly
      T_PLATE=1.270E-3
      T_PLATE2=1.270E-3
C     T_PLATE2 = Thickness of first and last plates in a subassembly
      W_PLATE=0.07102
      T_CLAD=0.381E-3
C     Side plates with grooves
      H_SIDEP=0.7747
      T_SIDEP=4.78E-3
      W_SIDEP=0.0798
      D_GROOV=2.667E-3
      T_GROOV=T_PLATE
C     Guide plates data
      H_GUIDP=H_PLATE2
      T_GUIDP=3.18E-3
      W_GUIDP=W_PLATE
C     VOL_AL5 = Volume of 2 guide plates
      VOL_AL5=2.0*H_GUIDP *W_GUIDP *T_GUIDP
      AM_AL5=VOL_AL5*RHO_AL
C
C     Shock absorber data. It has 75% of 0.461"x2.995"x2.995" plus
C     a cylindrical shell of dia 2.543"xlength 4.5"x ave thickness 0.1075"
      VOL_AL6=16.387E-6*(PI*2.543*4.5*0.1075 + 0.75*0.461*2.995*2.995)
C     VOL_AL6 = Volume of control assembly shock absorber
      AM_AL6=VOL_AL6*RHO_AL
C
C     V_AL1 = Volume of Al in all fuel plates of an assembly, m**3
      V_PLATE =H_PLATE * T_PLATE * W_PLATE
      V_PLATE2=H_PLATE2* T_PLATE2* W_PLATE
      V_AL1=V_PLATE*FLOAT(NPLATE-2) +V_PLATE2*2.0 +(VF_AL -1.0)*V_MEAT
      AM_AL1=V_AL1*RHO_AL
C
C     Get volume of two side plates
      V_SIDEP=H_SIDEP*T_SIDEP*W_SIDEP-
     1 FLOAT(NPLATE)*H_SIDEP*D_GROOV*T_GROOV-
     2 2.0*H_SIDEP*D_GROOV*T_GUIDP
      V_SIDEP=V_SIDEP*2.0
      AM_AL2=V_SIDEP*RHO_AL
C
C     AM_AL3 = Mass of lower plus upper end boxes in a fuel subassembly, kg
C              Circular cross section, 6.03 cm OD, 5.08 cm ID, 12.70 cm long &
C              Rectangular cross section, 6.57 by 7.37 cm on outside with
C              6.35 cm ID hole, 4.45 cm long, combined length 17.15 cm
      VOL_AL3=(12.70*PI*0.25*(6.03*6.03 - 5.08*5.08) +
     1         4.45*(6.57*7.37-PI*0.25*6.35*6.35))*1.0E-06
      AM_AL3=RHO_AL*VOL_AL3
C
C     AM_AL4 = Mass of grid plate per pitch, kg
C              The rectangular area per fuel subassembly, 7.71 by 8.1 cm,
C              is determined by grid spacing, in which there is a hole of
C              6.03 cm D for nozzle. The grid plate is 12.70 cm thick.
      VOL_AL4=(7.71*8.1-PI*0.25*6.03*6.03)*12.70*1.0E-06
      AM_AL4=VOL_AL4*RHO_AL
C
C     CPM= Fuel assembly mass * specific heat (MJ/F)
      AM_AL=AM_AL1+AM_AL2+AM_AL3+AM_AL4+AM_AL5+AM_AL6
      CPM=AM_AL*CP_AL + AM_UAL4*CP_UAL4
C     Convert the units of CPM from J/C to MJ/F
      CPM1=CPM/(1.8E+06)
      WRITE(6,1) WF_U
    1 FORMAT(/,'U wt fraction in U-Al alloy meat =',F6.3,/,
```

```
     1 'It should be < 0.25 for this calculation to be good.')
      WRITE(6,2) AM_AL1,AM_AL2,AM_AL3,AM_AL5,AM_AL6,AM_AL4,
     1 AM_AL,AM_UAL4,CPM,CPM1
   2  FORMAT(/,'Mass of Alumunum per subassembly:',/,
     2 '      in fuel meat and cladding, kg            =',1P,E12.4,/,
     3 '      in the pair of side plates, kg           =',E12.4,/,
     4 '      in the nozzles, kg                       =',E12.4,/,
     5 '      in guide plates, kg                      =',E12.4,/,
     6 '      in shock absorber, kg                    =',E12.4,/,
     7 '      in grid plate, kg                        =',E12.4,/,
     8 '      Total Aluminum, kg                       =',E12.4,/,
     9 'Mass of UAl4 (fuel) per subassembly, kg       =',E12.4,/,
     1 'Fuel assembly mass * specific heat, J/deg C   =',E12.4,/,
     2 'Fuel assembly mass * specific heat, MJ/deg F  =',E12.4)
      END
```

APPENDIX G – FORTRAN Programs to Find the Heat Capacitance of an Assembly of the RPI Low Enriched Uranium Core

Program for a LEU Standard Fuel Assembly

```
C     Calculate Al mass per fuel assembly, U3Si2 mass per fuel assembly,
C     M*Cp per fuel assembly for use in the one-node LOCA analysis code.
C     Portuguese Research Reactor (RPI) LEU Core, Nov 14, 2006, ANL
C
      DATA CP_U/116.0/, CP_AL/984.0/, CP_U3SI2/220.0/
      DATA RHO_U/19070.0/, RHO_AL/2700.0/, RHO_U3SI2/12200.0/
C     CP_U, CP_AL, CP_U3SI2 = Sp heat of U, Al, U3SI2 at 200C, J/kg-C
C     RHO_U, RHO_AL, RHO_U3SI2 = Density of U, Al, U3SI2, kg/m**3
      PI=3.14159265
C     Fuel meat data
      NPLATE=18
      H_MEAT=0.5969
      T_MEAT=0.608E-3
      W_MEAT=0.06335
      AM_U235=0.376
C     AM_U235 = Mass of U-235 per fuel assembly, kg
      AM_U=AM_U235/0.20
C     U enrichment of LEU core = (U-235 mass)/(U mass) = 0.20
C     U enrichment of HEU core = (U-235 mass)/(U mass) = 0.934
C
C     Find U3Si2 mass in meat per subass, Al mass in meat per subass, and
C     Al mass in rest of plate per subass.
      AM_U3SI2=AM_U/0.925
      V_U3SI2=AM_U3SI2/RHO_U3SI2
      V_MEAT=H_MEAT *T_MEAT *W_MEAT *FLOAT(NPLATE)
      VFU3SI2=V_U3SI2/V_MEAT
      VFP=0.072*VFU3SI2 -0.275*VFU3SI2**2 +1.32*VFU3SI2**3
C     See IAEA-TECDOC-463, Vol. 4, Porosity vs Vol frac of U3Si2 in meat
      VF_AL=1.0-VFU3SI2-VFP
C     VFU3SI2= Volume fraction of U3SI2 in meat
C     VFP = Porosity volume fraction in meat
C     VF_AL = Volume fraction of Aluminum in meat
C
C     Fuel plate data
      H_PLATE=0.6255
      H_PLATE2=0.7144
C     H_PLATE2 = Height of first and last plates in a fuel assembly
      T_PLATE=1.370E-3
      T_PLATE2=1.370E-3
C     T_PLATE2 = Thickness of first and last plates in a fuel assembly
      W_PLATE=0.07102
      T_CLAD=0.381E-3
C     Side plates with grooves
      H_SIDEP=0.7144
      T_SIDEP=4.78E-3
      W_SIDEP=0.0798
      D_GROOV=3.505E-3
      T_GROOV=T_PLATE
C
C     V_AL1 = Volume of Al in all plates of a fuel assembly, m**3
      V_PLATE =H_PLATE * T_PLATE * W_PLATE
      V_PLATE2=H_PLATE2* T_PLATE2* W_PLATE
      V_AL1=V_PLATE*FLOAT(NPLATE-2) +V_PLATE2*2.0 +(VF_AL -1.0)*V_MEAT
      AM_AL1=V_AL1*RHO_AL
C
C     Get volume of two side plates
      V_SIDEP=H_SIDEP*T_SIDEP*W_SIDEP-
     1 FLOAT(NPLATE)*H_SIDEP*D_GROOV*T_GROOV
      V_SIDEP=V_SIDEP*2.0
      AM_AL2=V_SIDEP*RHO_AL
C
C     AM_AL3 = Mass of lower plus upper end boxes in a fuel assembly, kg
C              Circular cross section, 6.03 cm OD, 5.08 cm ID, 12.70 cm long &
C              Rectangular cross section, 6.57 by 7.37 cm on outside with
```

```
C              6.35 cm ID hole, 4.45 cm long, combined length 17.15 cm
      VOL_AL3=(12.70*PI*0.25*(6.03*6.03 - 5.08*5.08) +
     1         4.45*(6.57*7.37-PI*0.25*6.35*6.35))*1.0E-06
      AM_AL3=RHO_AL*VOL_AL3
C
C     AM_AL4 = Mass of grid plate per pitch, kg
C              The rectangular area per fuel assembly, 7.71 by 8.1 cm,
C              is determined by grid spacing, in which there is a hole of
C              6.03 cm D for nozzle. The grid plate is 12.70 cm thick.
      VOL_AL4=(7.71*8.1-PI*0.25*6.03*6.03)*12.70*1.0E-06
      AM_AL4=VOL_AL4*RHO_AL
C
C     CPM= Fuel assembly mass * specific heat (MJ/F)
      AM_AL=AM_AL1+AM_AL2+AM_AL3+AM_AL4
      CPM=AM_AL*CP_AL + AM_U3SI2*CP_U3SI2
C     Convert the units of CPM from J/C to MJ/F
      CPM1=CPM/(1.8E+06)
      WRITE(6,2) AM_AL1,AM_AL2,AM_AL3,AM_AL4,AM_AL,AM_U3SI2,CPM,CPM1
    2 FORMAT(/,'Mass of Aluminum per fuel assembly:',/,
     2 '     in fuel meat and cladding, kg            =',1P,E12.4,/,
     3 '     in the pair of side plates, kg           =',E12.4,/,
     4 '     in the nozzles, kg                       =',E12.4,/,
     5 '     in grid plate, kg                        =',E12.4,/,
     6 '     Total Aluminum, kg                       =',E12.4,/,
     7 'Mass of U3Si2 (fuel) per fuel assembly, kg    =',E12.4,/,
     8 'Fuel assembly mass * specific heat, J/deg C   =',E12.4,/,
     9 'Fuel assembly mass * specific heat, MJ/deg F  =',E12.4)
      END
```

Program for a LEU Control Fuel Assembly

```
C     Calculate Al mass per subassembly, U3Si2 mass per subassembly,
C     M*Cp per subassembly for use in the one-node LOCA analysis code.
C     Portuguese Research Reactor LEU Control Assembly, Dec 12, 2006
C
      DATA CP_U/116.0/, CP_AL/984.0/, CP_U3SI2/220.0/
      DATA RHO_U/19070.0/, RHO_AL/2700.0/, RHO_U3SI2/12200.0/
C     CP_U, CP_AL, CP_U3SI2 = Sp heat of U, Al, U3SI2 at 200C, J/kg-C
C     RHO_U, RHO_AL, RHO_U3SI2 = Density of U, Al, U3SI2, kg/m**3
      PI=3.14159265
C     Fuel meat data
      NPLATE=10
      H_MEAT=0.5969
      T_MEAT=0.608E-3
      W_MEAT=0.06335
      AM_U235=0.2089
C     AM_U235 = Mass of U-235 per fuel subassembly, kg
      AM_U=AM_U235/0.1975
C     U enrichment of LEU core = (U-235 mass)/(U mass) = 0.1975
C     U enrichment of HEU core = (U-235 mass)/(U mass) = 0.934
C
C     Find U3Si2 mass in meat per subass, Al mass in meat per subass, and
C     Al mass in rest of plate per subass.
      AM_U3SI2=AM_U/0.925
      V_U3SI2=AM_U3SI2/RHO_U3SI2
      V_MEAT=H_MEAT *T_MEAT *W_MEAT *FLOAT(NPLATE)
      VFU3SI2=V_U3SI2/V_MEAT
      VFP=0.072*VFU3SI2 -0.275*VFU3SI2**2 +1.32*VFU3SI2**3
C     See IAEA-TECDOC-463, Vol. 4, Porosity vs Vol frac of U3Si2 in meat
      VF_AL=1.0-VFU3SI2-VFP
C     VFU3SI2= Volume fraction of U3SI2 in meat
C     VFP = Porosity volume fraction in meat
C     VF_AL = Volume fraction of Aluminum in meat
C
C     Fuel plate data
      H_PLATE=0.6255
      H_PLATE2=0.7144
C     H_PLATE2 = Height of first and last plates in a subassembly
      T_PLATE=1.370E-3
      T_PLATE2=1.370E-3
```

```
C     T_PLATE2 = Thickness of first and last plates in a subassembly
      W_PLATE=0.07102
      T_CLAD=0.381E-3
C     Side plates with grooves
      H_SIDEP=0.7747
      T_SIDEP=4.78E-3
      W_SIDEP=0.0798
      D_GROOV=2.667E-3
      T_GROOV=T_PLATE
C
C     Guide plates data
      H_GUIDP=H_PLATE2
      T_GUIDP=3.18E-3
      W_GUIDP=W_PLATE
C     VOL_AL5 = Volume of 2 guide plates
      VOL_AL5=2.0*H_GUIDP *W_GUIDP *T_GUIDP
      AM_AL5=VOL_AL5*RHO_AL
C
C     Shock absorber data. It has 75% of 0.461"x2.995"x2.995" plus
C     a cylindrical shell of dia 2.543"xlength 4.5"x ave thickness 0.1075"
      VOL_AL6=16.387E-6*(PI*2.543*4.5*0.1075 + 0.75*0.461*2.995*2.995)
C     VOL_AL6 = Volume of control assembly shock absorber
      AM_AL6=VOL_AL6*RHO_AL
C
C     V_AL1 = Volume of Al in all fuel plates of an assembly, m**3
      V_PLATE =H_PLATE * T_PLATE * W_PLATE
      V_PLATE2=H_PLATE2* T_PLATE2* W_PLATE
      V_AL1=V_PLATE*FLOAT(NPLATE-2) +V_PLATE2*2.0 +(VF_AL -1.0)*V_MEAT
      AM_AL1=V_AL1*RHO_AL
C
C     Get volume of two side plates
      V_SIDEP=H_SIDEP*T_SIDEP*W_SIDEP-
     1 FLOAT(NPLATE)*H_SIDEP*D_GROOV*T_GROOV-
     2 2.0*H_SIDEP*D_GROOV*T_GUIDP
      V_SIDEP=V_SIDEP*2.0
      AM_AL2=V_SIDEP*RHO_AL
C
C     AM_AL3 = Mass of lower plus upper end boxes in a fuel subassembly, kg
C              Circular cross section, 6.03 cm OD, 5.08 cm ID, 12.70 cm long &
C              Rectangular cross section, 6.57 by 7.37 cm on outside with
C              6.35 cm ID hole, 4.45 cm long, combined length 17.15 cm
      VOL_AL3=(12.70*PI*0.25*(6.03*6.03 - 5.08*5.08) +
     1         4.45*(6.57*7.37-PI*0.25*6.35*6.35))*1.0E-06
      AM_AL3=RHO_AL*VOL_AL3
C
C     AM_AL4 = Mass of grid plate per pitch, kg
C              The rectangular area per fuel subassembly, 7.71 by 8.1 cm,
C              is determined by grid spacing, in which there is a hole of
C              6.03 cm D for nozzle. The grid plate is 12.70 cm thick.
      VOL_AL4=(7.71*8.1-PI*0.25*6.03*6.03)*12.70*1.0E-06
      AM_AL4=VOL_AL4*RHO_AL
C
C     CPM= Fuel assembly mass * specific heat (MJ/F)
      AM_AL=AM_AL1+AM_AL2+AM_AL3+AM_AL4+AM_AL5+AM_AL6
      CPM=AM_AL*CP_AL + AM_U3SI2*CP_U3SI2
C     Convert the units of CPM from J/C to MJ/F
      CPM1=CPM/(1.8E+06)
      WRITE(6,2) AM_AL1,AM_AL2,AM_AL3,AM_AL5,AM_AL6,AM_AL4,
     1 AM_AL,AM_U3SI2,CPM,CPM1
    2 FORMAT(/,'Mass of Aluminum per subassembly:',/,
     2 '     in fuel meat and cladding, kg            =',1P,E12.4,/,
     3 '     in the pair of side plates, kg           =',E12.4,/,
     4 '     in the nozzles, kg                       =',E12.4,/,
     5 '     in guide plates, kg                      =',E12.4,/,
     6 '     in shock absorber, kg                    =',E12.4,/,
     7 '     in grid plate, kg                        =',E12.4,/,
     8 '     Total Aluminum, kg                       =',E12.4,/,
     9 'Mass of U3Si2 (fuel) per subassembly, kg      =',E12.4,/,
     1 'Fuel assembly mass * specific heat, J/deg C   =',E12.4,/,
     2 'Fuel assembly mass * specific heat, MJ/deg F  =',E12.4)
      END
```

APPENDIX H – Effect of the RPI LEU Core Lower Thermal Conductivity on the Calculated Maximum Plate Surface Temperature

The one-node LOCA model assumes that the reactor being analyzed has fuel and cladding thermal conductivities nearly equal to those of the Low Intensity Testing Reactor (LITR) because the model is semi-empirical and is calibrated to LOCA tests done in the LITR. In the following discussion, an assessment is made of the effect (on the calculated maximum plate temperature) of the thermal conductivity differences between the RPI LEU fuel assembly and the LITR fuel assembly. The effect in each direction (across plate thickness, plate width, and plate length) is discussed.

Effect across Plate Thickness: When the fuel plate surface temperature reaches its maximum during the LOCA transient, a quasi-steady state exits. Assuming all the decay heat flows out of the plate surfaces, the temperature drop from meat center to the cladding surface (ΔT_1) can be estimated by the following equation.

$$\Delta T_1 = \frac{P_d}{2\,N_p\,L_f\,w_f}\left(\frac{t_f}{4K_f}+\frac{t_c}{K_c}\right) \qquad \text{(H.1)}$$

where P_d is the decay heat power (W) of the fuel assembly, and other symbols are defined in Nomenclature after section 9. Putting into Eq. (H.1) the thermal conductivities of U-Al alloy meat, 1100 Al cladding, U_3Si_2 meat, and AG3NE cladding (158, 200, 75 and 130 W/m-°C respectively), ΔT_1 is found to be 0.002 °C and 0.004 °C for the standard fuel assembly N9 in the HEU and LEU cores respectively when the assembly is at its maximum plate surface temperature during the LOCA transient. It happens at 60.7 minutes from scram (14 minutes after draining + 46.7 minutes after draining to maximum temperature, see Table 14). At that time the reactor decay heat power is 9880 W (see Table 12 at 60 minutes from the scram). This reactor decay power gives the decay power of the assembly N9: $P_{d,HEU}$ = 9880×0.1187 = 1173 W (65 W per plate), and $P_{d,LEU}$ = 9880×0.1129 = 1115 W (62 W per plate). In conclusion, the temperature variation across the plate thickness is negligible in assembly N9.

When the control fuel assembly C3 is at its maximum plate surface temperature during the LOCA transient (at 87.3 minutes from scram), the reactor decay power is 8505 W. This reactor decay power gives the decay power of the assembly C3: $P_{d,HEU}$ = 8505×0.0815 = 693 W (69 W per plate), and $P_{d,LEU}$ = 8505×0.0823 = 700 W (70 W per plate). The decay power per plate in assembly C3 is nearly equal to that in assembly N9. In conclusion, the temperature variation across the plate thickness is negligible in assembly C3 also.

Effect along Plate Width: Having shown that the thermal resistance across the plate thickness is negligible, we proceed to estimate the temperature variation along the plate width. For heat flow along the plate width to the side plates of the fuel assembly, the heat source in the meat can be smeared over the plate thickness. If all the decay heat flowed along the plate width out to the side plates of the fuel assembly (and none to the cladding surfaces), the temperature drop from plate mid-width to the side plate (ΔT_2) can be estimated by the following equation. This is an upper bound on the temperature variation over plate width because some heat is actually removed by air as the heat flows to the side plates.

$$\Delta T_2 = \frac{P_d\, w_p}{8 N_p\, L_f\, (2K_c t_c + K_f t_f)} \tag{H.2}$$

Putting the above thermal conductivity values into Eq. (H.2), ΔT_2 is found to be 4.1 °C and 6.4 °C for the standard fuel assembly N9 in the HEU and LEU cores when the reactor decay heat power is 9880 W after 60 minutes from the scram, i.e., when the fuel assembly reaches the maximum plate surface temperature (as mentioned in section 3). The decay power per plate in the control fuel assembly C3 is nearly equal to that in the assembly N9, as shown above. In conclusion, the temperature variation over the plate width in the assemblies N9 and C3 are also small during the LOCA transient.

Effect over Plate Length: In the LITR tests 17 and 18, the plate surface temperature drop from its axial peak to a position six inches above was recorded to be 14 °C and 12.5 °C when the fuel assembly had reached the maximum temperature. The decay heat power of the LITR fuel assembly was 633 W and 794 W respectively at that time (see Tables 5 and 7). This temperature difference can be interpreted as the peak-to-average temperature difference ($\Delta T_{p\text{-}ave,LITR}$) because the temperature six inches above the core mid-height (in a 24 inch long plate) approximately represents the axial average temperature.

When the fuel assembly has reached its maximum temperature, a balance between heat generation and heat removal by air convection is established. *All the decay heat* is removed by air convection, either locally at the axial location where the heat is generated or after it has flowed by conduction to an axial distance from its location of generation. The axial temperature shape is therefore due to two causes: (1) mainly due to the axial shape of the decay heat source, and (2) to a lesser extent due to the thermal resistance of the fuel plate to heat conduction in the axial direction. Only *the latter* is worsened by meat and cladding thermal conductivities if they are lower than those in the LITR. The LITR is referred to here because the model is based on the LOCA tests performed in the LITR. Since the latter cause of axial temperature drop is smaller than the former, less than half of $\Delta T_{p\text{-}ave,LITR}$ ($0.5\Delta T_{p\text{-}ave,LITR}$ = 7 °C in LITR test 17) is worsened by lower-than-LITR thermal conductivities.

If U-Al alloy fuel and 1100 Al cladding (used in the LITR) were used in the RPI LEU fuel assembly, the RPI LEU plate will still have a peak-to-average plate temperature drop, say $\Delta T_{p\text{-}ave,LEU1}$. If it were the case, no correction would be required to the temperatures calculated by the model because the model is based on those fuel and cladding materials. The use in the LEU core of fuel and cladding having lower than the LITR thermal conductivities causes an *increment* in the peak-to-average temperature drop. This *increment* is not accounted for in the model and hence it provides an estimate of a correction to the calculated maximum plate temperature. If $\Delta T_{p\text{-}ave,LEU2}$ is the peak-to-average plate temperature drop in the actual RPI LEU plate (having U_3Si_2 fuel and AG3NE cladding), the correction is $\Delta T_{p\text{-}ave,LEU2} - \Delta T_{p\text{-}ave,LEU1}$.

Since the temperature drop is directly proportional to the decay power and inversely proportional to the thermal conductance of six inches of the plate length, the drop $\Delta T_{p\text{-}ave,LEU1}$ is estimated by scaling 7 °C (= $0.5\Delta T_{p\text{-}ave,LITR}$) by the ratio of the decay powers of RPI LEU and LITR fuel plates. The drop $\Delta T_{p\text{-}ave,LEU2}$ is estimated by scaling $0.5\Delta T_{p\text{-}ave,LITR}$ by two ratios: (1) the ratio of the decay powers of RPI LEU and LITR fuel plates, and (2) by the ratio of the thermal conductance of six inches of their fuel plate lengths. Using these ratios, the temperature drops are given by the following equations.

$$\Delta T_{p-ave,LEU1} = 0.5\Delta T_{p-ave,LITR}\ \frac{(P_d / N_p)_{LEU}}{(P_d / N_p)_{LITR}} \tag{H.3}$$

$$\Delta T_{p-ave,LEU2} = 0.5\Delta T_{p-ave,LITR} \frac{(P_d / N_p)_{LEU}}{(P_d / N_p)_{LITR}} \frac{\left|2K_c(t_c + a) + K_f t_f\right|_{LITR}}{\left|2K_c(t_c + a) + K_f t_f\right|_{LEU}}$$

$$\text{where } a = \frac{w_s t_s}{N_p w_p} \qquad \text{(H.4)}$$

The symbols used are defined in Nomenclature after section 9. The length (6 inches) cancels out in the ratio. The thickness "a" added to the cladding thickness in Eq. (H.4) accounts for the parallel conduction path provided by the side plates in the fuel assembly. The values of all parameters of Eq. (H.3) and Eq. (H.4) and the results are tabulated below.

Table H.1. Values of Parameters in Equations (H.3) and (H.4)

Parameter	LITR Fuel Assembly	RPI LEU Core	
		Standard Assembly N9	Control Assembly C3
K_c, W/m-°C	200	130	
K_f, W/m-°C	158	75	
t_c, mm	0.381	0.381	
t_f, mm	0.508	0.608	
a, mm	0.299	0.298	
w_s, mm	80.5	79.8	
t_s, mm	4.78	4.78	
w_p, mm	71.12	71.02	
$2 K_c (t_c + a) + K_f t_f$, W/°C	0.352	0.222	
$\Delta T_{p-ave,LITR}$, °C	14.0 [a]		
P_d, W	633 [a]	1115	700
N_p	18	18	10
$\Delta T_{p-ave,LEU1}$, °C		12.3	13.9
$\Delta T_{p-ave,LEU2}$, °C		19.6	22.1

Note a. For LITR test 17

For the standard fuel assembly N9, Eq. (H.3) gives $\Delta T_{p-ave,LEU1}$ = 12.3 °C, and Eq. (H.4) gives $\Delta T_{p-ave,LEU2}$ = 19.6 °C. The increment is 7.3 °C (= 19.6 – 12.3). This is the estimated correction for lower-than-LITR meat and cladding thermal conductivities. This correction may be added to the LEU core maximum plate surface temperatures for the assembly N9 given in Table 14.

For the control fuel assembly C3, Eq. (H.3) gives $\Delta T_{p-ave,LEU1}$ = 13.9 °C, and Eq. (H.4) gives $\Delta T_{p-ave,LEU2}$ = 22.1 °C. The increment is 8.2 °C (= 22.1 – 13.9). This is the estimated correction for lower-than-LITR meat and cladding thermal conductivities. This correction may be added to the LEU core maximum plate surface temperatures for the assembly C3 given in Table 14. No such correction is needed for the HEU core because the thermal conductivities of the HEU core and the LITR core are equal.

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