EVALUATION OF THE POSTULATED FRESH FUEL DROP SCENARIO IN THE RBMK INGALINA NUCLEAR POWER PLANT

B.R. Sehgal, A. Romas, and H.W. Cheng
Royal Institute of Technology
Nuclear Power Safety, S-10044 Stockholm, Sweden
sehgal@ne.kth.se; antanas@ne.kth.se; cheng@ne.kth.se

ABSTRACT

This paper is devoted to investigation of single fresh fuel drop scenario that is postulated to occur in the Ignalina Nuclear Power Plant with the modified ARROTTA code in combination with the CASMO-4 and WIMS-D4 lattice codes for cross section generation. The modified ARROTTA code can model the large size of a typical RBMK core, and the unique control rod configuration. It was also extensively validated. In order to properly analyse the dynamic consequences on the fresh fuel drop event, a simple hydraulic model was developed to estimate the drop velocity of the fresh fuel as a function of time. The force balance accounted for gravity, friction between fuel and coolant, local resistance, and buoyancy. The ARROTTA results show that the increase in reactivity is only about 0.3$ when a fresh fuel is dropped into a central empty channel without initiation of any control rod action. The overall core power is increased only by 3.5% although the local power variations are much larger. Therefore, for the Ignalina plant, it has been demonstrated that no core damage occurs for the postulated single fresh fuel drop event without any control or protection system activation.

1. INTRODUCTION

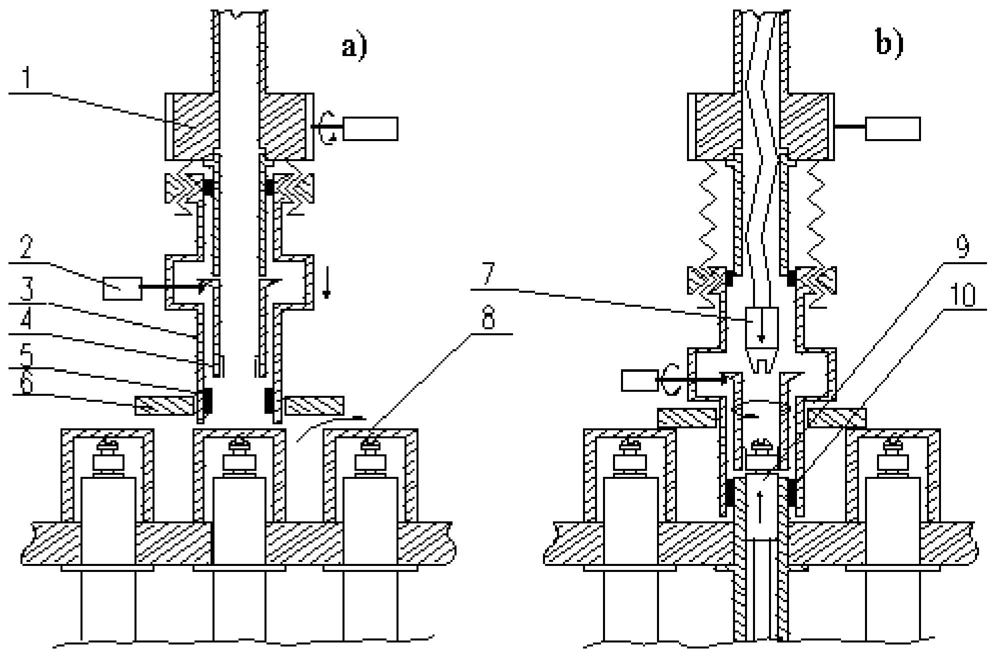
RBMK-type reactors, such as the Ignalina Nuclear Power Plant (INPP), employ the on-line refuelling capability as CANDO plants. This complicated operation is accomplished normally by an especially designed fuel handling system with a refuelling machine. The whole reloading process is comprised of several operations: 1) increase the pressure in the shell containing 30 ^{0}C water of the refuelling machine by pumps in order to force 30 ^{0}C water into the fuel channel being loaded with a fresh fuel, 2) unload a spent fuel assembly, and 3) load the fresh fuel assembly, lowering it slowly into the fuel channel. During on-line refuelling, a fresh fuel being loaded could be dropped into the active core from the refuelling machine. The work presented in this paper is devoted to investigation of the postulated incident of a fresh fuel drop with ARROTTA code.

For this study, the ARROTTA source code was modified. The problem size that ARROTTA can deal with was relaxed from 40x40x40 to 60x60x60 nodes since the RBMK core is much larger than a LWR core. More importantly, a RBMK control rod configuration was implemented into the ARROTTA source code. This configuration contains four types of control rods, i.e. traditional manual control rod (MCR), shortened absorber rod (SAR), fast acting scram rod (FASR) and re-designed manual control rod (RE+MCR). MCRs, RE-MCRs and FASRs are inserted from the top of the core while SARs are inserted from the bottom of the core like in a BWR. In the axial direction, these rods, except the fast acting scram rods, are generally comprised of absorber, linker, and follower, which were also modelled in the modification. So, cross sections for all the nodes in the control rod channels can be calculated during any static and dynamic analysis. The velocity function by which control rods may travel in CPS channels during transients can be defined, so that this modified ARROTTA version is able to investigate RBMK accidents such as control rod withdrawal, and control rod drop.

In addition, for analysis of a fresh fuel drop, a model was developed for estimating the drop velocity for the disconnected fresh fuel. The forces accounted for are gravity, friction between fuel and coolant, local resistance, and buoyancy. With this calculated drop velocity of a fresh fuel, the modified ARROTTA code can be used to analyse the dynamic consequences of the fresh fuel drop incident.

2. DESCRIPTION OF THE REFUELING PROCEDURE

The refuelling procedure begins by adjusting local reactor conditions according to the regulations, so that the water flow rate is increased up to 45 m^3/sec in the fuel channel being changed before the refuelling of fuel starts. The axial positions of surrounding control rods are constantly changed during refueling by the Automatic Control System (ACS). The ACS detectors located close to the refueled channel record the changes in neutron fluxes, and control rods are re-located according to these signals.



1 - standpipe control mechanism, 2 - special sealing key control mechanism, 3 - standpipe, 4 - special key, 5 - inflatable rubber sealing gaskets, 6 - bottom biological shield, 7 - grabber, 8 - enclosing clock, 9 - fuel channel seal plug, 10 - fuel channel body

Figure 1. The Schematic for the Refuelling Procedure

The schematic for the refuelling procedure is shown in Figure 1. The operation starts by positioning the refuelling machine above the top of fuel channel. After the refuelling machine is positioned, the machine and the channel are sealed. The standpipe control mechanism (1) lowers the standpipe (3), which encloses the upper portion of the fuel channel (10) as indicated on the right side of Figure 1. The joint is sealed by the rubber gasket (5), and the standpipe is filled with water of 30^0C from the tank. Then, the closing mechanism dampers are opened, and the feed-water pumps, which exist in the refuelling machine, pressurise the fuel casket. The pressure is increased until it matches the pressure in the fuel channel. The grabber (7) is lowered, and the sealing mechanism (2) unseals the channel. The seal plug (9) of the fuel channel is disengaged by a special key (4), and the volumes of the standpipe and fuel channel are joined together. Water is transported from the machine into the fuel channel by the feed-water pump, and the cold water prevents steam and hot water from entering the refuelling machine from the fuel channel.

The depleted fuel assembly is lifted 7.5 m into the cooling zone, where it stays for about 10 minutes. Afterwards, the fuel assembly is pulled into the refueling machine. The empty fuel channel is inspected by using a movable gauge, and then a new fuel assembly is lowered. The re-sealing of the fuel channel is performed after the sealing plug (9) reaches the nest. The refueling machine is disconnected, and the spent fuel is transported to the fuel storage. The more detailed description of the refueling procedure can be found in Reference 1.

3. A SIMPLE MODEL FOR ESTIMATION OF THE DROP VELOCITY

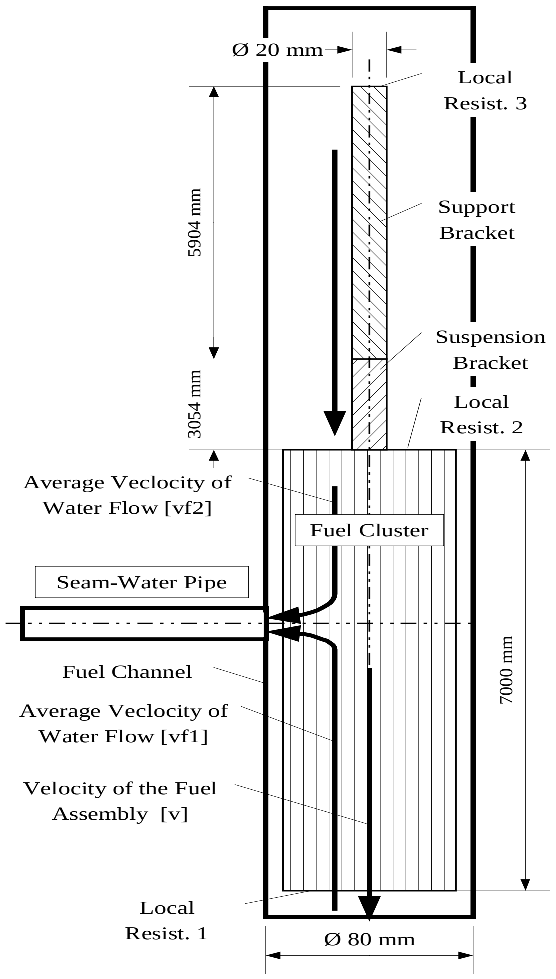


Figure 2. The Simplified Computational Geometry of a Fresh Fuel Bundle

In order to analyze the postulated accident that a fresh fuel bundle disengages from the grabber, and falls into the fuel channel, a model was developed to estimate the drop velocity of a fuel bundle. The model is based simply on the balance of four forces, namely gravity, friction, local resistance and buoyancy. This balance ignores the friction between the fuel channel and the fuel cluster rods. These forces are not in balance at the beginning of the fuel drop and the fuel bundle is accelerated. The acceleration is determined by the balance of four forces as shown below:

$$F_A = F_G - F_B - F_{FR} - F_{lR} \tag{1}$$

where F_G is the gravity force that drives the fuel assembly down; F_B stands for the buoyancy force; F_{LR} is the local resistance force, and F_{FR} is the friction between the water and the fuel assembly surface. The velocity of the dropped fuel assembly can be determined as follows:

$$F_A = m\frac{dv}{dt} \approx m\frac{v_i - v_{i-1}}{t_i - t_{i-1}} \tag{2}$$

where m is the mass of the fuel assembly and dv/dt is the acceleration. The gravity force of the fuel bundle is estimated to be 2744 N. The buoyancy force is dependent on the coolant density, and the local resistance and friction forces depend on the geometry, velocity of the fuel bundle, and properties of the coolant.

A fuel assembly normally contains the fuel cluster, suspension bracket and fuel assembly support bracket as shown in Figure 2. The geometry of a fuel bundle is simplified to be a uniform cluster 7m long. The local resistance due to spacers is neglected. The cross section of the fuel cluster in the fuel channel is shown in Reference 1. The support and suspension brackets are approximated as 8.96m long cylinder of 20mm in diameter. The internal diameters of the fuel channel and fuel casket are assumed to be 80mm.

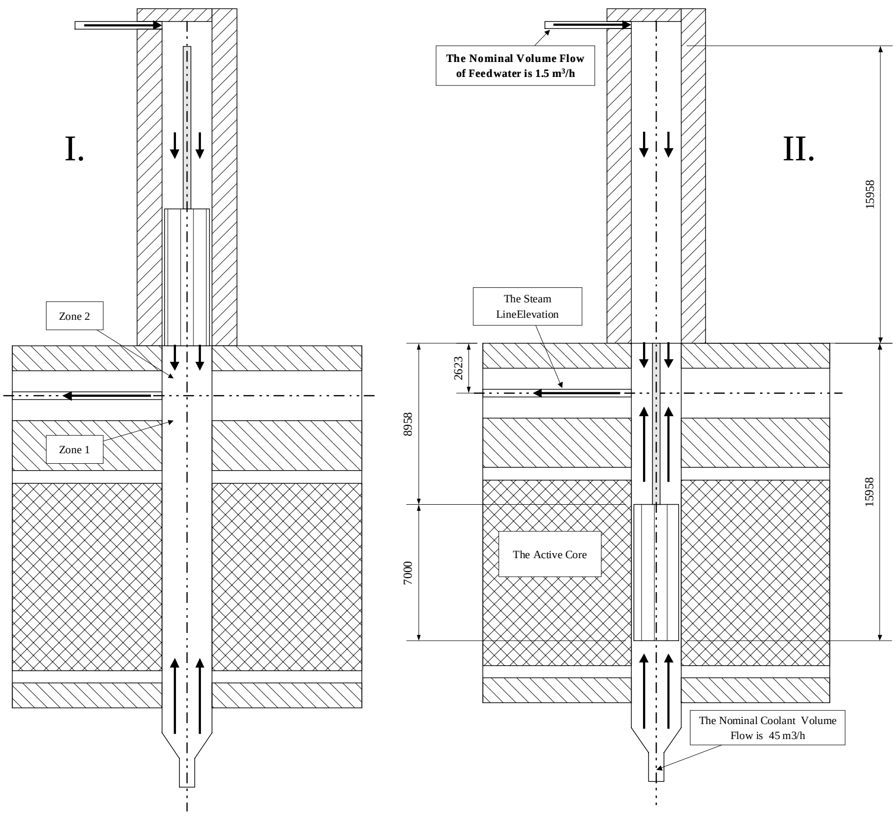


Figure 3. The Description of the Flow Conditions in the Fuel Channel and Refuelling Machine

The local resistance and friction forces are also dependent on the location of the fuel assembly in the channel. They are affected by two water flows as shown in Figure 3-I and II. The first water flow moves up at $45m^3/h$ from the lower part of the channel, and leaves the channel through the steam-water pipe. The coolant temperature is 263 ^{0}C and the pressure is 70bar. The second water flow is fed into the upper part of the refuelling machine with a flow-rate of $1.5m^3/h$. This water is 30^{0}C temperature. These two flow streams meet at the elevation of the steam-water pipe, thus forming a boundary where the water flow directions are changed. In this model, the volumes of the fuel channel and casket are regarded as two separate zones as indicated in Figure 3-I. The first zone is the space below the steam-water pipe elevation, and is influenced by the coolant flowing up. The other zone is affected only by the feed-water flowing downwards in the refuelling machine.

The buoyancy force is calculated by taking into account different coolant densities in the zones. The buoyancy force is re-calculated at each time step, when the assembly position is estimated with reference to the steam-water pipe elevation. The total friction force is calculated as the sum of friction forces, which are computed separately for each part of the fuel bundle. The calculations performed start by first identifying the position of the fuel bundle with respect to the steam-water pipe, since different zones have different flow conditions and geometrical configurations. The friction force of each fuel assembly part is determined by,

$$F_{FR} = C_{FR} \frac{\gamma \left| v - v_f \right| (v - v_f)}{2} S_{FR} \tag{3}$$

where C_{FR} stands for the friction coefficient, γ is the coolant density, and S_{FR} is the surface area in contact with water. v stands for the drop velocity of the fuel bundle while v_f indicates the fluid velocity. The coolant density and friction surfaces for each part of the fuel assembly are estimated by considering the location of each part with reference to the steam-water line. The friction coefficient is calculated by employing the empirical equations that are used to estimate the friction coefficient for the water that flows in a cylindrical channel[3]. This rough friction coefficient is corrected with some parameters that relate the flow in the cylindrical channel to the flow in the cluster and the annular geometry channels[3].

The local resistance force is calculated as the sum of three local resistance forces, which act on the lower and upper parts of the cluster, and on the upper part of the support bracket (see Figure 2). The local resistance force is determined by the following equation,

$$F_{LR} = C_{LR} \frac{\gamma \left| v - v_f \right| (v - v_f)}{2} S_{LR} \tag{4}$$

where F_{LR} stands for the local resistance force, C_{LR} is the local resistance coefficient, and S_{LR} is cross sectional area of the water flow. The other parameters in Equation 4 are the same as in Equation 3. The local resistance coefficients are calculated by employing the standard empirical equations introduced in Reference 2. There are two types of equations. The first type is used for the calculation of the local resistance coefficient in case the cross-sectional area of the flow is sharply decreased like the lower part of the cluster shown in Figure 2. The second type is applied in case the water flow cross-sectional area sharply increases, like the upper part of the cluster and the support bracket shown in the Figure 2.

4. ESTIMATION OF THE POSTULATED FRESH FUEL DROP SCENARIO

For this study, an INPP core with 2.4% enriched erbium fuels loaded in more than one-half of the core was selected. The information on the core configuration and burn-up distribution is provided in the INPP database, which was recorded on March 5, 1994. The reactor was operating at 4060 MWth, and the average fuel burn-up was 7.48 MWd/kg. The hypothetical fuel drop scenario is assumed to occur in a central channel of this core. Before performing dynamic calculations with the modified

ARROTTA code, the drop velocity of the fresh fuel is determined below, with the model introduced above.

It is assumed that a fresh fuel disengages from the grabber of the refuelling machine, when the lowest point of the fresh fuel assembly is at the top of fuel channel as shown in the Figure 3-I. The bundle falls while the sealing plug reaches its nest at the top of the fuel channel. The final position of the fresh assembly is shown in the Figure 3-II. The drop velocity of this fuel assembly is determined, and its variation in time is shown in Figure 4. It increases from 0 up to 3 m/sec during 1sec, and then decreases to 1.7 m/sec after 4.5 sec. The decrease of the velocity is caused by the fact that a considerable surface of the cluster is submerged in the water flow.

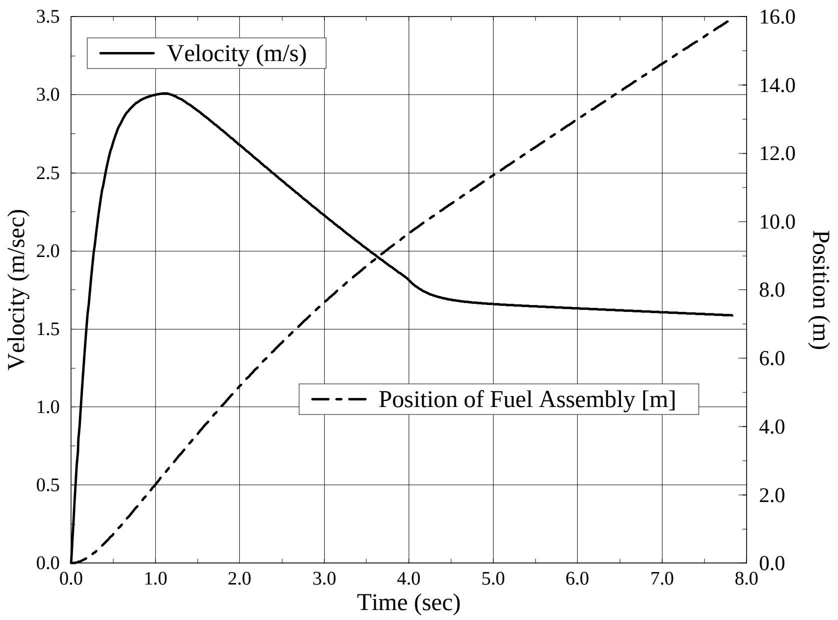


Figure 4.The Drop Velocity and Position of the Dropped Fuel as a Function of Time

The neutron transient of the fresh fuel drop starts off as the lowest point of the dropped fuel cluster arrives at the top of the active core. That happens at 3.63 seconds, as Figure 4 indicates that the lowest point of the fuel is situated 8.95 m below the top of the fuel channel. The fuel continues to drop down to the bottom of the channel until 7.83 seconds. Thus, the fuel assembly is fully inserted in the active core in 4.2 seconds. The drop velocity of the fuel in the active core as a function of time is shown in Figure 5 where time zero is when the fuel assembly arrives at the top of the active core. Since the velocity must be defined as a discrete function in the ARROTTA code input deck; the continuous velocity function shown in Figure 4 was converted into the discrete values. The conversion was conducted by calculating the average velocities every 0.2 second as shown in Figure 5.

When performing the dynamic analysis of this fresh fuel drop scenario, it is assumed that all the various control and protection systems are inactive. For generation of cross sections for the various types of fuel assemblies, the CASMO-4 code was employed while for non-fuel assemblies such as control rod channels, the WIMS-D4 code was employed since the CASMO code is incapable of performing 3x3 multi-assembly calculations. In the ARROTTA calculations, the dropped fresh fuel assembly must be regarded as a fictitious rod[3], otherwise the ARROTTA code could not cope with simulation of such a fresh fuel drop event. The velocity variation shown in the Figure 5 was used in the ARROTTA input deck. The initial condition for this scenario is chosen to be at the critical hot-full-power state with equilibrium xenon.

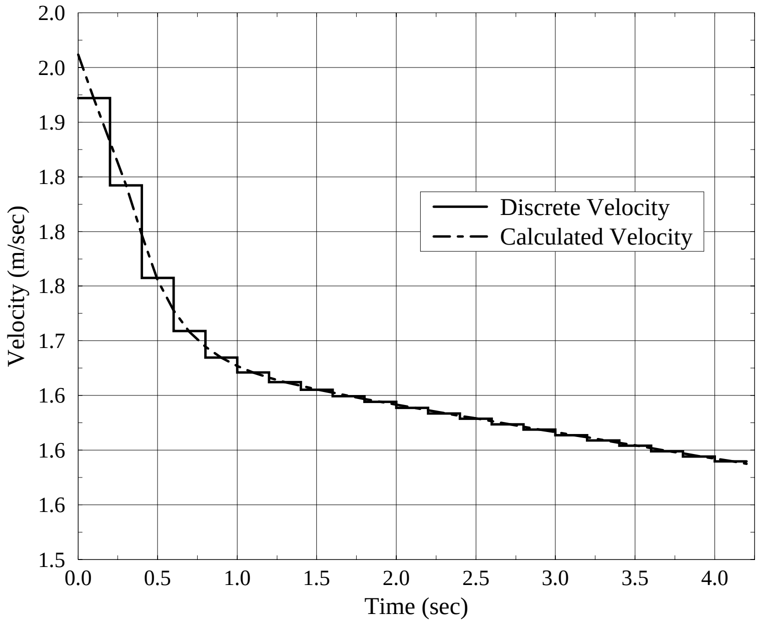


Figure 5. The Discretized Drop Velocities in the Fuel Channel Versus Time

The results calculated by the ARROTTA are presented in Figures 6-8. Figure 6 shows the reactivity change with the time after the lowest point of the fuel cluster reaches the top of the active core. The excess reactivity reaches a maximum value of 0.35$ between 2.5 and 4.0 seconds, and later decreases to zero in 250 sec due to the negative Doppler feedback. The overall core power goes up to 4190 MWth from the nominal value of 4050 MWth. It is seen in Figure 8 that the maximum fuel temperature is only about 608 ^{0}C, which can not cause any fuel damage.

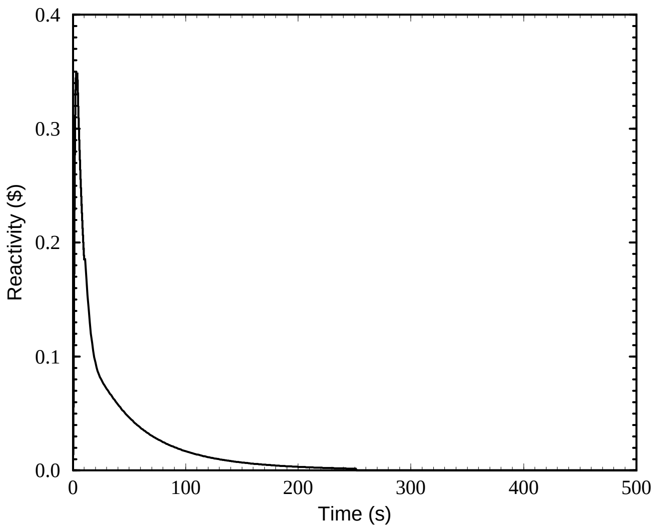


Figure 6. The Reactivity Change as a Function of Time

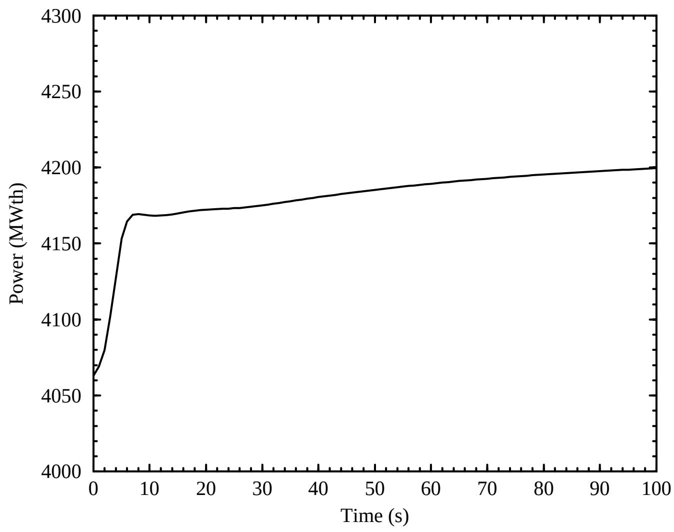


Figure 7. The Core Power Change as a Function of Time

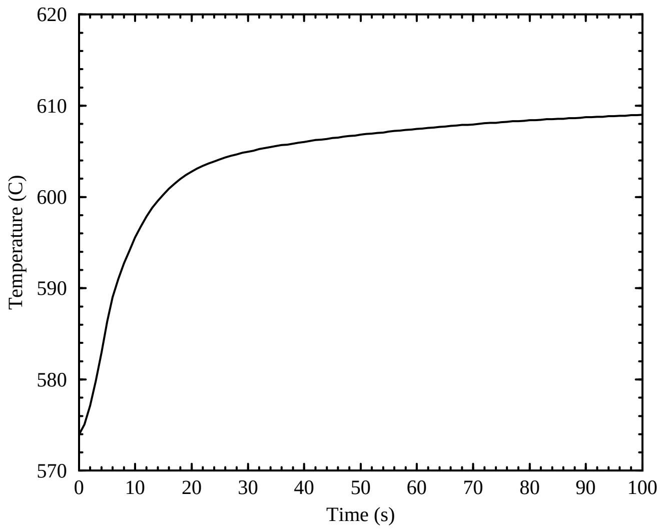


Figure 8. The Peak Fuel Temperature Change as a Function of Time

CONCLUSIONS

A simple but reasonably accurate hydraulic model was developed to account for the realistic conditions of a postulated fuel drop event in the Ignalina RBMK nuclear plant. Several simplifying assumptions are made. First, the geometry of the fuel assembly was assumed to be without spacers. Second, the uniform pressure of 70bar was considered in the whole channel. Third, the friction between the fuel channel and the fuel cluster, is neglected. We believe that the drop velocity of the fuel assembly would be slightly lower if all the facets, which could affect the drop velocity, would be considered. Hence, the results presented are conservative.

The hydraulic study of the fuel drop event indicates that the fuel cluster would reach the top of the active core in 3.63 seconds with the velocity of 1.95 m/sec, and the bottom of the core in 7.83 seconds with the velocity of 1.57 m/sec.

The dynamic analysis of this event with the modified ARROTTA code, while assuming that all the control rods do not move, indicates that the reactivity increases only by 0.3$, and the increase in power is about 3.5%. The core power is stabilized in approximately 250 seconds due to the Doppler feedback.

It also turns out that the fuel temperature increases to 882K which is much lower than the allowed maximum temperature of 2373K. Therefore, the fresh fuel drop scenario would not cause any fuel damage, even when the control and protection system is not activated during the transient.

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