An Analysis of Disassembling the Radial Reflector of a Thermionic Space Nuclear Reactor Power System

By M. S. El-Genk and D. V. Paramonov[a]

Abstract: *An analysis was performed to investigate the effect of disassembling the radial reflector of the TOPAZ-II space nuclear reactor following a postulated reactivity initiated accident (RIA). In this RIA, the control drums, starting in the full-in position, are assumed to run out at their maximum speed of 1.4°/s to their full-out position and remain out. This noncredible event occurs because of a malfunction in the drive mechanism of the control drums. Results indicate that the disassembly of only 3 of 12 radial reflector panels would successfully shut down the reactor with little overheating of the fuel and the moderator.*

The Russian TOPAZ-II space nuclear reactor thermionic power system is designed to produce up to 6 kW of electricity for at least 3 years. To "leapfrog" the system level experience and capitalize on the Russians' experience with thermionic (TI) systems, the U.S. Government purchased a number of the Russian TOPAZ-II system units with electrically heated thermionic fuel elements (TFEs) for testing at the Thermionic System Evaluation Test (TSET) facility in Albuquerque, N. Mex.[1] The knowledge gained from TSET will be incorporated into the ongoing effort by industry to develop thermionic space nuclear reactor power systems.

Extensive system analyses are currently being performed by the Air Force Phillips Laboratory (AFPL) and other members of the New Mexico Thermionic Alliance (namely, Los Alamos National Laboratory, Sandia National Laboratories, and the University of New Mexico) to investigate the safety and operation characteristics of the TOPAZ-II system during both steady-state and transient operations.

For the proposed Nuclear Electric Propulsion Space Test Program (NEPSTP), a TOPAZ-II reactor will be used to power electric propulsion devices. For the very high initial orbit (5250 km), electric propulsion devices will be used to increase orbital altitude while conducting scientific measurements. At this high altitude, operational accidents should have no significant effect on the earth and its population.[2] Nonetheless, it is useful to explore noncredible events to bound the consequences and to provide information for a probabilistic risk assessment.

The objective of this article is to assess the effect of the disassembly of the radial reflector of the TOPAZ-II reactor as well as to determine the minimum number of the radial reflector panels that need to be disassembled to shut down the TOPAZ-II reactor following a postulated reactivity initiated accident (RIA). In this RIA, the control drums, starting in the full-in position, are assumed to run out at their maximum speed of 1.4°/s to their full-out position and remain out. The Thermionic Transient Analysis Model (TITAM)[3–9] is used to explore this noncredible accident, which is assumed to occur because of a malfunction in the drive mechanism of the control drums. In addition to the temperatures of the different core components (fuel, moderator, coolant, core support plates, and TFE electrodes), the reactivity excursion and feedback effects in the reactor core are calculated, before and after the disassembly of the radial reflector panels, as functions of time during the transient.

SYSTEM DESCRIPTION

The primary components of the TOPAZ-II space nuclear reactor power system are (1) sodium potassium (NaK) (78%) cooled nuclear reactor with an epithermal neutron energy spectrum, (2) electromagnetic (EM) pump for circulating the coolant through the reactor coolant loop and the radiator, (3) lithium hydride radiation shadow shield, (4) volume accumulator, and (5) radiator for heat rejection into space. Other important components include startup batteries for the EM pump; cesium reservoir assembly, helium gas system, and instrumentation and control subsystem. A schematic of the TOPAZ-II space nuclear power system is shown in Fig. 1.

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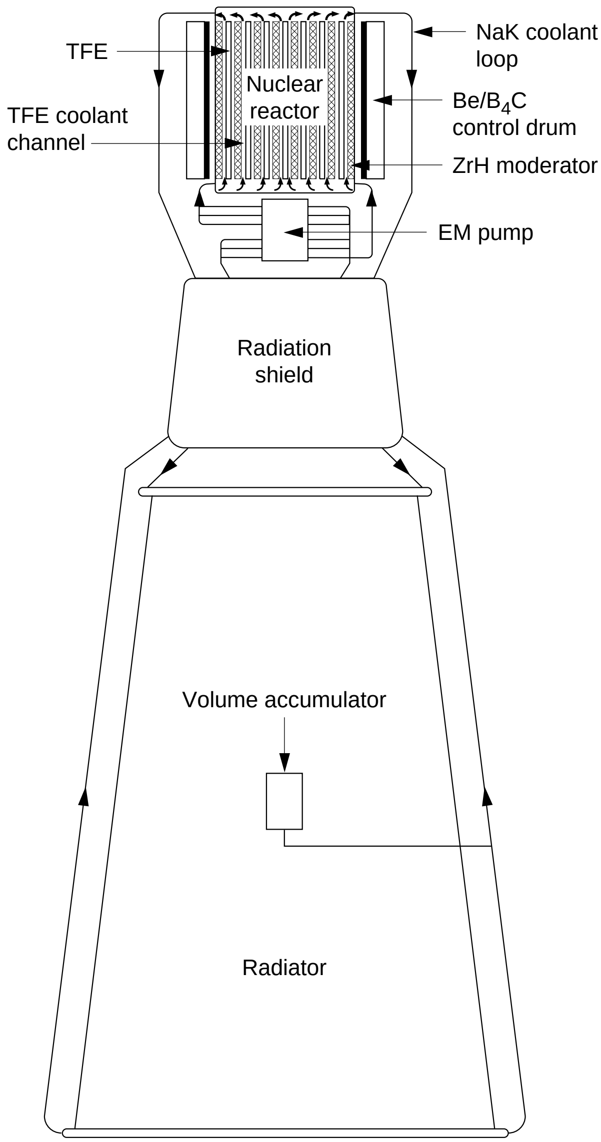

Fig. 1 Schematic of the TOPAZ-II Space Nuclear Reactor Power System. TFE is thermionic fuel element; EM is electromagnetic.

The reactor core is a right circular cylinder with monolithic zirconium hydride ($ZrH_{1.8}$) moderator blocks. These blocks are covered with a CO_2–He-based gas mixture and coated with a special sealer to minimize hydrogen losses during reactor operation. The moderator blocks are contained in a stainless steel canister with 37 circular vertical channels that are arranged in a triangular lattice. Each channel accommodates a TFE and its coolant duct. Of the 37 TFEs in the TOPAZ-II reactor, 3 are connected electrically in parallel to supply power to the EM pump and the other 34 TFEs are connected in series to supply up to 6 kW of electric power to the load at 27 ± 0.8 V dc. During nominal operation at 115 kW thermal power, the EM pump consumes 750 A at about 0.35 V while maintaining a total coolant flow rate of approximately 1.3 kg/s.

The coolant for the TFEs flows through annular channels between the stainless steel cladding and the moderator canister wall. The reactor is fueled with highly enriched UO_2 pellets, with a central hole for venting fission gases, stacked inside the cylindrical emitter tubes of the TFEs. The thin-walled, stainless steel vessel of the core supports the TFEs and provides plena for the NaK coolant, the helium gas for the TFEs sheath/insulator gap, and the cesium vapor.[10]

A detailed description of the TOPAZ-II nuclear reactor system, the design parameters, and dimensions of the TFEs is available elsewhere.[7–10]

Figure 2 contains a radial cross-sectional view of the TOPAZ-II nuclear reactor core showing the arrangements of the TFEs in the core and of the safety and control drums in the radial reflector. In addition to the axial beryllium (Be) and beryllia (BeO) reflector at the bottom and the top of the reactor core, respectively, the stainless steel vessel of the reactor is surrounded by a radial Be reflector with 12 Be/B_4C rotating safety and control drums. These drums are divided into two groups: safety and control. The first group consists of three safety drums with a total reactivity worth of 2 dollars and a single rotation speed of 22.5°/s. The second group is comprised of nine control drums with a total reactivity worth of 4 dollars and 80 cents and can be operated at angular speeds up to 1.4°/s.

The radial reflector, including both the safety and control drums, is held together by retention metal straps that can be served by command or during reentry heating. The assembly of these straps, which measure 10 mm by 0.5 mm in cross section, is similar to that of the SNAP-10A. They are kept closed with two electric locks with meltable stainless steel elements. In case of an emergency, the stainless steel elements are melted on command by passing an electric current through them or by reentry heating, which unlocks the metal straps. Subsequently the radial reflector is disassembled with the aid of compression springs. Unlocking the retention metal straps and disassembling the reflector take less than 0.5 second.

MODEL DESCRIPTION

A version of the TITAM has been developed for the TOPAZ-II space nuclear reactor power system by

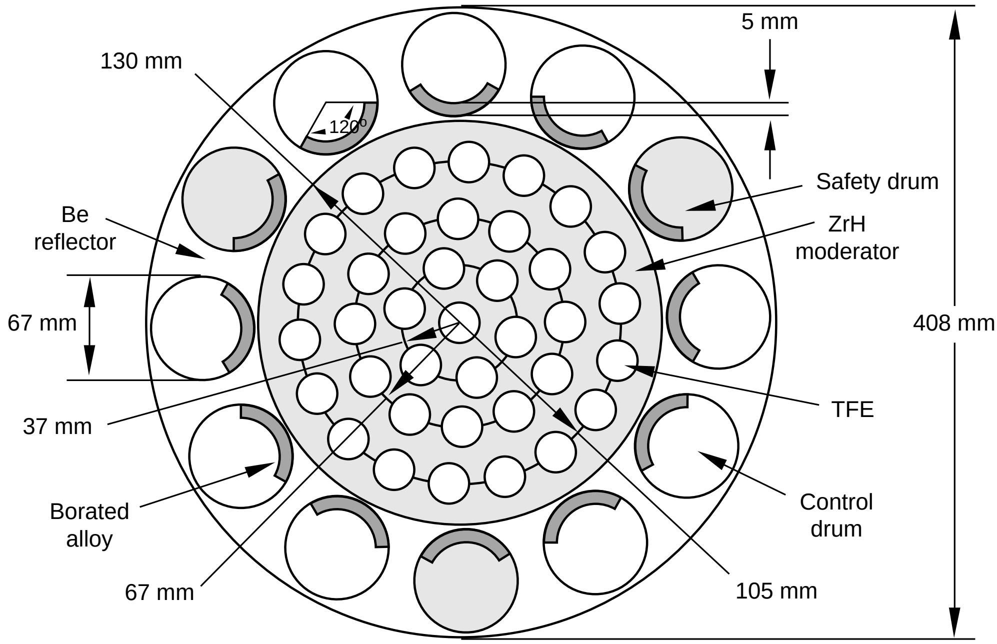

Fig. 2 Radial cross-sectional view of the TOPAZ-II reactor core. TFE is thermionic fuel element.

thermal–hydraulic coupling of the reactor model in TITAM to the power system primary loop and radiator.[7–9] Figure 3 shows a line diagram of the TITAM model for the TOPAZ-II system, which consists of a reactor model, a coolant loop thermal–hydraulic model, an EM pump model, a radiator model, and a volume-accumulator model. The thermal–hydraulic model couples these component submodels through the system's overall energy and momentum balance equations. The TOPAZ-II reactor model in TITAM is based on a single TFE that is thermally coupled to an equivalent cell of the zirconium hydride moderator having an adiabatic outer surface.[7–9] The reactor model consists of several intercoupled submodels: (1) a six-group point-kinetics model; (2) a one-dimensional transient thermal model of a fully integrated, single-cell TFE; (3) an electric circuit model for

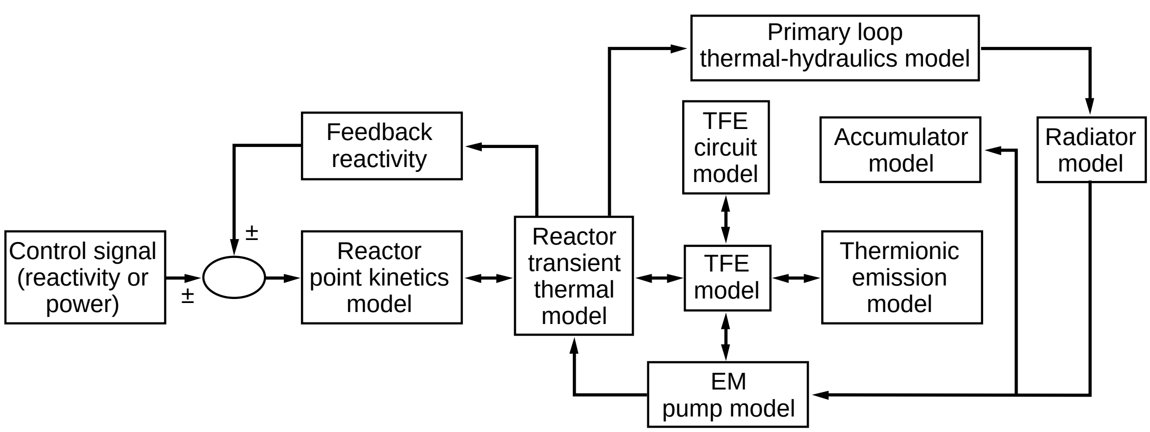

Fig. 3 Line diagram of TITAM for the TOPAZ-II Space Nuclear Power System. TFE is thermionic fuel element; EM is electromagnetic.

the TFEs; and (4) a thermionic-emission model.[11] More details on the description and verification of these models are available in Refs. 2 to 9.

The heat losses from the coolant loop structure by radiation to space is assumed to be 3.5% of the thermal energy removed from the reactor core. Thermal end losses of the electrodes are accounted for in the TFE model. The effective radiator area for TOPAZ-II is 7.2 m^2, and the mass of the radiator and of the primary loop structure is 50 kg each. The structure material of the primary loop is stainless steel, whereas that of the radiator is 80% stainless steel for piping and 20% copper for radiation fins. Fission heating of the TFEs is assumed uniform along their length, and about 4% of the fission power is deposited in the moderator. The fill gas in the gap between the stainless steel canister and the ZrH moderator blocks is taken to be CO_2. The thermophysical properties of the electrode materials, He and CO_2 gases, Cs, stainless steel, coolant, and moderator are taken to be temperature dependent.[6] In addition to the temperature reactivity feedback effects for the fuel, electrodes, moderator, reflector, and the core support plates, the TOPAZ-II reactor model in TITAM incorporates a correlation of the control drums reactivity worth as a function of angular position.[7–9]

During the system startup, the reactor thermal power is calculated by the reactor kinetics model on the basis of the rotation angle and speed of the drums and the temperature reactivity feedback for the different components in the reactor (fuel, ZrH moderator, TFE electrodes, coolant, reflector, and core support plates).[7] For a given reactor thermal power, the coolant temperature and mass flow rate are determined from the solution of the system's overall energy and momentum balance equations. Then the EM pump model is used to calculate the pressure rise in the pump. The pump current and voltage are determined from the thermionic emission model for the pump TFEs.[8] With the pressure rise for the EM pump calculated, the coolant loop thermal–hydraulic model is solved for the new coolant temperature and flow rate. These iterative solution procedures are repeated until conversion is achieved when both the overall energy balance and momentum balance equations of the system are satisfied. After each iteration, the thermal, physical, and electrical properties of the liquid–metal coolant and structure materials are updated.

MODEL VERIFICATION

The TITAM predictions are benchmarked with the use of results of other calculations that had been performed by Russian scientists[12] and actual experimental data from the TEST facility in Albuquerque, N. Mex.[1,13,14] The TITAM results of the startup simulation of the TOPAZ-II system were in agreement with reported values of the total temperature reactivity feedback at steady-state nominal power of 110 to 115 kW thermal (1 dollar and 43 cents) and of the rotation angle of the control drums at the end of the reactor startup process (88 to 90°).[10,l5,16]

The predictions of TITAM are also compared with experimental measurements in Figs. 4 to 7.[9,l3,14] These measurements were taken at the TSET facility for the TOPAZ-II, V-71 system that was tested in November 1992 and May 1993 in which electrically heated TFEs were used. In these tests the middle 0.3 m of the active length of the emitter (0.375 m) in the TFEs was uniformly heated with tungsten electrical heaters. The recorded measurements are for steady-state operation at different electrical power inputs to the heaters of the 37 TFEs in the TOPAZ-II reactor core. As Figs. 4 to 7 show, the calculated coolant temperatures were within 15 K and the calculated coolant pressure was within 12% of the measurements. The model predictions of load electric current and voltage were also in good agreement with measurements (Figs. 6 and 7). This agreement between the TITAM version for TOPAZ-II and experimental data of the system verifies the soundness of the modeling approach.

STARTUP PROCEDURE OF TOPAZ-II IN ORBIT

At cold startup, when the B_4C segments in the safety and control drums are facing inward, the TOPAZ-II reactor is 6 dollars subcritical (k_{eff} = 0.952). The startup procedures assumed herein, which may not represent an accurate account of the actual procedures of the TOPAZ-II system,[5,7] call for the reactor startup to begin by rotating the three safety drums 180° outward, which increases the core reactivity to a negative 4 dollars (k_{eff} = 0.968). Subsequently the nine control drums are rotated 154° outward, at their maximum speed of 1.4°/s, and then inward to 145°. The reactor becomes critical (k_{eff} = 1.0) when the control drums are rotated 125° outward (Figs. 8 and 9).

The control drums are then held in place until the reactor thermal power reaches 5 kW. When this power level is reached, the drums resume their rotation; however, their rotational speed and direction are adjusted to increase the reactor power to a constant rate of 600 W/s until it reaches 35 kW and then at 80 W/s until it reaches 115 kW. At this point the control drums are rotated inward to maintain criticality of the TOPAZ-II reactor.

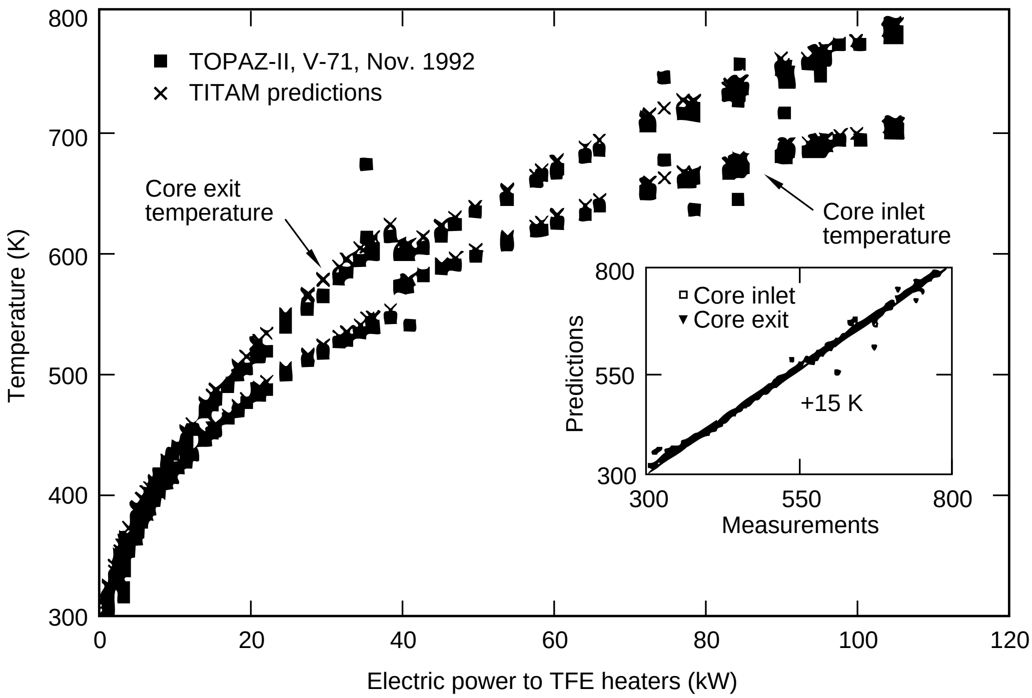

Fig. 4 Comparison of TITAM predictions with measured coolant temperatures in TOPAZ-II, V-71 unit tests in the Thermionic System Evaluation Test Facility. TITAM is Thermionic Transient Analysis Model.

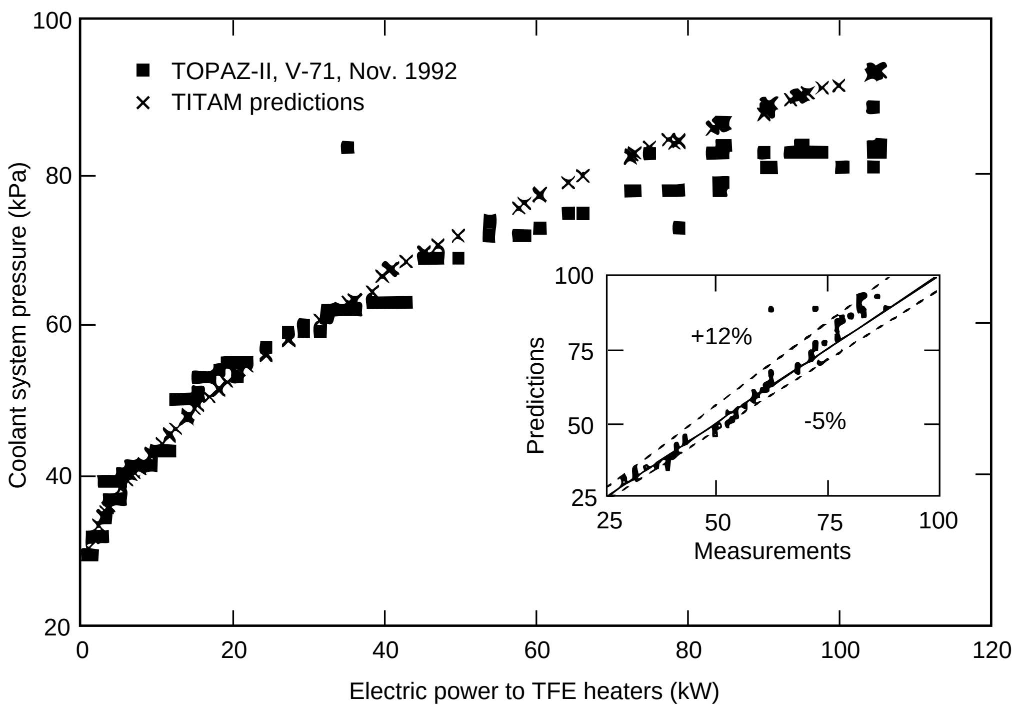

Fig. 5 Comparison of TITAM predictions with measured coolant pressures in TOPAZ-II, V-71 unit tests in the Thermionic System Evaluation Test Facility. TFE is thermionic fuel element; TITAM is Thermionic Transient Analysis Model.

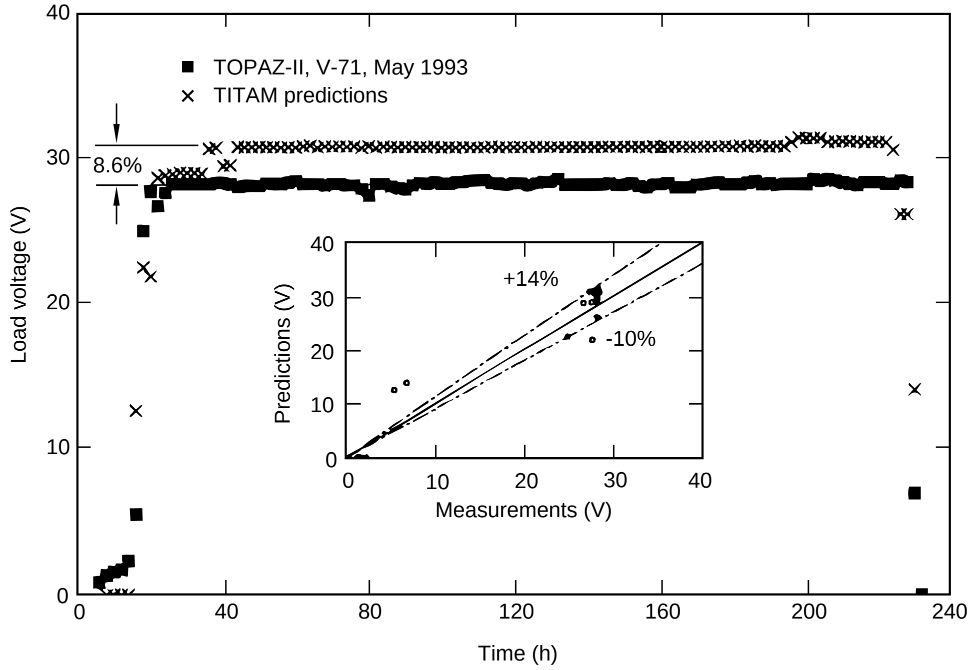

Fig. 6 Comparison of TITAM predictions with measured load electric voltage in the TOPAZ-II, V-71 unit tests. TITAM is Thermionic Transient Analysis Model.

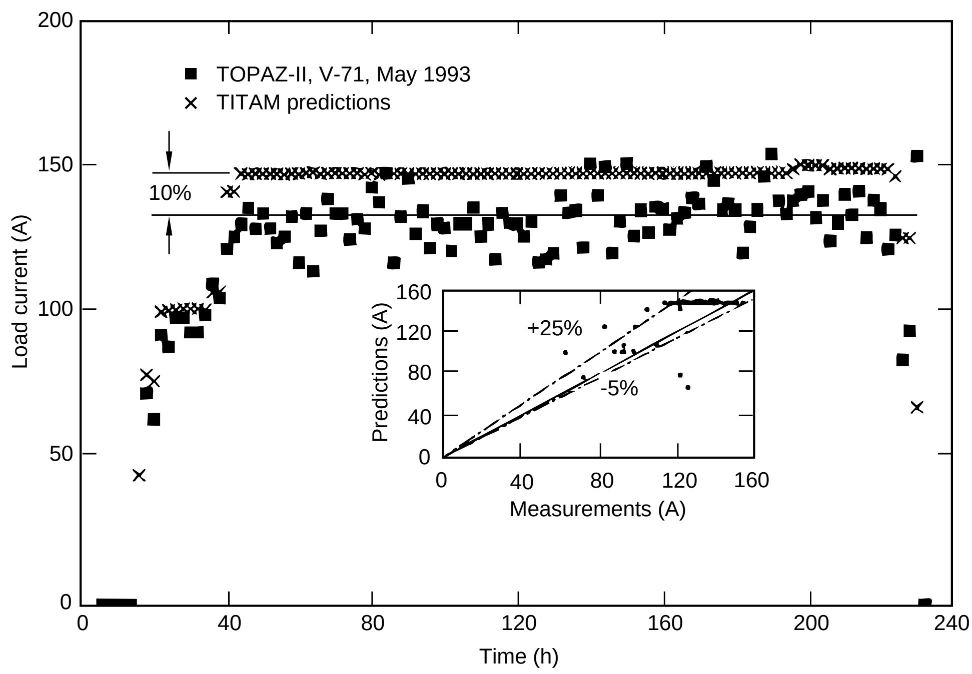

Fig. 7 Comparison of TITAM predictions with measured load electric current in the TOPAZ-II, V-71 unit tests. TITAM is Thermionic Transient Analysis Model.

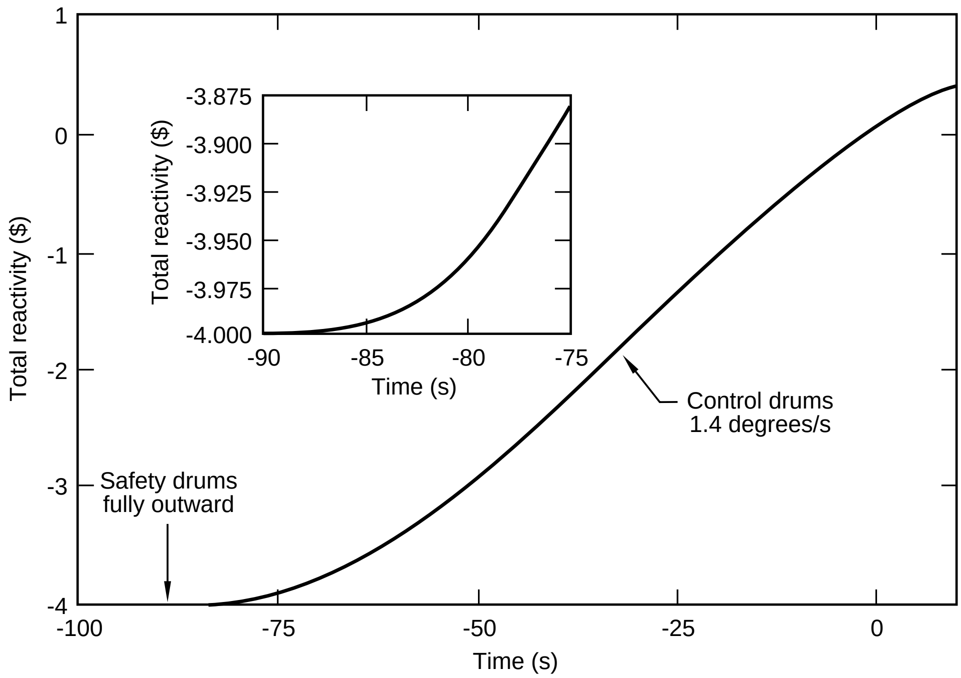

Fig. 8 Total reactivity insertion in the TOPAZ-II reactor during startup simulation.

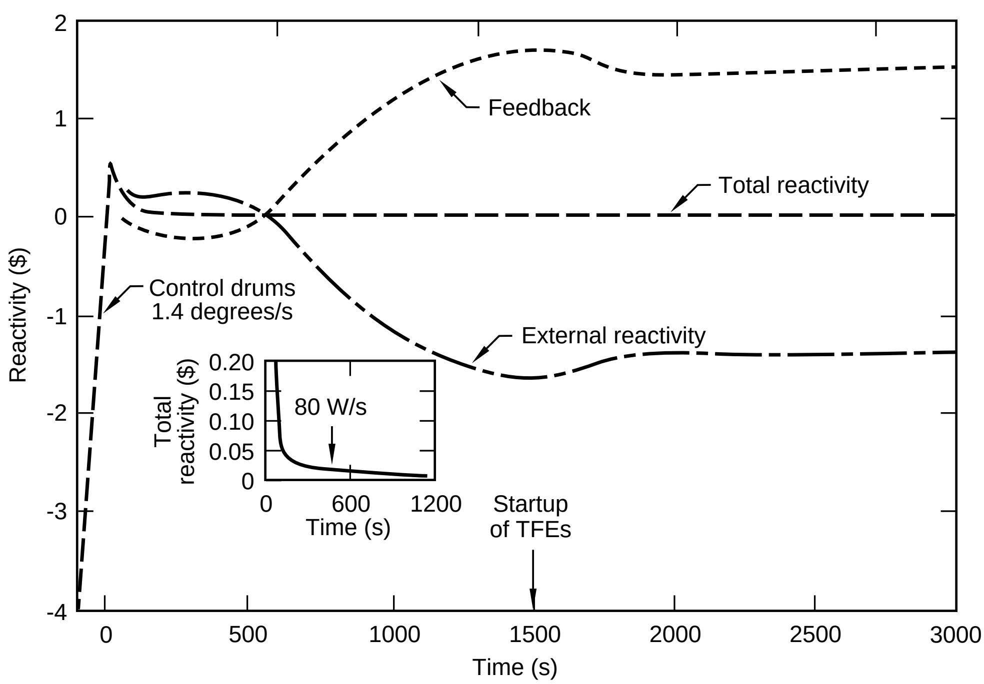

Fig. 9 Calculated changes in reactivity during startup simulation of the TOPAZ-II Space Nuclear Reactor Power System in orbit. TFE is thermionic fuel element.

Figures 9 and 10 show the calculated changes in reactivity and the reactor fission power during startup simulation, respectively, of the TOPAZ-II space nuclear reactor power system in orbit. As Fig. 9 indicates, when the steady-state condition is reached, the total temperature reactivity feedback in the reactor core is about 1 dollar and 43 cents; the angular position of the control drums is about 88° outward.[7] At this angular position, the total excess reactivity remaining in the reactor core is about 2 dollars and 20 cents, which is used to compensate for the fuel burnup through the lifetime of reactor operation.

RESULTS AND DISCUSSION

The TOPAZ-II reactor radial reflector consists of 12 reflector panels, each housing either a safety or a control drum (Fig. 2). This section investigates the effect of the disassembly of the reflector panels of the TOPAZ-II reactor following a postulated RIA. This accident is assumed to occur because of a malfunction of the drive mechanism that causes the control drums to rotate outward the full 180° range at maximum speed of 1.4°/s and remain out.

During a nominal startup of the TOPAZ-II system in orbit, the reactor becomes critical when the control drums are approximately 125° outward. In Figs. 8 to 15, the zero time corresponds to reactor criticality or to when the rotation angle of the control drums equals 125°. As shown in Fig. 8, the control drums rotate outward for about 90 seconds before the reactor becomes critical.

As shown in Fig. 11, the total external reactivity insertion, 40 seconds after the reactor becomes critical, is approximately 80 cents. However, the corresponding total reactivity in the core is lower (about 75 cents) mostly because of the temperature negative reactivity feedback of the fuel and to a lesser extent because of the electrodes and the core plates (Fig. 13). As demonstrated in Figs. 12 and 13, the disassembly of only 3 of the 12 reflector panels following an RIA would successfully shut down the reactor with little overheating of the fuel.

The reactor fission power peaks at approximately 1.05 MW and then drops rapidly following the disassembly of the reflector panels (Fig. 13). The fuel and the emitter temperatures peak at only about 1410 K, drop rapidly to about 530 K, and decrease slowly thereafter (Figs. 14 and 15). The disassembly of three reflector pan-

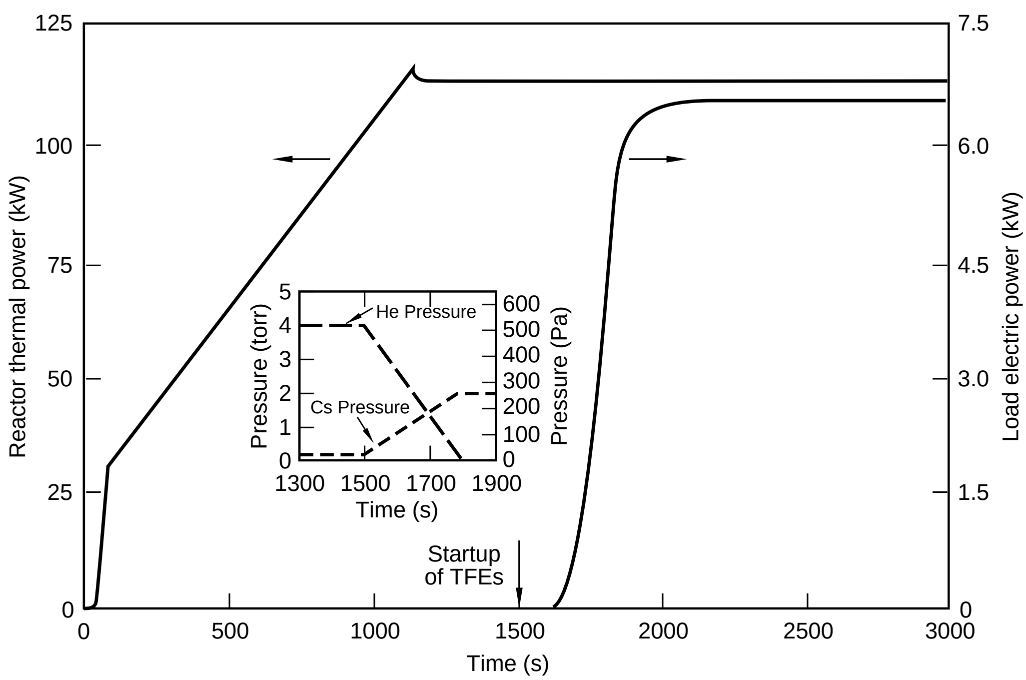

Fig. 10 Calculated reactor fission and electric power during startup simulation of TOPAZ-II Space Nuclear Reactor Power System in orbit. TFE is thermionic fuel element.

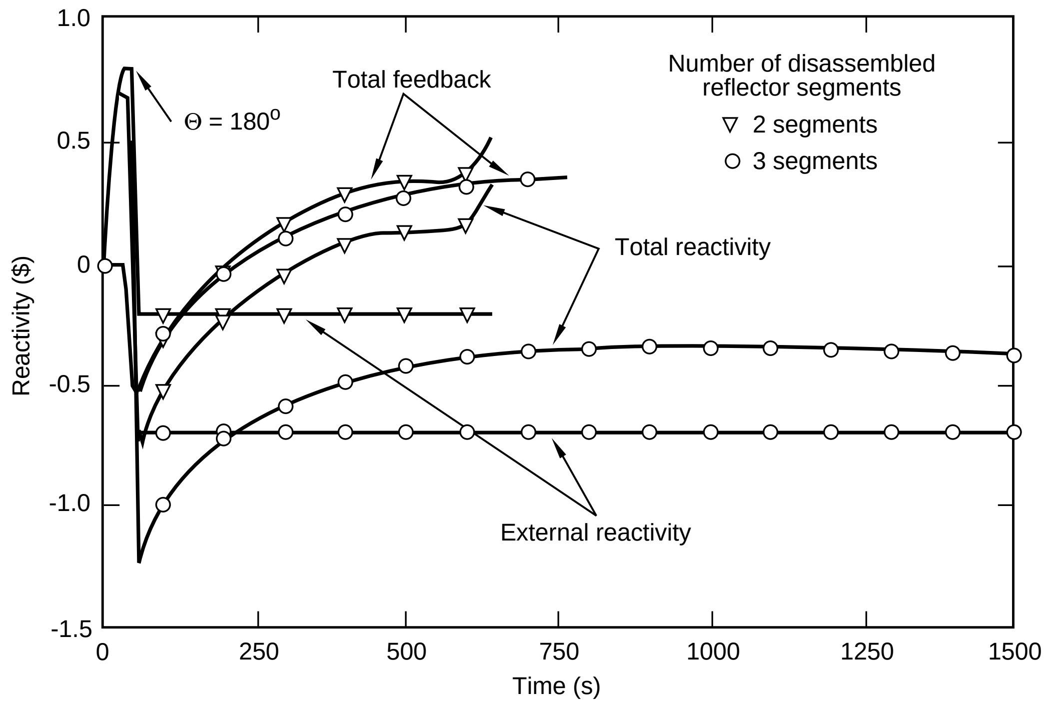

Fig. 11 Effect of the number of disassembled reflector panels on reactor conditions.

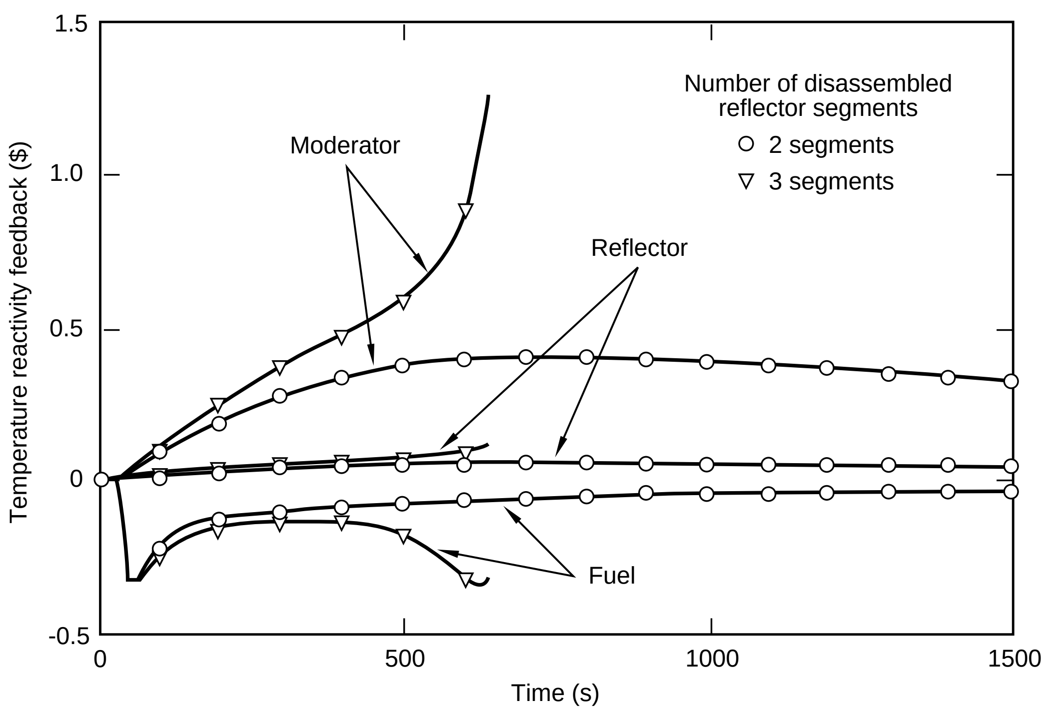

Fig. 12 Effect of disassembled reflector panels on temperature reactivity feedback.

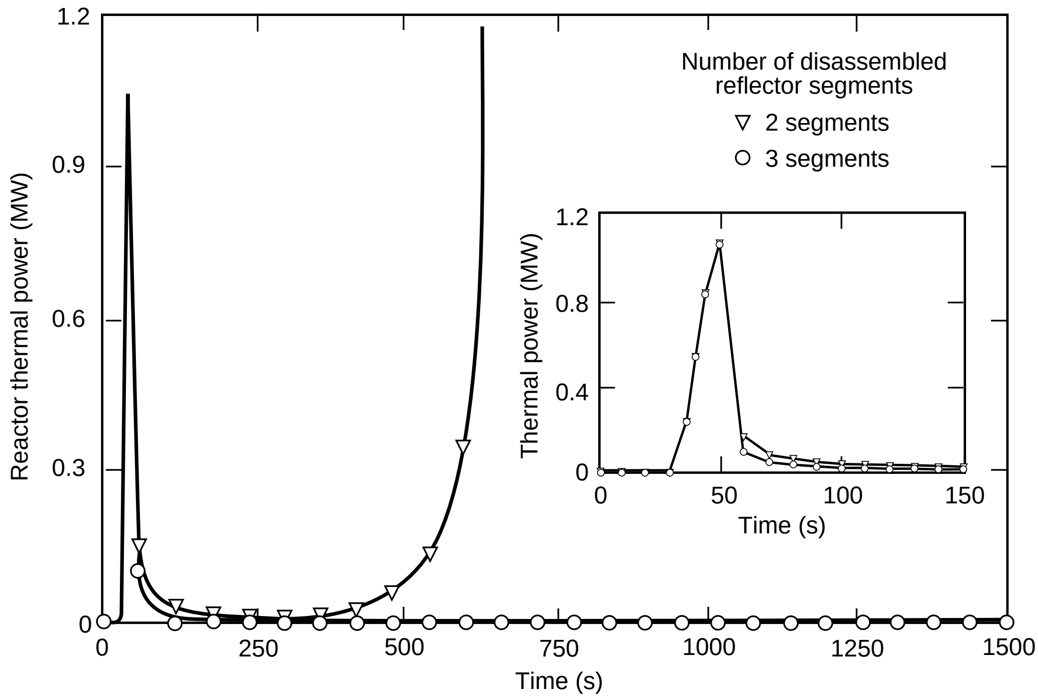

Fig. 13 Effect of disassembled reflector panels on fission power.

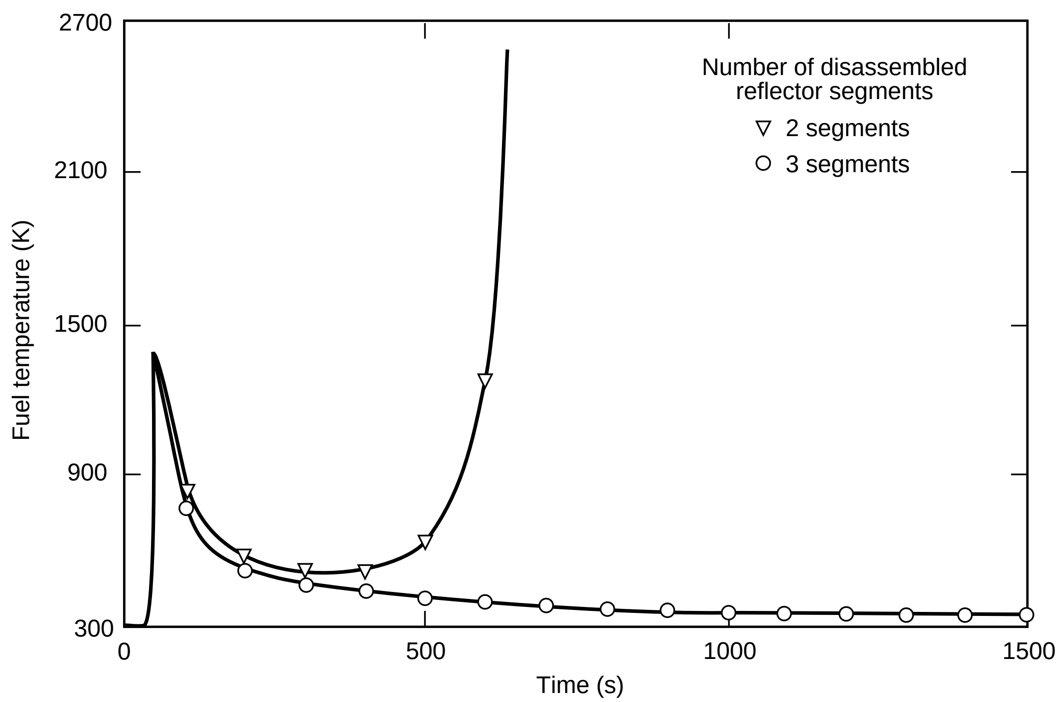

Fig. 14 Effect of disassembled reflector panels on fuel temperature.

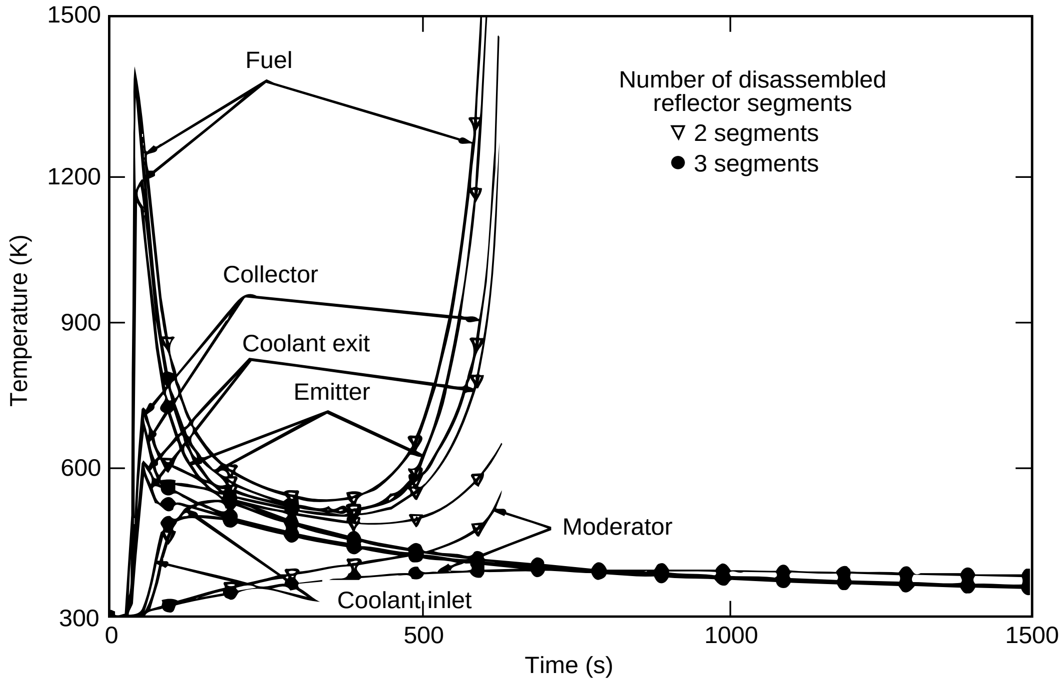

Fig. 15 Effect of disassembled reflector panels on temperatures of reactor core components.

els inserts a total of negative 1 dollar and 50 cents of external reactivity into the reactor core and thus causes the total reactivity to drop precipitously and reach a minimum of about negative 1 dollar and 25 cents (Fig. 11). Subsequently, the total reactivity increases are mostly caused by the temperature-positive reactivity feedback of the moderator. In approximately 15 min after reactor startup, the total reactivity decreases because of moderator cooling down (Figs. 11, 12, and 15).

The results in Figs. 11 to 15 clearly show that the disassembly of two reflector panels, instead of three, would not prevent a reactivity excursion in the TOPAZ-II reactor and overheating of the fuel and the TFE electrodes. Figure 11 indicates that, following the disassembly of two reflector panels (total external reactivity insertion of negative 1 dollar), the total reactivity in the reactor drops to negative 20 cents and then increases, which causes a reactivity excursion approximately 325 seconds after the reactor reaches criticality. As a result, the fission power (Fig. 13) and the fuel and emitter temperatures (Figs. 14 and 15) increase very rapidly.

The fuel temperature reaches about 2600 K within 11 minutes after the reactor becomes critical. The corresponding collector temperature is about 1450 K, and the coolant temperature at the exit of the reactor core is about 650 K, whereas that of the moderator is slightly less than 550 K. Note that during this time the reactor remains subprompt critical; for example, approximately 10 minutes after the reactor becomes critical during startup, the total excess reactivity only increases to about 50 cents. In these calculations and in those presented throughout the article, the initial temperature of the reactor core is taken to be uniform at 300 K.

CONCLUSIONS

An analysis was performed to determine the effect of the disassembly of the radial reflector panels of the TOPAZ-II reactor following a hypothetical severe RIA. The RIA considered in this article was assumed to occur because of a malfunction of the drive mechanism of the control drums that causes the drums to rotate the full 180° outward at their maximum speed of 1.4°/s and remain out.

Results indicate that the disassembly of only 2 of the 12 reflector panels could eventually cause a reactivity excursion and rapid overheating of the reactor core following a relatively long delay time (more than 10 minutes). Until such time the reactor remains subprompt critical with the total excess reactivity in the reactor core being approximately 50 cents. However, disassembly of only three of the radial reflector panels would successfully shut down the reactor with little overheating of the fuel and the moderator. These results demonstrate the effectiveness of and the built-in redundancy in the radial reflector disassembly for safely shutting down the reactor in a severe RIA event.

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