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ABSTRACT

A study has been performed on the passive safety features of low-sodium-void-worth metallic-fueled reactors with emphasis on using a bottom-supported reactor vessel design. The reactor core designs included self-sufficient types as well as actinide burners. The analyses covered the reactor response to the unprotected, i.e. unscrammed, transient overpower accident and the loss-of-flow accident. Results are given demonstrating the safety margins that were attained.

I. INTRODUCTION

The passive safety characteristics of two low-void-worth, metal fueled core designs using a bottom-supported reactor vessel have been investigated. One core design is a low void worth design with a breeding ratio near unity and the other is a design intended for burning of recycled reactor fuel transuranic isotopes which has a breeding ratio near 0.5. The response of each core design to unprotected (without scram) accidents is presented, providing a measure of the safety margins provided by these design concepts for accident initiators that in conventional oxide-fueled core designs would normally be expected to lead to coolant boiling, fuel element failures, and core disruption. The analyses show that the combination of a low-void-worth metal fueled reactor core design and the use of a bottom-supported reactor vessel provides a very high margin of self-protection in unscrammed accident sequences.

II. PASSIVE SAFETY FEATURES OF METALLIC FUELED CORES

An important measure of the safety performance provided by a reactor design is the ability to avoid coolant boiling and fuel element failures in unprotected (without scram)

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accidents. To achieve self-protecting behavior for these conditions without reliance on active engineered systems implies dependence on passive mechanisms which rely on the basic thermal, neutronic, mechanical, and fluid dynamic properties of the reactor core and plant to assure reactor shutdown and maintain reactor cooling. Metal fueled core designs with liquid sodium coolant offer the capability of providing such passive safety performance[1]. The high thermal conductivity of metal fuel results in a low radial temperature gradient in the fuel at normal operating conditions, with low fuel temperature and low stored heat in the fuel. The swing in reactivity due to Doppler feedback is also small during transients where the power is being reduced. In unprotected transients, the overall effect of low operating fuel temperature is to cause the component of the power coefficient related to the coolant temperature rise to be larger than that from the fuel temperature decrease. This partitioning in the power coefficient is the key to the favorable passive response of cores using metallic fuel.

A. Safety Implications of Low Sodium Void Worth Cores

The positive reactivity resulting from voiding of sodium coolant in traditional liquid metal cooled reactor designs has remained a significant safety concern since the early days of the concept's development. With the recent emphasis on passive response and avoidance of coolant boiling, the likelihood that sodium voiding could occur during an unprotected accident has been reduced. However, from the safety perspective, it is desirable to reduce the positive coolant void reactivity worth to near zero to eliminate mechanisms which could add reactivity in the event of coolant loss, possibly leading to energetic accident consequences.

The reduction or elimination of positive coolant density reactivity feedback is also desirable, as it may be the major or perhaps only positive reactivity feedback occurring in transients where coolant boiling is avoided. The reactivity feedback is generated by the reduction in coolant density as the sodium temperature rises during unprotected transients. Minimizing this component of the reactivity feedback increases the passive safety margins, and provides greater assurance that potential severe accident initiators will not lead to coolant boiling, fuel element failures, and core disruption.

B. Safety Implications of the Bottom-Supported Reactor Vessel

As compared to a top-supported reactor vessel (TSRV), a properly-configured bottom supported reactor vessel (BSRV) enhances the negative reactivity feedback effects of the reactor vessel heatup late in a transient sequence by limiting the withdrawal of the control rods which earlier in the transient sequence had thermally expanded into the core. The results of previous studies on the accident mitigation potential of the BSRV[2] are summarized as follows:

i) The BSRV system is effective in limiting the peak coolant temperature and the quasi-steady-state temperatures during unprotected loss-of-flow(LOF) and unprotected loss-of-heat-sink (LOHS) events. With a TSRV, the elongation of the reactor vessel wall tends to lower the core away from the control rods as the cold pool and hot pool temperatures increase during the transient. The BSRV system raises the core into the control rods under the same conditions. The potential improvement for the unprotected transient overpower (TOP) event is relatively diminished because of the assumed constant value of the core inlet temperature.

ii) Using the BSRV system instead of the TSRV with a mixed-oxide (MOX) fueled core shows a large improvement in response to the unprotected LOF accident due to the use of an extended pump flow coastdown. The improvement is less for the standard positive-void-worth metallic fueled core due to the small reactivity insertion by the thermal expansion of the control rod drive line (CRDL) and the faster flow coastdown.

iii) Table 1 lists the unprotected LOF coolant temperatures for the metallic fueled core, for BSRV and TSRV designs, as Case A in the table representing reference conditions. The transient response of the metallic fueled core is characterized by a relatively small control-rod worth and by a smaller coolant temperature rise as compared to the MOX fueled core.

III. SELF-SUFFICIENT CORE DESIGN

The self-sufficient core designs are homogeneous designs with two regions. In the first design the active fuel height is 1.0 m and there are no axial blankets. The total core power is 600 MWe. The second design has a flatter geometry, with a core height of 45 cm for the active fuel, and 30 cm long upper and lower axial blankets.[3] This core is designated BRI in which the reactivity coefficients are almost the same as the actinide burner core. Two unprotected accident sequences serve to demonstrate the passive safety response of a low-void worth, metal-fueled core design in a bottom supported reactor vessel. The first is the unprotected loss-of-flow (LOF) accident, in which loss of power to all coolant pumps is assumed to occur with simultaneous failure of the reactor scram systems. The second is the unprotected transient

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Table I. Summary of Results for Conventional[2] and Low-Void-Worth Cores

Case ID	Core Design	BSRV (°C)	TSRV (°C)
LOF Analysis[a]		Peak/QSS Coolant Temperature[b]	
case MOX	MOX (reference)[2]	910/694	Boiling/782
case A	metal (reference)[2]	862/579	862/578
case B	A+Void coeff. =4$	823/576	823/576
case C	A+Void coeff. =0$	802/563	801/578
case D	low void core (BRI)	———	753/550
case E	low void core (BRI)	745/533	———
	low void actinide burner	721/—	721/—
TOP Analysis[c]		Peak Fuel Temperature	
case G	metal(reference)[2]	1034	—
case H	G+Void coeff.=0$	991	—
case I	low void core (BRI)	945	—

a) halving time of primary flow coast down: 6 sec. for metallic fuel core, 30 sec. for oxide fuel core.

b) QSS: LOF quasi-steady state at t = 2000S

c) reactivity insertion of 60¢ at a rate of 1¢/sec.

overpower (TOP) accident, in which an inserted control rod is assumed to be withdrawn inadvertently, with simultaneous failure of the reactor scram systems.

A. LOF Analyses

The system dynamic analyses have been conducted by using the ARGO[2] code to make clear the effect of the sodium void reactivity coefficient on the LOF transient. The unprotected LOF is initiated by a loss of power to the coolant pumps, with failure to scram the reactor. The flow through the core decreases as the pumps coast down according to their inertial characteristics. The pump inertia is assumed to provide an initial flow-halving time of 6 seconds, i.e. the core flow is reduced to one-half of its initial value 6 seconds after the start of the transient. The reduction in flow causes the core temperatures to rise, which in turn introduces negative reactivity feedback to lower the reactor power. The reference case, case A, was calculated using the 600MWe homogeneous metallic fueled core with 3.11×10^{-2} $\Delta k/k$ ($\rho \sim 7.5\$$) as the sodium void coefficient, as listed in Table 2 for the end of an equilibrium cycle (EOEC).

Figure 1 shows a typical comparison of the reactivity components due to the relative displacement between the active core and the control-rods for BSRV and TSRV system. The reactivity components are as follows:

- axial expansion of the reactor vessel walls in contact with hot and cold pools (TSRV),
- axial expansion of the control rod driveline,
- axial expansion of the fuel and B_4C elements and duct walls, and
- axial expansion of the core supporting plate.

As can be seen from the figure, large positive feedback is induced by the axial expansion of the reactor vessel which is in contact with the hot and cold pools for the TSRV.

A parametric study has been performed on the change of the sodium void reactivity coefficient, and the results are shown in Table 1. Figure 2 shows the peak coolant temperature during the unprotected LOF. Comparing the peak coolant temperature as the void worth was changed from 7.5$ to approximately zero indicates that the effect of coolant void worth decrease to zero-value was found to be about a 60°C reduction for the peak coolant temperature using the with a control-rod worth axial derivative of about 5 ¢/cm (cases A, B, and C).

Calculated results are also shown in Table 1 for a low-void-worth core with the breeding ration near unity (BRI)[3]. As shown in the comparison between cases D and E in Table 1, the

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Table 2. Reactivity Coefficients of the Reference Metallic Fuel Core at EOEC.

Doppler (-Tdk/dt)	-5.16×10^{-3}
Na Void ($\Delta k/kk'$)	3.11×10^{-2}
Na Density ($\Delta k/d\rho/\rho$)	-3.10×10^{-2}
Fuel Density ($\Delta k/k/d\rho/\rho$)	3.65×10^{-1}
Steel Density ($\Delta k/k/d\rho/\rho$)	6.50×10^{-2}
Control Rod/Core Displacement ($\Delta k/k/cm$)	2.0×10^{-4} (5¢/cm)

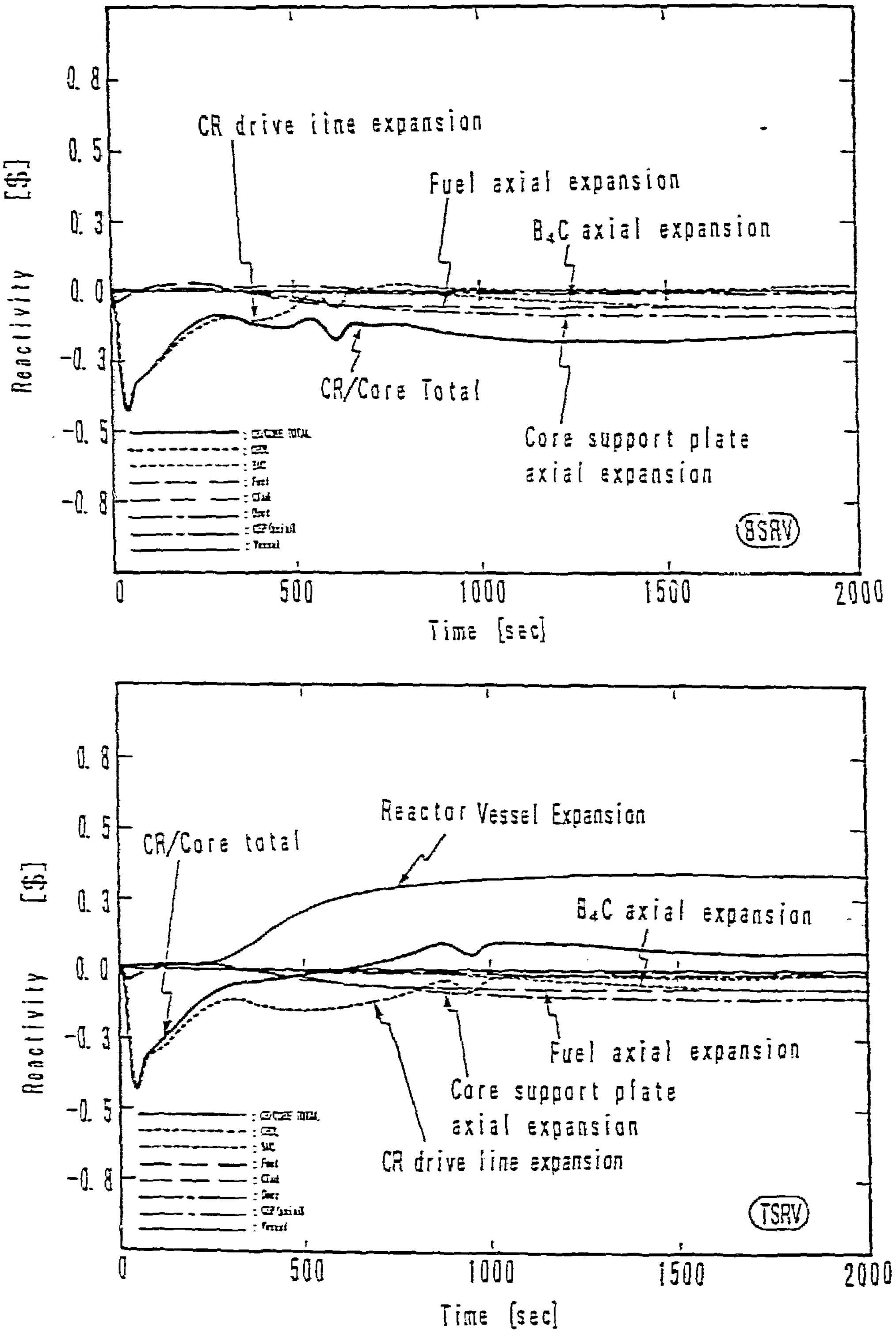

Figure 1. Component Reactivity Change of Relative Displacement Between Control Rod and Core for BSRV and TSRV

effect of the BSRV on the LOF transient coolant temperature of the BRI core was an 8°C reduction for the peak value and a 17°C reduction for the quasi-steady state. It was found that the BSRV was more effective for the low-void-worth metallic cores compared to the standard positive-void-worth core because the former has a flatter core geometry and thus a larger derivative value for the control-rod axial worth distribution, about 8 times larger than that of the standard one. The effect of the enhanced axial derivative of the control-rod worth on the peak coolant peak temperature was evaluated to be a reduction of about 60°C. Based on these analyses it can be emphasized that the LOF mitigation potential was over a 120° decrease on the coolant peak temperature for low-void-worth metallic fuel cores.

B. TOP Analyses

The unprotected TOP is initiated by the uncontrolled withdrawal of one or more control rods, with failure to scram the reactor. The withdrawal introduces positive reactivity into the core, increasing the core power. This in turn raises the core temperatures, introducing negative

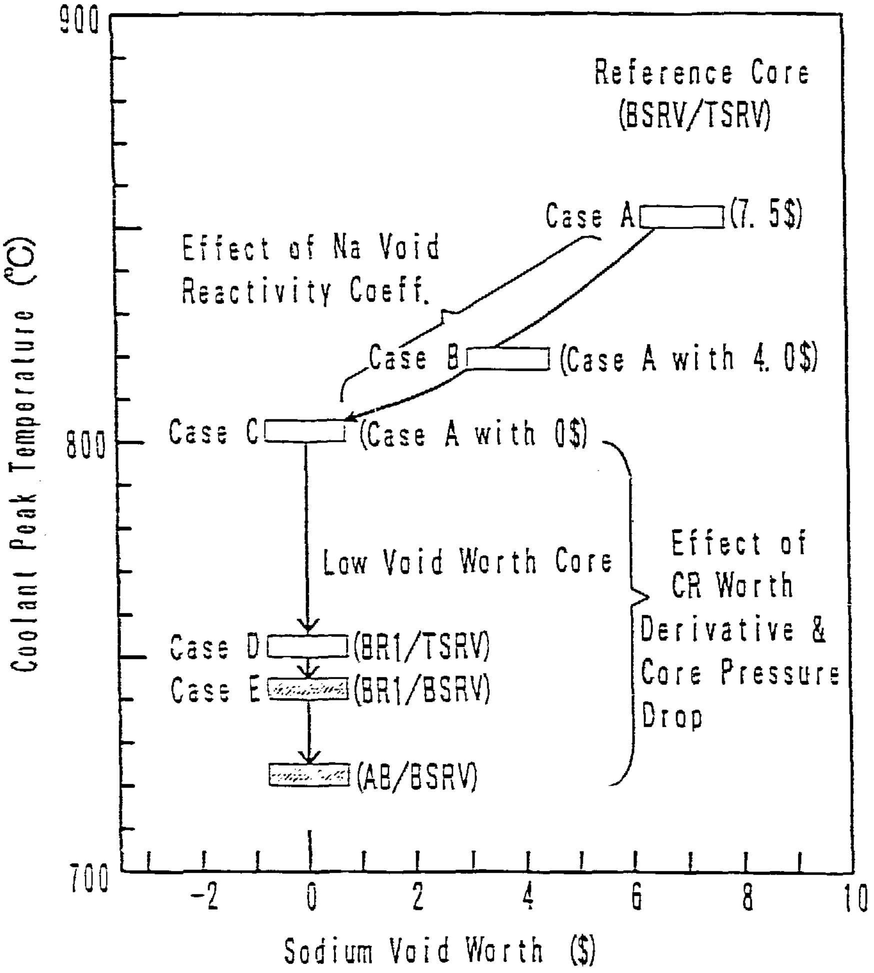

Figure 2. Safety Characteristics of Low-Void-Worth Metallic Fueled Cores for an Unprotected LOF

reactivity feedback and limiting the power rise. The balance between the rate of power increase and the rate and magnitude of the negative reactivity feedback will determine the limit on the power rise and the core temperatures. It is also assumed that the core inlet temperature is maintained at its nominal steady-state value, implying that the heat rejection at the heat exchanger is capable of handling the power generated in the core at all times during the transient. The system dynamic analyses have also been performed for the unprotected TOP event assuming a reactivity insertion of 60¢ at rate of 1¢/sec. Table 1 and Fig. 3 indicate the peak fuel temperature during a TOP for the standard positive void-worth core (case G), standard core with zero void reactivity coefficient (case H), and low-void-worth core BRI(case I). As shown in Fig.3, the effect of the coolant void coefficient decrease (cases G and H), was about a 45°C reduction in peak fuel temperature. The flatter core geometry and larger control rod worth gradient contributed about another 45°C, (cases H and I). Thus for the assumed reactivity insertion of 60¢, it can be concluded that the TOP mitigation potential, in terms of a reduction of the fuel temperature change, was about 90°C for the low-void-worth metallic fueled core.

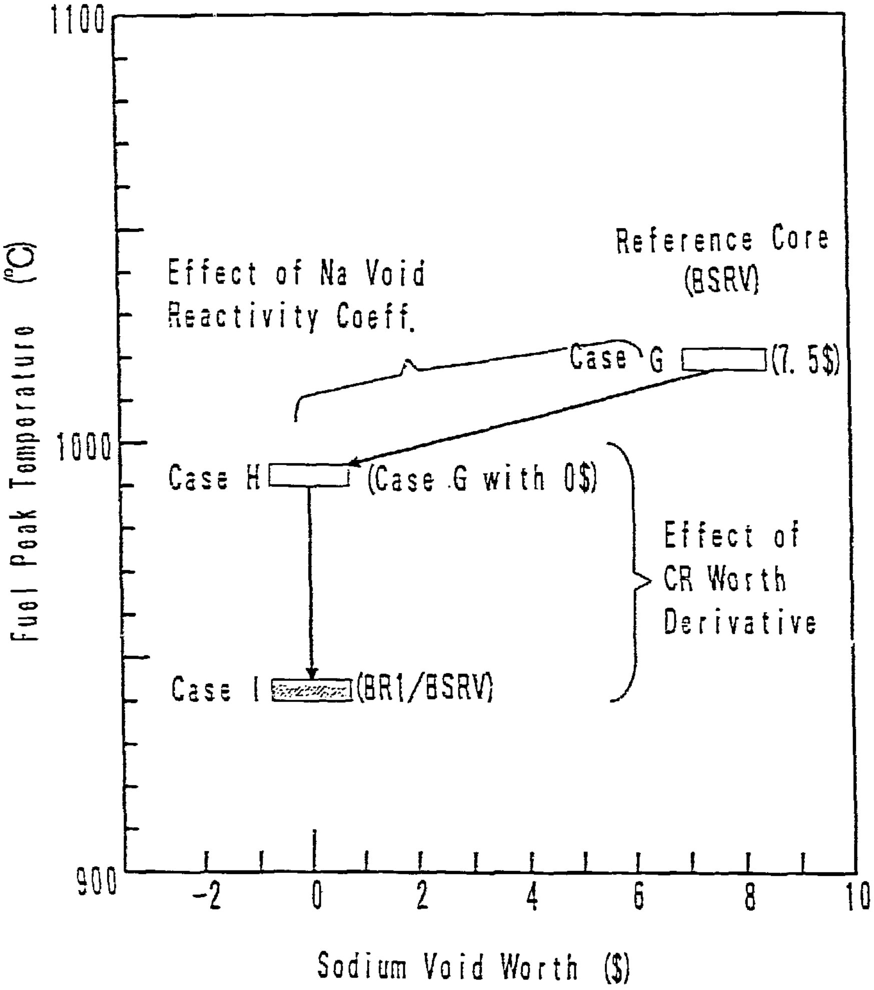

Figure 3. Safety Characteristics of Low-Void-Worth Metallic Fueled Cores for an Unprotected TOP

IV. LOW-VOID-WORTH ACTINIDE BURNER

The recycled fuel burner design has an annular homogeneous layout with a low height-to-diameter ratio.[3] The central region of the core contains absorber and steel reflector assemblies which both reduce the radial power peaking factor and help to mitigate the positive component of the sodium void reactivity worth. The design also features enhanced transuranic burning capability since the radial and axial blankets which provide external breeding were removed.

The core characteristics of most importance in evaluating the transient core response are the reactivity feedback characteristics associated with changes in core temperatures, and the coolant temperature rise and the peak coolant temperature in the hottest assemblies. The sodium density worth at the end of an equilibrium cycle (EOEC) is almost zero, $0.16. The major reactivity feedback components are from control rod driveline expansion and radial expansion of the core, with coefficients at EOEC of -41.4 $/m and -148.0 $/m, respectively. The accidents were evaluated at EOEC because the reactivity feedback coefficients at that time in the cycle are least favorable to the accident response, and would yield the highest temperature and the smallest margin to coolant boiling. The steady-state average outlet temperature in the hottest assembly is 550°C, with a coolant temperature rise of 206°C in the assembly. The average outlet temperature is 510°C, with an average core temperature rise of 166°C.

The accident consequences are calculated using a model of the low-void-worth actinide burner core design in the SASSYS[4] computer code. The core assemblies are modelled in detail. The ex-core components for the primary and intermediate coolant circuits are modelled, based on an existing pool-type plant design. The results are presented for the assemblies which experience the highest steady-state and transient coolant temperatures, thereby displaying the minimum margin to coolant boiling during the transient.

A. LOF Analyses

As with the self-sufficient core design, the unprotected LOF is initiated by a complete loss of power to the coolant pumps, with failure to scram the reactor. The pump inertia for this study is assumed to provide an initial flow-halving time of 6 seconds. The transient variation in core reactivity in response to the core temperature changes is shown in Fig. 4. The main reactivity feedback components are control rod driveline expansion and radial core expansion. The feedback from radial core expansion is largest early in the transient, but after 60 seconds, the feedback from control rod driveline expansion becomes dominant. The long-term effectiveness of the control rod driveline expansion is a direct beneficial result of the bottom support for the reactor vessel. A transient peak in coolant temperature is achieved, as the magnitude and rate at which the power is being reduced overtakes the flow coastdown rate at approximately 35 seconds after the start of the transient. A maximum coolant temperature of 721°C is reached, which then decreases rapidly to less than 600°C by 100 seconds. The minimum margin to coolant boiling is 212°C. These results are also listed in Table 1 and plotted in Fig. 2.

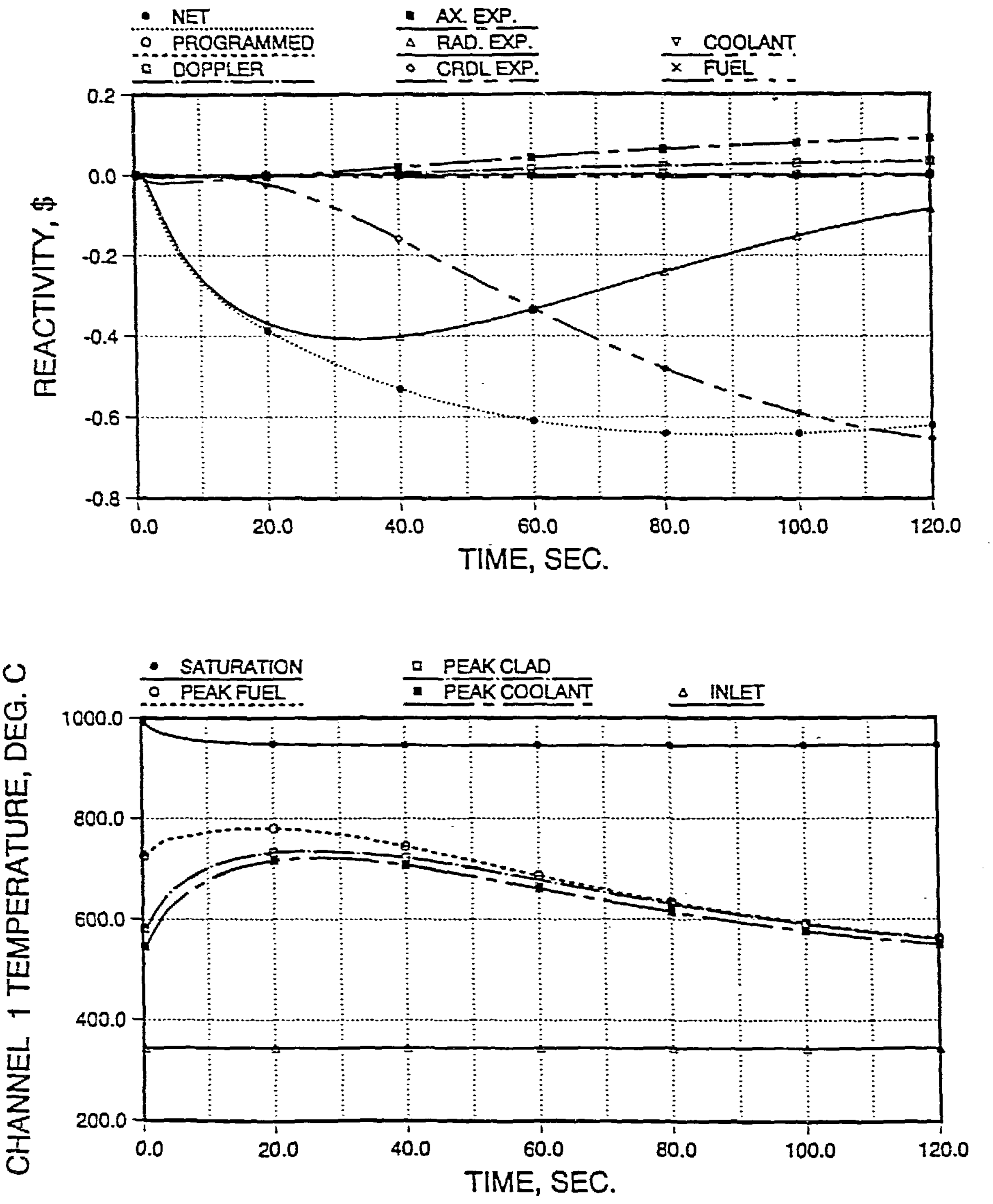

Figure 4. Reactivity and Peak Core Temperatures as a Function of Time After the Initiation of an Unprotected LOF for a Low-Void-Worth Metallic Fueled Actinide Burner

B. TOP Analyses

For the low-void-worth actinide burner design, the maximum single rod worth of $0.78 is used as the TOP initiator; includes the effects of the control rod interaction factor. It is assumed that the reactivity is added at 0.01 $/sec. It is also assumed that the core inlet temperature is maintained at its nominal steady-state value, implying that the heat rejection at the heat exchanger is capable of handling the power generated in the core at all times during the transient. The peak in power and core temperature occurs at 78.5 seconds, which is just after the end of the reactivity addition. A peak coolant temperature of 675°C is reached, for a minimum margin to coolant boiling of 258°C. The peak cladding temperature is 713°C. The temperatures then decrease slowly. The long-term temperatures will depend on subsequent events, especially those involving the balance-of-plant and the ability to handle power generation in excess of nominal power.

IV. Summary and Conclusions

Analyses of metal-fueled fissile self-sufficient and actinide burner cores, each designed to have a low sodium void worth and assuming a bottom-supported reactor vessel using metal fuel have shown that the combination of these concepts produces significant passive safety margins for unprotected accidents. The measure of the passive safety response is the margin to coolant boiling in the core as a result of either unprotected LOF or unprotected TOP accidents. The coolant boiling margins obtained are a direct result of the thermal and neutronic properties of metal fuel and of the beneficial thermal expansion behavior of the bottom-supported reactor vessel.

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