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SAFETY AND LICENSING ANALYSIS OF 471 MWt PRISM REACTOR MODULE*

Gregory J. Van Tuyle**
Gregory C. Slovik**
Edward D. Throm***
Stephen P. Sands***

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ABSTRACT

Independent analyses of unscrammed events postulated for the 471 MW_t PRISM reactor module, as performed by Brookhaven National Laboratory for the U.S. Nuclear Regulatory Commission, are discussed. Peak fuel, cladding, and sodium temperatures for several postulated events were compared against current temperature limits. For the postulated unscrammed loss of flow (ULOF) events, the newly added Gas Expansion Modules (GEMs), have improved the passive shutdown response. For the unscrammed transient over-power (UTOP) events, uncertainties with respect to the behavior of ternary metal fuel leave unresolved the issue of how large a UTOP initiator (between 20 and 40 cents) may be acceptable.

I. INTRODUCTION

The Nuclear Regulatory Commission (NRC), with technical support provided by the Brookhaven National Laboratory (BNL), is continuing a pre-application review of the 471 MWt PRISM advanced reactor design. The evaluation of the initial PRISM design has summarized[1], with the supporting technical analyses performed by BNL[2]. Among the findings of that initial evaluation, was the determination that there existed vulnerabilities in the so-called "passive shutdown", which refers to the tendency of a metal-fueled advanced liquid metal-cooled reactor (ALMR) to make a transition to a much lower power level in response to overheat conditions in the core. In particular, events involving rapid flow reductions without scram were the principal concern, since the decrease in power might not be quick enough to prevent sodium boiling, which would result in a reactivity insertion.

In response to the initial findings by the NRC,[1)] the General Electric Team revised the PRISM design.[3)] In several cases, the changes were made to directly address the NRC concerns, although some other changes requested by

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**Brookhaven National Laboratory, Upton, NY 11973

***U.S. Nuclear Regulatory Commission, Washington, DC 20555

the U.S. Department of Energy were made for economic reasons and actually reduced some safety margins (e.g., by increasing the power production and operating temperatures). As the result of these changes, nearly all of the BNL analyses[2)] had to be repeated, factoring in both the new components and the revised operating conditions. Key findings with respect to the postulated unscrammed cases are summarized in this paper.

II. THE BASIC PRISM DESIGN

PRISM is a small modular LMR, with the reactor situated near the bottom of a tall slender reactor vessel. There is a "Cold Pool" of sodium below and beside the core, and a larger "Hot Pool" above the core. Under normal operating conditions, the four electromagnetic pumps draw sodium from the cold pool and drive it through eight pipes to the reactor inlet plenum. The sodium is heated as it passes upward through the reactor assemblies (hexagonal cans containing wire-wrapped pins), and then it passes into the hot pool. This heat is transferred to the intermediate loop sodium via the intermediate heat exchangers as it passes from the Hot Pool to the Cold Pool.

For responding to unscrammed events, the reactor design and the reliability of the "synchronous machines", which supply the EM pumps with a coastdown mechanism, are crucial. Because the Doppler feedback in a metal-fueled core is comparatively small, all other reactivity feedbacks become more important, and the reactor power production is much more sensitive to the structural and coolant temperatures, as well as to reactivity insertions. The list of pertinent feedbacks includes; Doppler, sodium density, grid plate and load pads (which combine to produce radial expansion and bowing), control rod drive line expansion, and reactor vessel thermal expansion (which also moves the control rods). The maximum amount of reactivity that can be inserted by control rod withdrawal defines the maximum UTOP initiator, so the size of the burnup reactivity swing can be very important, i.e., if the burnup swing is small, one never needs to insert the control rods very far into the core. (Initially GE and the metal fuel specialists at the Argonne National Laboratory (ANL) predicted a burnup swing close to zero, keeping the potential UTOP initiator limited to about 35 cents.) With the various reactivity feedbacks at work, the PRISM "passive shutdown" mechanism is believed to be quite effective, as long as there is time for the power to decrease before there is fuel damage or sodium boiling. The synchronous machines are crucial, because they provide the energy to the pumps for a gradual flow coastdown, which precludes excessive core temperatures as the power transitions to a lower level.

III. PERTINENT DESIGN CHANGES

There were several changes made to the PRISM design, including addition of a containment dome, but here we will focus on those impacting on the unscrammed events. These changes fall into two categories: modified reactor/system behavior and new components.

In order to improve the economics, GE increased the normal operating power and temperatures, which reduced some relatively large safety margins in the earlier version. In addition, there were some other changes that evolved as more data became available on the ternary (U-Pu-Zr) metal fuel, as is discussed in the next section.

GE also added some devices to the PRISM design to strengthen the safety characteristics. In order to address concerns about fast loss of flow (pumping) events, they added three Gas Expansion Modules (GEMs) around the perimeter of the fueled portion of the core. The GEM assemblies are open to the core inlet region, closed at the top, and contain a trapped pocket of gas. When the pumps are operating normally, the gas pocket is above the top of the core, and the sodium within the GEMs act to reflect neutrons back into the core. However, if the pumps trip and the pressure drops, the gas pocket expands into the core perimeter region, allowing many more neutrons to stream out of the core. For the reference conditions, GE expects a negative reactivity insertion of 69 cents when the GEMs complete this transition.

Because of the potential for a significantly increased UTOP initiator, GE added another device, called the "Rod Stops", to limit the degree to which any given control rod can be withdrawn. For instance, if each of the six rods was exactly 20 cents into the core, the combined reactivity insertion would be roughly 120 cents. If one then wants to limit the possible UTOP initiator to 30 cents, for example, one adjusts the rod stops to prevent each rod from coming out by more than 5 cents. Of course, the rod stops must be repositioned every few weeks or months, in order to cover the burnup reactivity swing. In addition, the new position of the rod stop is determined based on an estimate of the new rod worth, so there is some uncertainty involved. As a result, the maximum UTOP initiator is now assumed to be 40 cents (of which 10 cents is meant to cover uncertainties). Effectively, the addition of rod stops is not so much a design improvement as a fairly simple method of compensating for a newly recognized characteristic of the metal fuel, i.e., the axial fuel expansion during burnup.

In response to concerns about prolonged unscrammed events, GE added the "Ultimate Shutdown System" (USS), which replaces a fuel assembly in the center of the core. If actuated by the operator, the USS drops boron carbide balls into the center of the core, shutting down the reactor. This is not a rapid shutdown device, but it does strengthen the passive shutdown arguments, in that the presence of the USS allows one to terminate a prolonged event where the reactor otherwise remains critical.

IV. NEW INFORMATION ON METAL FUEL

Early data indicate that the burnup response of the ternary fuel[4] is more complex than that for the original U-Zr fuel, showing axial expansion early in the burnup cycle, as well as fuel component migration. In theory, the behavior of the three component ternary fuel should be more complex than binary fuel, and it should require some time to characterize fully. ANL will be obtaining much more data on the ternary fuel within the next year, and hopes to address some of the questions that have resulted from the data obtained from the first few pins. The fuel axial expansion adds to the burnup reactivity swing, and more control rod worth insertion is therefore required. As a result, the maximum UTOP initiator for PRISM is now believed to be over one dollar, but potentially limited by the rod stops to about 30 to 40 cents. The radial migration of the uranium and zirconium components during burnup is very substantial and causes large changes in local fuel thermal conductivities and significant changes in the fuel solidus and liquidus temperatures. In addition, there may be some radial relocation of the plutonium component, which could change the radial power distribution within the fuel pin.

V. METHODS OF ANALYSIS AND REPORTING OF RESULTS

The analyses of the postulated unscrammed events involve application of systems codes, such as GE's ARIES Code,[5] ANL's SASSYS Code,[6] or BNL's SSC and/or MINET Codes.[7,8] Typically, these analyses represent the reactor, the pools and piping, the pumps, the IHXs, and other portions of the coolant system that might impact on the progression of the postulated events. For such analysis, it is essential to adequately represent the various reactivity feedback mechanisms, including Doppler effects, sodium density changes, radial expansion of the grid plate and load pads, fuel axial expansion, control rod drive line expansion, and the contribution from the GEMs. Once the system has been adequately represented, one simply initiates a transient by adding reactivity (for the UTOP), tripping the pumps (for the ULOF), cutting off heat removal through the IHX (for the ULOHS), or some combination or variation on this set of boundary conditions. The simulation continues for a few minutes, until a trend is established, and in many cases, the peak temperatures have passed. Typically, the pertinent variables are the reactor power and sodium flow; the peak fuel, cladding, and sodium temperatures; and the various reactivity feedbacks as the transient progresses. The plotted results have already been shown in several publications, and will not be shown explicitly here.[2,3]

The peak fuel, cladding, and sodium temperatures during the various transient calculations, as calculated using the SSC and MINET Codes, will be summarized here in bar chart form, which facilitates a direct comparison with key temperature limits and against the results from other calculations. Of course, this strips away information regarding the length of time at given temperatures. However, one can safely generalize that ULOF events develop quickly and peak briefly, that UTOP events usually result in an early power peak and then settle in at lower power levels, and that the ULOHS events develop slowly and may not reach equilibrium temperatures for a few tens of minutes.

VI. PERTINENT TEMPERATURE LIMITS

In evaluating the PRISM system response to various postulated events, one must consider the peak fuel, cladding, sodium, and structural temperatures. For the sodium, one must stay below the boiling point to avoid a reactivity addition and undercooling of the fuel pins. The boiling temperature for sodium within the PRISM vessel (near the reactor level) is about 1350 K if the pumps are running, and about 1240 K when the pumps are off. The highest sodium temperatures also dictate the hottest structural temperatures, although there are time delays and other factors involved. The structural temperature limit that is of concern for the relatively short unscrammed events is 1040 K.

The fuel and cladding temperature limits are less precise, and are based on empirical data. Further, since the data are only now coming in for high Pu ternary fuel, the base applicable to PRISM is quite limited. Based on the available data, it appears that very slow cladding damage begins around 970 K, but becomes much faster above 1050 K. The fuel solidus temperature varies between 1200 K and 1300 K, depending on the local mix of uranium, plutonium, and zirconium. Therefore, both the fuel and cladding temperature limits are not rigid, and depend on the timing of the event and the fuel condition and performance.

These temperature limits are included in Figures 1 and 2, and are shown in both Kelvin (K) and Fahrenheit (F). For the very unlikely unscrammed events, small amounts of fuel, cladding and/or structural damage might be acceptable, but a close approach to sodium boiling would be a major concern.

VII. REVISED ANALYSES OF UNSCRAMMED LOSS OF FLOW CASES (ULOFs)

For the ULOF events, it is assumed that the power is cut to all four EM pumps, and that the coastdown energy for the EM pumps is provided by the synchronous machines. It is also assumed that there is no scram or activation of the USS shutdown, so the passive shutdown is required. For their reference ULOF event, GE also postulates a loss of cooling through the intermediate heat exchangers (IHXs), which results in a combined ULOF & ULOHS. The peak fuel, sodium, and cladding temperatures from the GE analysis are shown in the first set of bars in Figure 1. The corresponding peak temperatures from the BNL calculations are shown in the second set of bars.

Since the models were quite similar (the codes were different), the similarity in results is not unexpected. When we changed the BNL model to allow continued heat removal through the IHX, the peak cladding and coolant temperatures dropped about 70 K, as indicated in the third set of bars in Figure 1. Next, it was assumed that the GEMs failed for the same event, resulting in the peak temperatures showed by the fourth set of bars.

In looking at the four results, it appears that the ULOF events are not very damaging, as long as the GEMs and synchronous machines work. Also, it is apparent that the GEMs were added, in part, to prevent significant cladding damage during ULOF events.

VIII. REVISED ANALYSIS OF THE UNSCRAMMED LOSS OF HEAT SINK (ULOHS)

For the ULOHS event, it is assumed that all heat removal through the IHXs is stopped, e.g., by dumping the intermediate loop sodium in response to a steam generator tube rupture. It is assumed the EM pumps continue to operate and that scram fails.

Because the gradual heat-up allows plenty of time for the power to decrease, this event is generally fairly mild. Peak temperatures from our analysis are shown in the fifth set of bars in Figure 1. The only difficulty with this event is that it continues slowly for many minutes before a new equilibrium can be established. However, the addition of the USS reduces the likelihood of the ULOHS continuing for such an extended period of time.

IX. REVISED ANALYSES OF THE UNSCRAMMED TRANSIENT OVER-POWER (UTOP)

The reference UTOP event includes a 2¢/second reactivity insertion for 20 seconds, to a total of 40 cents. The pumps continue pumping and the IHXs continue to function normally. The characteristic response is an increase in power to about 1.7 times full power, which is then countered by core expansion and other feedbacks, which return the power into the 1.3 times full power range. Peak temperatures for this event, as calculated by GE and as calculated by BNL using GE's assumptions, are shown in the first two sets of bars in Figure 2. In both cases, some localized fuel melting is predicted, although the cladding and sodium temperatures are not very high. However, in order to match GE's results, we had to match their assumptions. If, however, we assume some plutonium migration and re-analyze the case, we get peak temperatures corresponding to the third set of bars. Clearly, fairly significant fuel melting would result if the plutonium migration really occurs.

The fourth set of bars in Figure 2 correspond to the peak temperatures if the pumps are tripped early in the UTOP event. The much lower peak fuel temperature is caused largely by the negative reactivity introduced by the GEMs, which trigger a near-shutdown of the reactor. In contrast, before the GEMs were added the inadvertent tripping of the pumps, under UTOP conditions, was considered to be very hazardous. By adding the GEMs, GE may have changed the UTOP-response strategy from avoiding pump trips at almost any cost to intentionally tripping the pumps to get a "passive" shutdown!

X. COMPONENT MIGRATION AND THE UTOP EVENT

There is considerable evidence about the formation of annular zones within the fuel pin,[8] with each having differing composition, in the ternary metal fuel utilized in EBR-II. Clearly there is relocation of both zirconium and uranium, as illustrated in Figure 3. Unfortunately the sharp differences in fuel density between these annular zones makes it difficult to be certain about possible plutonium migration. Component migration will certainly change local thermal conductivity and solidus and liquidous temperatures, which impact on the peak fuel temperatures and the likelihood of local melting. In addition, any plutonium migration could cause significant changes in the power distribution.

Peak fuel centerline temperatures from 5 calculated UTOP events are included in Figure 4. For the 40 cent case and nominal thermal conductivity, both the GE and BNL calculations indicate similar peak fuel temperatures, as well as some localized melting. However, if the component migration (including plutonium) is factored in, we project peak fuel temperatures at least 100 K higher.

We also analyzed postulated 20 cent and 30 cent UTOP events, getting the peak fuel temperatures indicated in Figure 4. Note that to get peak fuel temperatures below the solidus temperature, even if we ignore the component migration, the maximum UTOP initiator would have to be 22 cents or lower. Thus, it may not be practical for GE to reduce the size of the possible UTOP initiator to a point where no localized damage would occur.

XI. SUMMARY AND CONCLUSIONS

The 471 MW_t version of PRISM, currently under review by the NRC, has several features and characteristics that are different than the version evaluated in Reference 1. The addition of the containment dome and the USS are clearly improvements, and the addition of the GEMs also appears to be a significant improvement (potential failure modes have not yet been evaluated). The increased operating power and temperature levels caused the peak temperatures to increase in some cases, although this doesn't seem to be a problem, with the fairly large safety margins for most events. However, it is the new information on the metal fuel performance that has most altered our perception of the PRISM reactor safety. In order to cover the larger burn-up induced axial fuel expansion, GE had to add rod stops to limit the size of potential UTOP initiators. While this probably an acceptable adjustment, it does add some questions about the precision of the adjustments and potential errors in executing the adjustments.

It is the metal fuel, and potential advantages of the proposed IFR fuel cycle that make the ALMR unique among advanced reactor designs. However, at this time, it is the possible behavior of the metal fuel under accident conditions that remains to be resolved before one can be certain regarding the reliability of the passive shutdown capability in PRISM.

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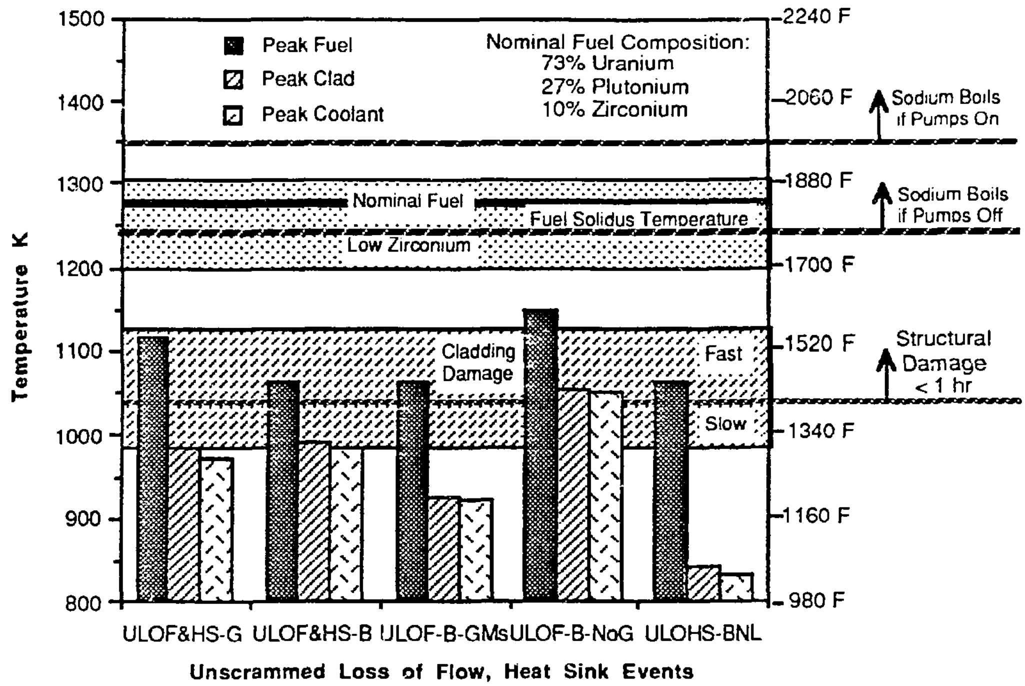
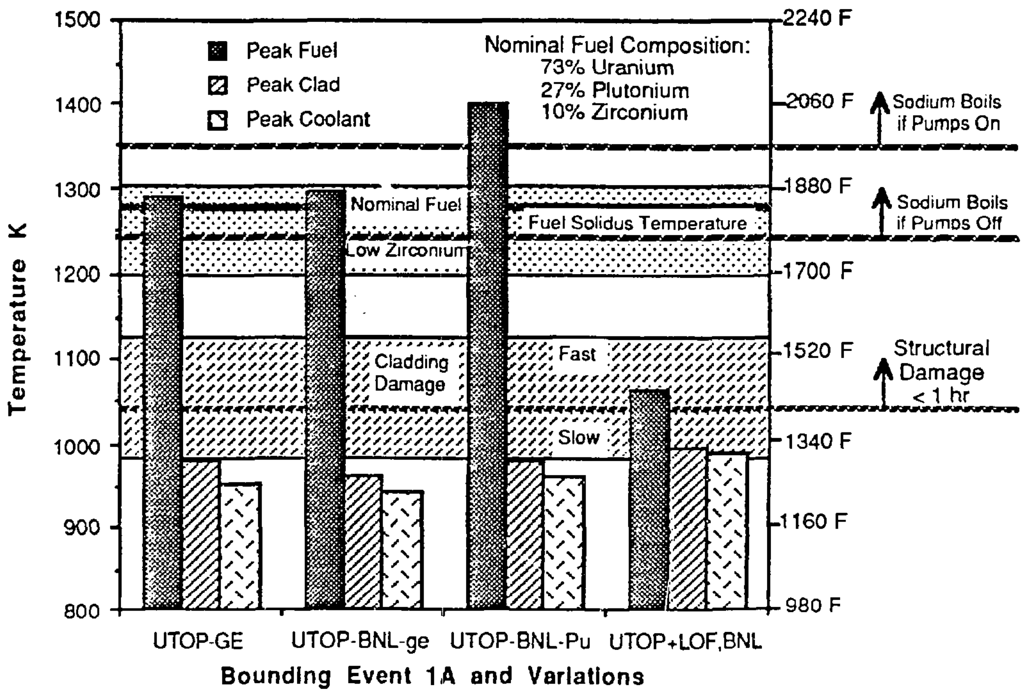
Figure 1. Peak Fuel, Cladding, and Sodium Temperatures for Various Loss of Flow and/or Loss of Heat Sink Events



Note: Structure Temperatures Would Be Lower Than the Peak Coolant Temperatures (by 50 to 100 K)

Figure 2. Peak Fuel, Cladding, and Sodium Temperatures for UTOP Events: by GE, by BNL, by BNL with Pu Migration, and by BNL with Loss of Flow



Note: Structure Temperatures Would Be Lower Than the Peak Coolant Temperatures (by 50 to 100 K)

Figure 3. Per Cent of Pin Annular Zone Occupied by Three Components: Uranium, Plutonium, and Zirconium

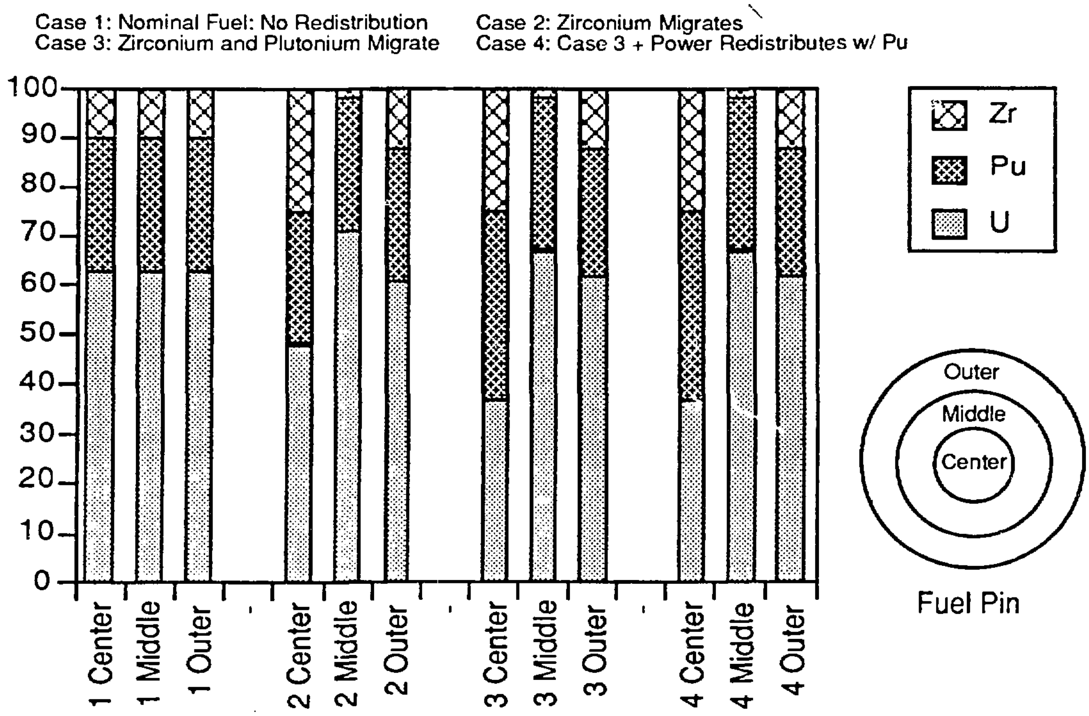


Figure 4. Peak Fuel Centerline Temperatures for UTOP Cases Postulated for PRISM Reactor System