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AN ASSESSMENT OF THE CONSEQUENCES OF BOILING IN THE RADIAL BLANKET DUE TO HYPOTHETICAL MAJOR PIPE LEAKS

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INTRODUCTION

Consideration of boiling initiation in an LMFBR, whether in the core or blankets, has been assumed in the past to lead inevitably to clad and/or fuel melting, with the potential for loss of coolable geometry [1]. This approach was based on analyses for core assemblies and was used to assure conservatism. An examination of the physical properties of sodium and the operating conditions in the reactor indicates that consequences of incipient boiling are more adverse in LMFBRs than in PWRs [1].

This led to the approach of precluding boiling under all accident conditions in core assemblies in order to maintain coolable geometry although recent experiments have indicated that boiling does not in itself result in loss of coolable geometry [2, 3]. Other coolable geometry criteria for assemblies with steep power skews and radial temperature gradients, which are characteristic of radial blanket assemblies, have not been quantitatively assessed. However, it may be possible to show that a local boiling transient is acceptable in assemblies having steep power and temperature gradients in the vicinity of the point of inception of boiling [2, 4, 5].

This paper addresses the potential consequences of localized boiling in radial blanket assemblies that could be associated with a hypothetical major leak in the main inlet coolant pipe of the Clinch River Breeder Reactor (CRBRP). The design parameters used correspond to the Reference Design of CRBRP but it should be noted that such analyses are conducted in the context of risk analysis, since a major loss of piping integrity does not constitute a design base event for CRBRP. The range of locations where the major leak can lead to boiling is larger for the radial blanket than for the core. The nuclear and thermal conditions in the radial blanket are sufficiently different from the core to justify examination of the acceptability of limited coolant boiling in the radial blanket as a consequence of this highly improbable accident. Any capability to tolerate boiling would reduce the risk associated with loss of piping integrity.

For major leaks postulated at most locations, the hot channel coolant temperature is well below saturation in the core, but may approach saturation in the radial blanket. The case examined in this analysis was a major leak at the flow meter exit on the main inlet coolant pipe because the predicted radial blanket hot channel temperature is higher than for hypothetical major leaks at other locations except those that would also result in sodium boiling within fuel assemblies. The analysis of the accident consequences used scoping calculations because the analytical tools have not yet been developed to consider the consequences in detail. The scoping calculations are useful to assess whether the application of more sophisticated tools is likely to permit relaxation of the boiling criterion for loss of coolable geometry.

The thermal power causing boiling was taken as the sum of the decay power and the stored energy in the pin that initiated boiling. The possibility of rapid condensation of vapor occurring due to the steep temperature gradients was investigated. Under the unlikely conditions that the hot pin becomes thermally isolated, estimates were made of the temperature of the cladding from stored heat in the pellet and the time to reach clad melting from decay heat.

CALCULATIONAL PROCEDURES

Computer Codes

The transient hot channel coolant temperatures, the temperature profile in the pellet, the axial coolant temperatures and the clad mid-wall temperature were calculated using the DEMO Code [6], which is a simulation program designed to analyze thermal hydraulic plant transients in the CRBR. The subchannel temperatures under steady state conditions were calculated using the COTEC code [7].

Estimation of Transient Subchannel Temperatures

The steady state temperatures used to obtain the transient subchannel temperature distribution were based on end-of-equilibrium-cycle conditions when thermal ratings in the radial blanket are a maximum. The transient subchannel temperature distribution was obtained from the steady state distribution using a superposition principle with a transient factor calculated from DEMO results. This course was followed because the codes with transient two-dimensional voiding models are still under development. The superposition requires the assumption that the relative subchannel flow distribution remains invariant in time during the transient. The transient factor was defined in terms of hot channel radial blanket temperatures in the assembly with the highest power rating as follows:

$$\text{Transient Factor, } TF\ (t) = \frac{T(t) - Ti}{T(0) - Ti} \qquad (1)$$

where, t = time; $t = 0$ corresponds to steady state
T = sodium temperature associated with the hot pin in the radial blanket at the elevation corresponding to the top-of-the-core (calculated by DEMO Code)
Ti = inlet sodium temperature

The subchannel temperatures during the transient were calculated using:

$$Ts(j,t) = Ts(j,o) \times (H.C.F.) \times (U.F.) \times TF(t) \quad (2)$$

where, $Ts(j,t)$ = temperature rise in subchannel j from inlet to top of core elevation at time t (thus Ts is a rise from Ti)
H.C.F. = Hot Channel Factor
U.F. = Uncertainty factor on coolant enthalpy rise

The highest power radial blanket assemblies may be expected to have the highest transient factors, thus ensuring that the transient subchannel temperature Ts(j,t) are conservative. The steady state temperature distribution Ts(j,o) is conservative because interassembly heat transfer was not considered in the COTEC computation. Interassembly heat transfer tends to increase the margin to boiling in the subchannels in the vicinity of the hot channel [8].

Figure 1 shows the radial blanket hot channel coolant temperature as a function of time after the initiation of the transient. Also shown is the plot of saturation temperature which decreases as the local pressure decreases. Both quantities correspond to the top-of-the-core elevation where the maximum coolant temperatures would occur. The coolant temperature could not actually exceed saturation (dashed curve) as shown because local boiling would occur at the saturation temperature. The excess over saturation only indicates the potential for boiling.

Estimation of Thermal Power Causing Boiling

The thermal power generation associated with the hot channel top-of-the-core elevation was calculated using the end-of-cycle assembly power and the reactor decay power calculated by DEMO. The power from the hot pin at the top-of-the-core elevation was calculated by multiplying the average pin power by the heat flux uncertainty, the statistical factor at the 3σ level applicable to heat flux, the radial power factor applicable to the subchannel and the axial power factor.

The release of stored energy in the fuel pin was estimated using the time dependent temperature distributions computed by DEMO. Using a constant specific heat approximation, the energy out of the fuel pin per unit length was calculated as follows for the time when the hot channel coolant temperature first exceeds saturation:

$$\left(A_f \rho_f C_f \frac{\Delta \overline{T}_f}{\Delta t} + A_c \rho_c C_c \frac{\Delta \overline{T}_c}{\Delta t}\right) \quad (3)$$

where, A = crossectional area, ft^2.
ρ = density, lb/ft^3.
$\underline{C}$ = specific heat, Btu/lb.°F
$\overline{T}$ = change of mean temperature during Δt, °F.

and, subscripts f and c apply to the fuel pellet and cladding respectively.

The total power input to the hot channel coolant when the coolant temperature just exceeds saturation is estimated by summing the decay thermal power and the stored energy components. This analysis used a conservative quasi-steady state approximation by assuming that the power input remains constant at the level which exists when the coolant saturation temperature is first exceeded.

In assessing the potential for condensing the bubble formed by the coolant exceeding saturation, the heat sink must be capable of absorbing the energy input to the vapor. The most likely surface for condensation is the vapor-liquid interface with the subcooled sodium acting as the major heat sink, with some energy being absorbed by cooler pins, which are exposed by the expanding bubble. Heat transfer to the cooler pins occurs through the sodium film that would exist on the surface. In this analysis, energy balances were applied separately to estimate the heat absorption capability available in the sodium and the cooler pins surrounding the hot pin.

The film thickness on the clad in a voided subchannel was estimated using liquid fraction values in the literature [9] quoted for slug voiding processes. For conservatism, the calculated flow area ignored the surface of the wire-wrap, which would also contribute area for the film. The time to dryout the film was estimated as the time required to supply enough energy to vaporize the film. Thus, to preserve the simplicity of the calculations, dynamic film stripping processes were not considered.

Voiding Consequences to Clad

If continued voiding is postulated, the thermal state of the clad is determined by the stored heat in the pellet and the decay heat. The equilibrium temperature of the clad from the stored heat component, if the pin became thermally isolated, was estimated using the energy balance as:

$$\frac{\text{Heat capacity of clad per unit length}}{\text{Heat capacity of pellet per unit length}} = \frac{\overline{T}_f - T}{T - \overline{T}_c} \qquad (4)$$

where, T = equilibrium temperature of a fuel pin assuming adiabatic conditions and not considering decay heat

and, $\overline{T}_f$ and $\overline{T}_c$ are as defined earlier.

If prolonged thermal isolation is postulated the decay power could eventually melt the clad. The time required for this to occur was estimated as that required to raise the temperature of the clad to the melting point of 2600°F and then supply the heat of fusion.

RESULTS

Estimate of Number of Subchannels that Undergo Boiling

Subsequent to the hypothetical major leak postulated at the flowmeter exit, Figure 1 shows that boiling is predicted in the hot channel of the radial blanket approximately 5 seconds after the rupture. The maximum potential for boiling, which is indicated by the difference between the coolant and saturation temperatures, occurs approximately 8.5 seconds after the rupture. To find the maximum subchannel temperatures, the Transient Factor was calculated from Equation (1) at time t = 8.55 seconds to be 1.939. Figure 2 shows the calculated subchannel temperatures using Equation (2). It is seen from Figure 1 that a minimum occurs in the saturation temperature; the temperature at the minimum is 1640°F. In assessing the potential for boiling a saturation temperature of 1640°F was used in all calculations. The calculated subchannel temperatures exceed saturation in six subchannels (numbers 25, 26, 27, 28, 41 and 42). This number of subchannels is an overestimate because interassembly heat transfer would tend to decrease the temperatures of some of the subchannels involved and also because every subchannel has been considered as a "hot channel" (i.e., have hot channel factors applied). It is not possible for a relatively large number of contiguous subchannels to be hot channels because application of the hot channel factors imply that some adjacent channels are cooler than the hot channel. The conservative assumption of all hot channels is used since data to define the possible number of subchannels in an assembly that could approach the statistical hot channel are not available. Thus, Figure 2 represents a highly conservative assessment of the extent of boiling.

Figure 3 shows the subchannel temperatures computed in the same manner as Figure 2, with the exception that all subchannels were considered as being nominal, i.e., the hot channel factor was removed. It is seen that the highest nominal subchannel temperature if 184°F below saturation. An actual subassembly under the conditions analyzed would contain subchannels on both sides of nominal. Thus, Figure 3 is expected to represent a more realistic condition.

The course of events subsequent to the initiation of boiling depends on the three dimensional temperature profile in the vicinity of the point of initiation. Steep axial and radial temperature gradients would inhibit bubble growth. It is seen from Figure 2, that the temperature difference between adjacent subchannels varies from approximately 10°F to 70°F. Thus, it appears that steep temperature gradients would normally be available to promote collapse of the bubble. Also, formation of one bubble tends to inhibit formation of others in the immediate vicinity due to a local increase in pressure. Although the analysis here did not include a detailed consideration of the role played by pin power distribution, it is expected that the steep power profile would discourage bubble expansion across the crossection of the assembly.

An estimate of the possible size of the bubble in the axial direction was obtained by examination of the coolant temperature predictions in the axial direction from DEMO. The computed coolant temperatures indicate that the temperature could exceed saturation over a length of approximately 3.5 inches in the channel having the greatest potential for exceeding the saturation temperature. Thus void expansion over relatively small distances causes the vapor to encounter cold surfaces in all directions. For void dimensions corresponding to six subchannels in radial extent and 3.5 inches in axial extent there is strong evidence that flow reversal would not occur [10].

Heat Balance in the Voided Region

The decay thermal power generation associated with the hot channel top-of-the-core elevation was calculated at end-of-residence to be 0.45 Kw/ft. This power generation was calculated at 5 seconds after the initiation of the transient. At this time the power from stored energy, computed using Equation (3), was found to be 0.80 Kw/ft. Thus, the total power input into the hot channel when the coolant temperature just exceeds saturation is estimated to be 1.25 Kw/ft.

An estimate was made of the temperature difference required to transfer the above power by condensation into a temporary heat sink, such as the sodium in the surrounding subchannels or a cooler pin in the circuitry. A conservative condensation coefficient of 10,000 Btu/hr.ft^2°F (2.93 Kw/ft^2°F) was assumed [11, 12].

The pins most likely to be surrounded by a void, as seen in Figure 2 are numbers 16 and 17. Considering only heat transfer into the sodium in the six subchannels that are in immediate contact with the six subchannels which are assumed to have voided around each of the pins, the condensing surface area corresponds to the six pin-to-pin gaps. For the area between the pins, a temperature difference of 22°F would be sufficient to transfer 1.25 Kw/ft. Examination of the temperatures in Figure 2 shows that the gradients across the adjacent subchannels in the vicinity of pins 16 or 17 on the average are more than twice that required to transfer the heat. If the temperature in the boiling zone is assumed to be at the saturation temperature of 1640°F, the average temperature gradients for the two pins are respectively 30°F and 40°F, which are well above the minimum required.

If the temporary heat sink for the pin generating 1.25 Kw/ft is taken as another cooler pin, it was found that a temperature gradient of 3.2°F would cause the required heat transfer. Since the temperature differences between subchannels is of the order of 10°F to 70°F,even on a pin-to-pin basis, there is sufficient potential for condensation to make void progression across the assembly highly unlikely.

Dryout and Consequences

Using a conservative liquid fraction in the voided channel (0.15), it was estimated that 1.8 seconds would be required at the energy input rate of 1.25 Kw/ft to evaporate the liquid film before dryout could occur. This period of time is considerably longer than the time constants that characterize voiding and bubble collapse phenomena. Thus dryout is unlikely.

If dryout does occur and the hot pin becomes thermally isolated, the temperature of the clad in the short term is determined by the stored heat that flows into it from the pellet. Equation (4) was used to determine the equilibrium temperature of the clad. For the temperature profile across the pin that exists at 5 seconds after the initiation of the transient, it was found that the temperature of the clad would be 2030°F. This temperature is approximately 500°F below the melting point of the clad. Therefore, it is unlikely that the clad will melt due to short periods of dryout in the radial blanket although cladding failure with fission gas release would be expected.

If prolonged dryout is postulated, the decay heat from the pellets would eventually melt the clad. It was estimated that approximately 36 seconds would be required to melt the clad with a constant thermal power supply. Considering the decrease in decay power with time would extend this further. This period is expected to be much longer than the time for which dryout may last. Therefore, melting of the clad is highly unlikely due to the hypothetical major leak.

SUMMARY AND CONCLUSIONS

The orificing arrangement in CRBRP permits the possibility of limited boiling in the radial blanket for certain hypothetical transients that would not result in boiling in the core. Limited boiling in the radial blanket may result in acceptable consequences because of the steep power and temperature profiles which offer a high potential for condensation of the limited amount of vapor formed. The analysis presented indicates that the coolant in the highest power radial blanket assemblies may exceed saturation temperature in no more than six subchannels for a hypothetical major leak, even applying hot channel factors to all pins. The void thus formed is unlikely to expand across the crossection of the assembly because cooler sodium and pins in the vicinity could act as temporary heat sinks and cause the vapor to condense.

The void is likely to collapse before dryout occurs. Even if dryout is postulated, melting of the clad could only occur on a long time scale compared to expected flow recovery times.

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DEMO RADIAL BLANKET HOT CHANNEL COOLANT AND SATURATION TEMPERATURES

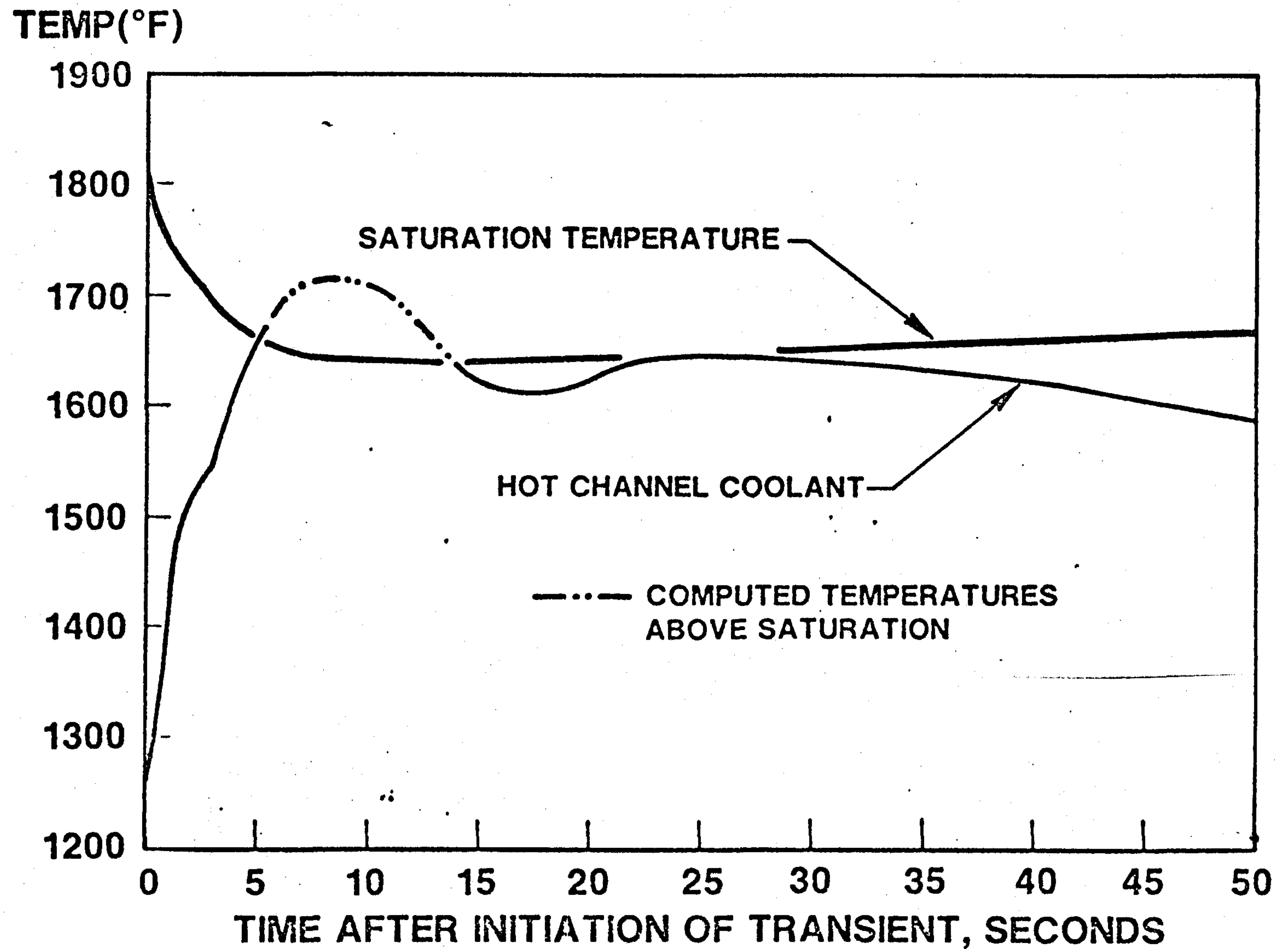

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Figure 1

COOLANT TEMPERATURE DISTRIBUTION IN HIGHEST POWER RADIAL BLANKET ASSEMBLY
(HOT CHANNEL FACTORS APPLIED ON ALL SUBCHANNELS)

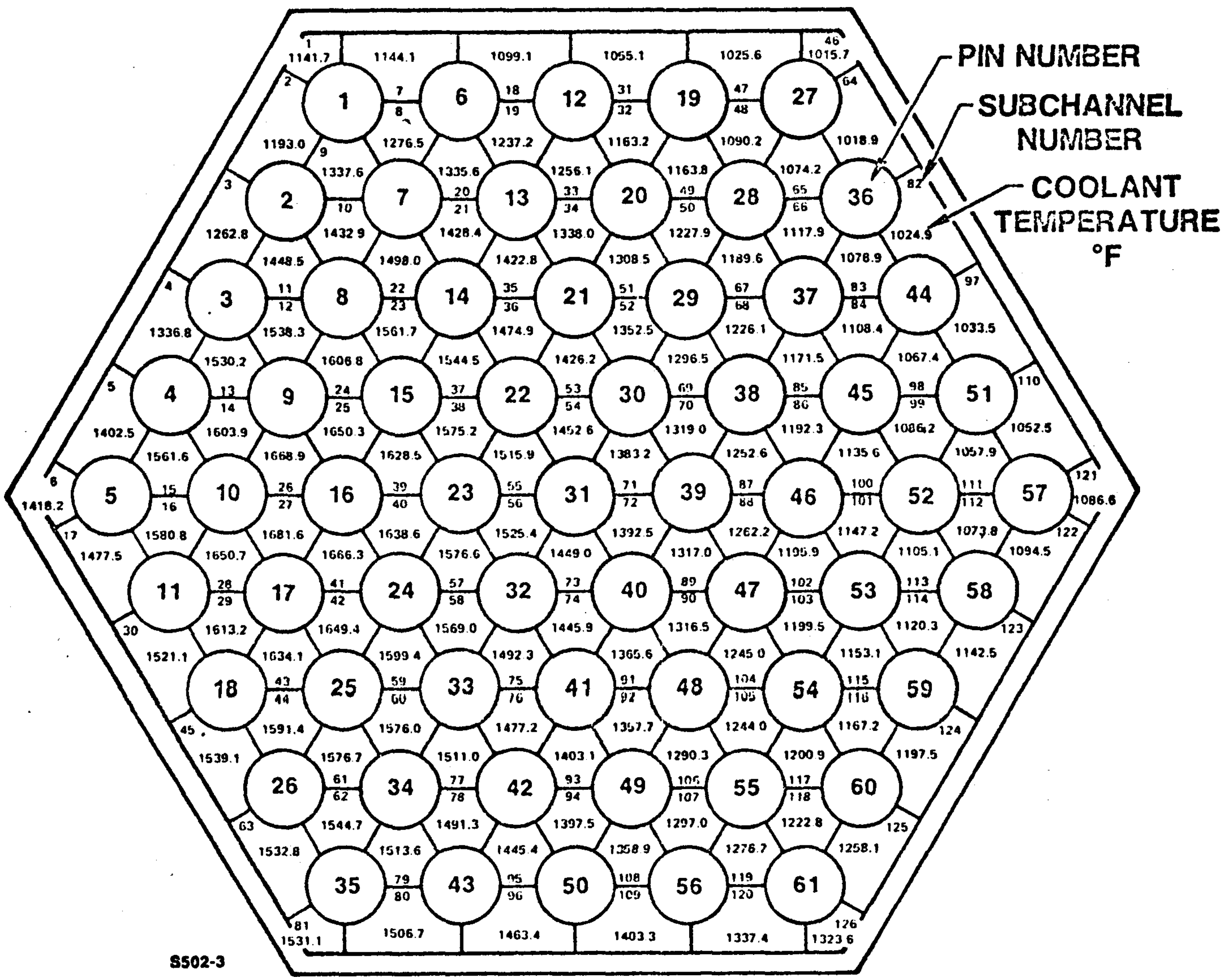

Figure 2

COOLANT TEMPERATURE DISTRIBUTION IN HIGHEST POWER RADIAL BLANKET ASSEMBLY
(ALL SUBCHANNELS NOMINAL)

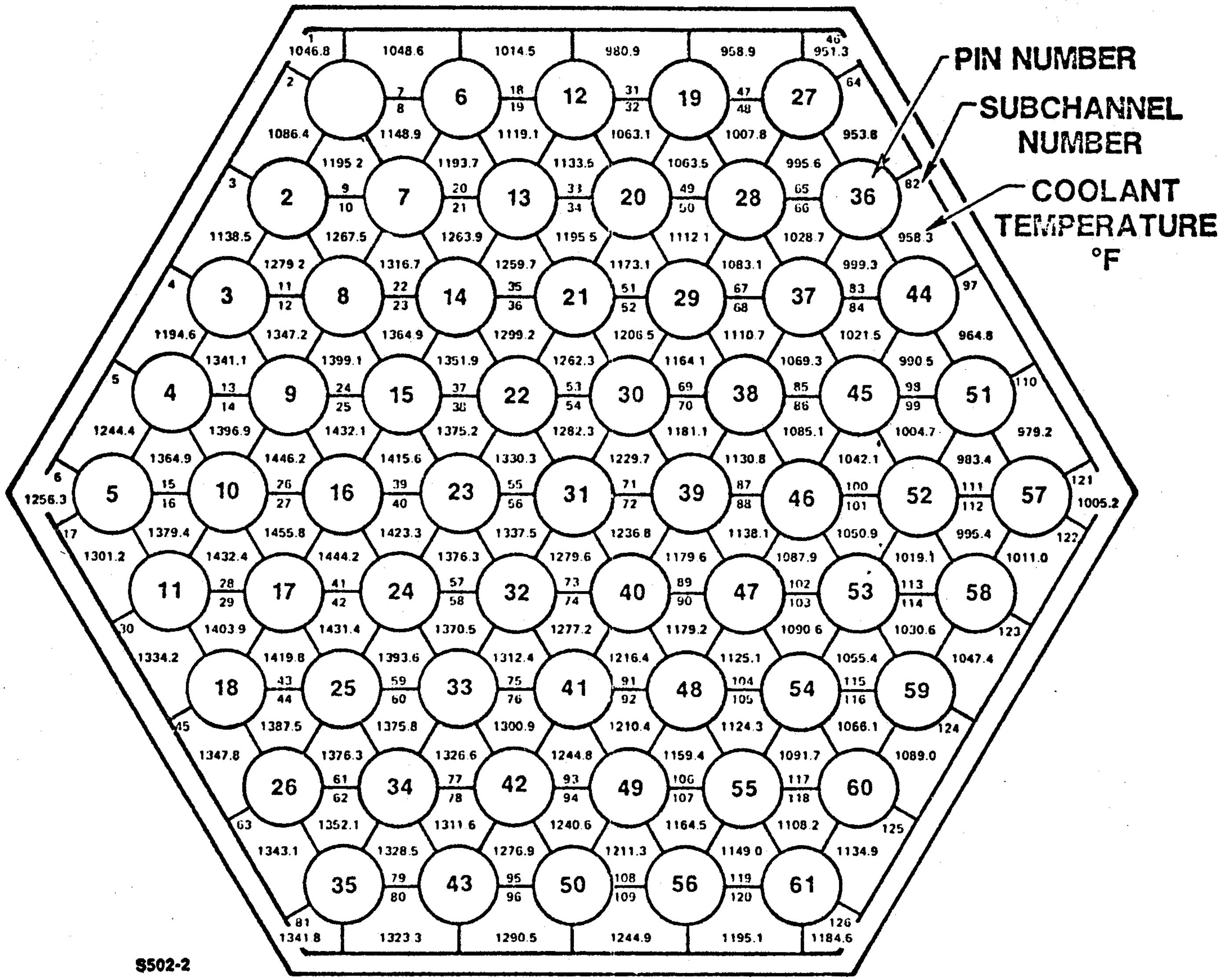

Figure 3

From : N. Prasad Kadambi
WIN :
Date : May 23, 1977
Subject: Transmittal of Paper, "An Assessment of the Consequences of Boiling in the Radial Blanket Due to Hypothetical Major Pipe Leaks", by Kadambi N. Prasad and Roger W. Tilbrook

ADVANCED REACTORS DIVISION
Waltz Mill Site

To : J. C. Housaman
Contract Administration

cc : E. H. Hemmerle R. W. Tilbrook
T. J. Iltis

Reference: (1) Letter, G. G. Ritter to J. E. Nolan, LW70242, dated April 11, 1977.

Reference (1) transmitted approval without comment of the subject paper for presentation at the ANS Meeting at New York in June 1977. There was also a stipulation that the paper must be forwarded to TIC prior to presentation.

Enclosed are four copies of the paper for transmittal to TIC. The paper incorporates comments received from the Westinghouse approval chain and those of Mr. T. J. Iltis, ERDA Site Representative at ARD.

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CRBRP Design Safety Analysis

/la
Attachment

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