WSRC-TR-91-545
SRL-SAG-910564

COOLABILITY OF A CONTROL ROD WHICH HAS MELTED AND FOAMED IN ITS SEPTIFOIL CHANNEL (U)

OCTOBER, 1991

Westinghouse Savannah River Company
Savannah River Laboratory
Aiken, SC 29808

Prepared for the U.S. Department of Energy
under Contract DE-AC09-89SR18035

WSRC-TR--91-545

DE93 006790

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WSRC-TR-91-545
SRL-SAG-910564

SARM
SAFETY ANALYSIS AND RISK MANAGEMENT

KEY WORDS: Control Rod
Loss of Control Rod
Cooling

RETENTION: PERMANENT

COOLABILITY OF A CONTROL ROD WHICH HAS MELTED AND FOAMED IN ITS SEPTIFOIL CHANNEL (U)

by

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Date: 10/1/91

ISSUED: OCTOBER, 1991

Ingle K. Paik 10/1/91
Ingle Paik, Authorized Derivative Classifier Date

SRL SAVANNAH RIVER LABORATORY, AIKEN, SC 29808
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PROJECT: N/A

DOCUMENT: WSRC-TR-91-545
SRL-SAG-910564

TITLE:

COOLABILITY OF A CONTROL ROD WHICH HAS MELTED AND FOAMED IN ITS SEPTIFOIL CHANNEL

QA TASK NUMBER: SRL-SAG-90-8001

REVISION NUMBER: 0

APPROVALS

01 OCT 91

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10/1/91

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1.0 INTRODUCTION

During a Loss of Control Rod Cooling (LCRC) event, the control rods which are in the affected septifoil can be postulated to melt. Melting of a control rod which has been irradiated creates a special concern since the entrapped gases expand rapidly and cause the melt to manifest itself initially in a foamed state. The foamed material then contacts the septifoil outer housing and the inner septifoil web material, where heat is conducted out of the foamed material. A second concern relating to the foamed melt is that its thermal conductivity is greatly reduced from that of the solid material, and also that of the non-foamed liquid. The purpose of this report is to address how, even in the presence of decreased thermal conductivity, the foamed melt may aid in cooling the control rod material.

2.0 SUMMARY

The control rod which has melted and foamed in its flow channel should be coolable by heat transfer out through the septifoil outer housing and into the bulk moderator. This is based on a power level of which corresponds to greater than 30% of historical power.

3.0 BACKGROUND

The LCRC event has been examined from many different aspects, one of which leads to a postulated melting of the control rod(s) in the septifoil housing. If the melting occurs very early in core life, the melted material will start to drain to the bottom of the septifoil, and it will either "freeze" on some member inside the septifoil or it will drain to the bottom of the septifoil. However, if the control rods have been exposed to an appreciable amount of irradiation, the entrapped gases will cause the melt to initially to be in a foamed state. Due to the increased volume of the foam, it will initially contact the septifoil outer housing and inner septifoil web material. The septifoil outer housing is exposed externally to the bulk moderator in the reactor tank. The bulk moderator will be at approximately 70°C which will aid the foam in "freezing" to the septifoil outer housing.

4.0 ANALYSIS

4.1 INPUT DATA

A typical rod power of 5.08 KW/ft is used and is characteristic of reactor operations at about 30 percent of historical power limits. This is based on the following:

1) historical maximum reactor power is approximately 2400 MW

2) for a reactor power of 1324 MW the maximum linear rod power is 9.34 KW/ft

3) thus, for a reactor operating at 30 percent power, the maximum rod power is 5.08 KW/ft. (=9.34 KW/ft*(2400 MW/1324 MW)*0.3)

The thermal conductivity of the melting lithium aluminum control rods is estimated to be that of pure lithium at 640 degrees C (or 913 K). This is estimated to be conservative because the thermal conductivity of Li-Al decreases monotonically with increased lithium content. The following comparison is made from Reference [1] (p. 50):

Pure Aluminum Thermal Conductivity at 400 K	**Lithium Aluminum Alloy (1.9 w/o) Thermal Conductivity at 400 K**
240 W/m K	100 W/m K

Pure Lithium at 400 K has a thermal conductivity which can be approximated by the following formula (from Reference [2], p. 1132):

$$k_s = 44.00 + 0.02019T + 8037/T \qquad (1)$$

Where T is the temperature in degrees K

$$k_s \text{ at } 400 \text{ K} = 72.2 \text{ W/m K}$$

Reference [2] (p. 1132) estimates the thermal conductivity of pure lithium at 640 degrees C (or 913 K) as follows:

$$k_l = 21.42 + 0.05230T - (1.371 \times 10^{-5})T^2 \qquad (2)$$

$$k_l = 57.7 \text{ W/m K}$$

This thermal conductivity is roughly half of that for pure aluminum, approximately 90 W/m K, as found in Reference [1] (p. 50) at a temperature of 640 C. Therefore, the following thermal conductivities will be used:

$$k_s \text{ at } 400 \text{ K} = 72.2 \text{ W/m K}$$

$$k_l \text{ at } 913 \text{ K} = 57.8 \text{ W/m K}$$

An average bulk moderator temperature is 70 degrees C.

The control rod diameter is 0.94 inches, an average of the tolerances specified in Reference [3].

The melting temperature of the control rods is about 640 degrees C (or 913 K).

Estimate the reactor pressure to be about 19.9 psia (this is comprised of normal atmospheric pressure plus the blanket gas pressure of approximately 5.0 psi).

4.2 ASSUMPTIONS

The two cadmium control rods are assumed to be completely removed from the core (normal mode of operation). The remaining five rods will be in a configuration which leaves at least one rod in the active core region per septifoil.

Due to the varying amounts of lithium (weak versus strong), and the varying active length of the control rods (full versus partial), the control rods are assumed to melt at different times during the LCRC transient. The first rod which should melt in the septifoil is either the partial strong rod or the full strong rod. These two rods have the same lithium content will have the highest heat generation rates due to lithium's large cross section for neutron absorbtion.

The control rod which does melt first is assumed to fully foam inside its septifoil housing channel, contacting the septifoil outer housing and the septifoil web.

Recent experiments here at SRL indicate that irradiated samples of fuel, just prior to melting, swell to a volume increase of approximately 2 to 3 times of their ambient volume. It is assumed that an irradiated control rod would swell in a corresponding fashion.

All heat from the control rod melt is conservatively estimated to be transferred via the outer septifoil housing with no credit for heat transfer taken via the septifoil web.

Heat generation within the melt is assumed to be uniform and constant with self shielding conservatively neglected.

4.3 CALCULATIONS

This section is divided up into a number of subsections which are as follows:

1. Determination of flow area in the septifoil for an individual control rod.

2. Determination of critical heat flux on the exterior housing wall.

3. Determination of nucleate boiling and exterior wall temperature

4. Determination of k_{foam} for lithium aluminum foam

5. Determination of available heat transfer area

6. Determination of the heat flux (q")

7. Determination of T_{wall} and h_{nb}

8. Determination of peak temperature in foam

4.3.1 Determination of Flow Area in the Septifoil for an Individual Control Rod

The control rods (seven) are housed in a septifoil, which has 7 different regions, one center position surrounded by the remaining six positions. Coolant flow is up from the bottom of the septifoil and out through slots at the top of the septifoil outer housing. Outside of the septifoil is the bulk moderator space. During normal operation/or start-up the first control rod to be removed completely from the core is the rod which occupies the center position, this is the first full length cadmium rod.

The second rod to be completely removed from the core is the other full length cadmium rod. This second rod typically occupies the position in the septifoil which is the closest to the axial centerline of the core. Since the remaining five rods (in some combination) will remain in the active core and can be subject to a LCRC, the area into which the rod could foam out into will be determined.

All dimensions are the nominal dimensions taken from References [4] and [5] and the approximate area was determined from basic trigonometric functions found in Reference [6].

$$\text{Total Area} = 1.195 \text{ in}^2$$

This area will be used as a portion of the calculation to develop the k_{foam}.

4.3.2 Determination of Critical Heat Flux on the Exterior Housing Wall

During the calculations, the heat transfer coefficient on the exterior housing wall will be calculated based on nucleate boiling correlations. However, should the heat flux be sufficiently high, film boiling may occur on this surface and the heat transfer coefficient will have to be recalculated in light of this. In this subsection, the Critical Heat Flux (CHF) above which film boiling will occur is calculated for use later in the calculations.

A correlation useful for determining the CHF in saturated pool boiling (CHF_{sat}) is (Reference [7], p. 13-31 and 13-32):

$$CHF_{sat} = 0.18 \ell_v h_{fg} \left[\frac{\sigma(\ell_l - \ell_v) g}{\ell_v^2}\right]^{1/4} \left[\frac{\ell_l}{\ell_l + \ell_v}\right]^{1/2} \qquad (3)$$

where: ℓ_v - vapor density
ℓ_l - liquid density
h_{fg} - heat of vaporization
σ - interfacial tension
g - gravitational constant

Subcooled liquid can increase the CHF since additional heat is required to sensibly heat the liquid. An estimate of the relationship between saturated CHF and subcooled CHF (CHF_{sub}) is given as (Reference [7], p. 13-33]:

$$CHF_{sub}/CHF_{sat} = 1 + \frac{0.1}{\ell_v h_{fg}} \left[\frac{\ell_v}{\ell_l}\right]^{1/4} c_{pl} \ell_l (T_{sat} - T_{liq}) \qquad (4)$$

where: C_{pl} - specific heat of liquid
T_{sat} - saturated liquid temperature
T_{liq} - subcooled liquid temperature

Equations (3) and (4) can be evaluated using the following D_2O properties (based on a pressure of 19.9 psia, Reference [8], Appendix A.2) and $g = 9.806$ m/sec^2.

ℓ_v = 0.8808 kg/m^3
ℓ_l = 1055.53 kg/m^3
σ = 0.05687 NT/m
h_{fg} = 2047320 NT-m/kg
c_{pl} = 4186.82 NT-m/kg-K
T_{sat} = 110°C
T_{sub} = 70°C

then

CHF_{sat} = 1702.5 KW/m^2 = 170 W/cm^2
CHF_{sub} = 4538.9 KW/m^2 = 454 W/cm^2

Thus, if the heat flux calculated in later sections exceeds 454 W/cm^2, the calculations will have to be reevaluated using film boiling heat transfer relationships for the exterior housing wall.

4.3.3 Nucleate Boiling and Exterior Wall Temperature

For high wall temperatures (about 5°C in excess of T_{sat}; approximately 115°C, Reference [9], p.497) and heat fluxes below CHF_{sub}, the heat transfer will be characterized by nucleate boiling. A method of estimating the heat transfer coefficient in nucleate boiling (h_{nb}) is given as follows in terms of the heat flux (q") and the outer wall temperature (T_w):

$$h_{nb} = q''/(T_{wall} - T_{sat}) \tag{5}$$

Where T_w is determined from the following relationship (Reference [7], p.13-28)

$$\frac{c_{pl}(T_{wall} - T_s)}{h_{fg}} = C[\frac{q''}{\mu_l h_{fg}}[\frac{\sigma}{g(\ell_l - \ell_v)}]^{1/2}]^{0.33} Pr_l \tag{6}$$

where: μ_l - dynamic liquid viscosity
Pr_l - Liquid Prandtl number
($= c_{pl}\mu_l/k_l$)
k_l - liquid thermal conductivity

The constant C is taken to be 0.0133, a value consistent with water on stainless steel (Reference [9], p.506). Equations (5) and (6) can be evaluated using the following D_2O properties (based on a pressure of 19.9 psia and a temperature of T_{sat} = 110°C, Reference [8], Appendix A.2):

μ_l = 296.3x10^{-6} NT-sec/m^2
k_l = 0.6360 W/mK
Pf_l = 1.95

A value for q" must be estimated to determine T_w and consequently, h_{nb}. This will be done in a following subsection in which an example calculation will be completed.

4.3.4 Determination of k_{foam} for Lithium Aluminum Foam

One of the most important factors in determining if the foamed melt will aid in cooling the control rod is the determination of what the thermal conductivity of foamed material will be. There is no direct data for what a value of k_{foam} might be. However, several studies indicate that the thermal conductivity is directly related to the density of the foam and the size of the bubbles. Reference [10] (pages 19-26) does provide a possible numerical solution with the following two formulas:

$$P = \frac{\text{Pore Volume}}{\text{Pore Volume + Volume of Solid}} \tag{7}$$

and

$$k_{eff} = 0.8k_s\left[\frac{1 - P}{1 + P/2}\right] \qquad (8)$$

Where: P = Volume Porosity
k_{eff} = effective thermal conductivity of porous material
k_s = either the thermal conductivity of the solid material or the liquid material

The conservative value of k_s which will be used was that defined in the input data of 57.8 W/m K.

In determining the value for P above, the assumption that irradiated control rod material will expand 2 to 3 times its original volume while melting will be used. First we will examine how much of the control rod flow area will be filled with the melt.

For the control rod to melt, it must not be withdrawn out of its flow area, therefore the area which was calculated earlier (1.195 in^2) will be used to "constrain" the size of the control rod volume change. Using the word "constrain" is somewhat inappropriate since the septifoil spider inside the housing has slots in it to allow for mixing of the coolant throughout the septifoil. However, as a first approximation the control rod will be considered to be constrained in its flow area.

The control rod diameter (from input data) is 0.94". This works out to a cross sectional area of:

$$\text{Area of Control Rod} = (0.94^2/4)\pi$$

$$= 0.694 \ in^2$$

Therefore, the control rod is greater than half the size of the flow area in which it resides. This will allow the control rod to completely fill the flow volume when it melts and foams. In determining k_{eff} (or k_{foam}) the higher expansion of 2.5 will be assumed even though the control rod will only expand by roughly a factor of 2. Determining P from equation 7 yields:

$$P = 1.5/(1.5 + 1)$$

$$P = 0.6$$

And solving for k_{foam}

$$k_{foam} = 0.8(57.8 \text{ W/m K})(1 - .6)/(1 + .6/2)$$

$$k_{foam} = 14.3 \text{ W/m K}$$

4.3.5 Determination of the Available Heat Transfer Area

The heat transfer area in this scenario will be limited to that of the outer housing out into the bulk moderator. The coolant that is in the center septifoil position, in positions with rods withdrawn, and around rods which have not yet melted will also aid in cooling the melting rod, however it cannot be counted on since it is assumed to change into steam early on in the transient. The heat transfer area available is equal to 1/6 the circumference of the outer housing multiplied by the length of the rod. This will be calculated in metric units.

I.D. of septifoil outer housing = 3.255 in
(from Reference [4])

Wetted Perimeter = $((1/6)\pi(3.255\text{ in})(2.54\text{ cm/in}))/100\text{ cm/m}$

$= 0.0433\text{ m}$

The length of the control rod is 170 inches. Therefore, the available heat transfer area is:

Heat transfer Area = $0.0433\text{ m}(170\text{ in})((2.54\text{ cm/in})/100\text{ cm/m})$

Heat transfer Area = 0.187 m^2

4.3.6 Determination of q"

Now that the available heat transfer surface has been determined, q", the thermal flux which is required to be transferred out of the surface will be determined. From the input data, the maximum linear heat rate of the control rod is 5.08 KW/ft which can be multiplied by the length of the rod, and this can be divided by the available heat transfer surface to determine q".

$q'' = 5080\text{ W/ft}(170\text{ in})(1\text{ft}/12\text{in})/(0.187\text{ m}^2)$

$q'' = 384{,}848\text{ W/m}^2$

It can be seen that when converted to W/cm^2 that $q'' = 38.5\text{ W/cm}^2$ which is less than the subcooled critical heat flux of 454 W/cm^2. Therefore, the bulk moderator will remove heat via nucleate boiling which is the most desirable condition.

4.3.7 Determination of T_{wall} and h_{nb}

All of the required information has been assembled to calculate T_{wall}. Again equation 6 is:

$$\frac{c_{pl}(T_{wall} - T_s)}{h_{fg}} = C\left[\frac{q''}{\mu_l h_{fg}}\left[\frac{\sigma}{g(\ell_l - \ell_v)}\right]^{1/2}\right]^{0.33} Pr_l$$

This equation can be rearranged so that only T_w is left on the left hand side. Solving this equation with the previously determined values yields:

$$T_{wall} = 124.5°C$$

Placing T_{wall} into equation 5 will produce h_{nb}:

$$h_{nb} = q''/(T_{wall} - T_{sat})$$

$$h_{nb} = (384848\ W/m^2)/(124.5°C - 110.0°C)$$

$$h_{nb} = 26541\ W/m^2\ K$$

4.3.8 Determination of Peak Temperature

The peak temperature of the foam after the initial melting period may drop below that of the melting temperature, thereby causing the foam to "freeze". The peak temperature will be estimated by using half slab heat transfer model. This is determined to be conservative since for the half slab model there is no heat transfer out of the control rod in the negative direction (which corresponds with no heat being removed except for the outer housing assembly). All of the heat will be assumed to transfer out in the positive direction through the foam, the cladding (which corresponds with the outer housing assembly vice the actual cladding of the control rod which had melted away), and into the bulk moderator. The half slab model is a one dimensional model, which is also conservative, since no heat is assumed to exit in either of the other two axes. Reference [11] (page 117) provides the following for the half slab model in terms of q:

$$q_s = \frac{t_m - t_{sat}}{\frac{s}{2k_{foam}A} + \frac{c}{k_c A} + \frac{1}{hA}} \qquad (9)$$

where:
- q_s = heat leaving the control rod melt= q
- t_m = maximum temperature
- t_{sat} = temperature in the moderator
- s = distance through the control rod melt
- c = width of the cladding (in this case the width of the outer housing assembly)
- k_{foam} = thermal conductivity of the control rod
- A = heat transfer area
- k_c = thermal conductivity of the cladding (in this case the outer housing assembly)
- h = heat transfer coefficient (in this case that of nucleate boiling h_{nb})

In the above formula the factor of 2 in $s/2k_{foam}A$ is a manifestation of heat conduction through a slab which has a uniformly distributed internal heat generation.

Rearranging equation 9 to solve for t_m yields:

$$t_m = q_s\left[\frac{s}{2k_{foam}A} + \frac{c}{k_cA} + \frac{1}{h_{nb}A}\right] + t_{sat} \qquad (10)$$

where:
- q_s = (5080 W/ft)(170in)(1ft/12in) = 71967 W
- t_{sat} = 110°C
- s = Dimension "a" + r_3 from Figure 1, = 1.06" = 0.02691 m
- c = 0.05" = 0.00127 m
- k_{foam} = 14.3 W/mK
- A = 0.187 m^2
- k_c = 218 w/mK (from Reference [1], p. 18)
- h_{nb} = 26541 W/m^2K

The solution to the above formula is 488.9°C, which is less than the melting point of 640°C for the lithium aluminum control rod. Therefore once the control rod has melted, foamed, and come into contact with the septifoil outer housing, the foam should be coolable by sufficient heat transfer out through the housing to the bulk moderator.

5.0 RESULTS

The previous calculations showed that for a single control rod which has melted and foamed in its flow channel in the septifoil that it should be coolable. Coolability is defined as the maximum control rod temperature being below that of the melting temperature of the rod ($T_{max} \leq 640°C$).

For the specific case cited in this report, if the foam has the liquid heat transfer characteristics of lithium (as modified by equations (7) and (8) to obtain k_{foam}) the foamed control rod should be able to transfer its heat out into the bulk moderator. The maximum temperature (post melting/foaming) is expected to be approximately 488.9°C.

6.0 ADDITIONAL CONCERNS

The section addresses concerns which were raised by the Rapid Steam Generation (RSG) panel. These concerns centered around three separate areas, which were:

1. Is the K_{foam} used conservative?

2. Does the geometry of the foamed melt have any effect on the results?

3. Does the surface conductivity of the foamed melt significantly impact the results?

Each of these areas will be discussed below using qualitative arguments which are logically supported in the body of this report.

First, the thermal conductivity of the foam used in this report is considered to be a realistic value based on the available technical information. It has added conservatism in that the material was assumed to be pure lithium, as opposed to either pure aluminum or an aluminum lithium mixture. The formula used to determine the K_{foam} given in Reference [10] has a 0.8 multiplier added to account for experimental data received on commercially available foam material made of aluminum. Finally, once the foamed melt is "frozen" in place on the outer housing, its thermal conductivity increases to provide better heat transfer. It is felt that these three factors make the estimation of the thermal conductivity realistic.

The second issue has been dealt with through various calculations performed at Savannah River Laboratory. Different geometries of foamed melts have been examined in detail. If the control rod melts, foams and drains down to the bottom of the septifoil where most of it collapses, it has been shown that the resulting configuration is coolable. This report shows that if the melt does not collapse immediately, and that if it can contact the outer housing, that it will be coolable. The only configuration that remains is one in which the melt foams, does not collapse immediately, and does not contact the outer housing. This configuration does not appear to be plausible given the small tolerances in the control rod channel in the septifoil, and the degree of swelling which is expected (due to gas expansion in the solid material prior to melt, and due to foaming during melt).

Finally, the effects of the surface conductivity of the foamed melt were not addressed in this report. Due to the limited amount of information available, these effects were neglected since it was felt that any penalty incurred would be more than offset by other conservative assumptions made. These conservative assumptions include:

1. the use of the maximum linear power generation in the control rod verses using an average.

2. the absence of cooling from any other source such as steam or steam water mixtures inside the septifoil.

3. the absence of heat transfer to other parts of the septifoil which would not be affected by the event.

7.0 CONCLUSIONS

The control rod which has melted and foamed in its flow channel should be coolable by heat transfer through the septifoil outer housing and into the bulk moderator. This conclusion is based on a power level of 5.08 kW/ft, which corresponds to the maximum control rod linear power for a reactor operating at greater than 30% of historical power.

The use of the half slab method for determining the heat transfer rate of the foam to the moderator is considered conservative since it takes no credit for heat transfer back into the septifoil (i.e., web, vacant center assembly, and other flow areas) and assumes that all of the heat transfer is through the septifoil outer housing.

A further conservatism is the low value of thermal conductivity (equal to that of pure lithium) assumed for the control rods which does not credit the presence of aluminum.

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