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April 19, 1979

R. W. Wright
Advanced Reactor Research Branch
U. .S. Nuclear Regulatory Commission
Washington, D. C. 20555

Dear Bob:

Attached is our preliminary report on the Three Mile Island cooling investigation. Let me know if you need further details.

Sincerely yours,

J. B. Rivard
Reactor Containment Safety
Studies Division 4422

R J Lipinski

R. J. Lipinski
Advanced Reactor Safety Physics
Division 4425

jc

Attach.

Copies to:
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Cooling of TMI Core Debris

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Summary of Results

The worst case considered is one in which fractured fuel relocates in the space between intact fuel pins with a void fraction of 0.3. For this case, the calculated specific power required to produce dryout is approximately a factor of 3 greater than current TMI specific power. For the other configurations, sizes, and void fractions considered, the margins to dryout are greater. It is concluded that reasonable confidence may be placed in the potential for cooling of the TMI debris, provided that the assumptions made are reasonably well satisfied.

On April 11, Dept. 4420 was asked by NRC/ABSR to assist in the Three Mile Island problem by performing calculations related to natural circulation cooling of the TMI core. Specifically, calculations of the permeability of core debris as that might affect the final cooldown of the core (and debris) in the planned natural convection mode were requested. J. B. Rivard (4422) and R. J. Lipinski (4425) performed the calculations outlined below. The results and methods were reviewed by D. J. McCloskey (4410), and J. F. Muir (4411) prior to transmittal of the results to R. W. Wright (APSR) on April 13 and 16.

Following initial fact-gathering on the specifics of the TMI core design (aided by B. V. Asselin-4412), the initial approach was to estimate the range of void fraction ε which the random arrangement of core debris might produce (see Table). Two sizes of debris were considered: undamaged fuel pellets (9.4 mm dia X 17.8 mm long) and fractured fuel with an effective particle size of 2.5 mm. Consultations with L. S. Nelson (5830) and R. A. Sallach (5846) regarding the form of severely oxidized zircalloy cladding resulted in estimates that the clad debris might be present in fractured platelets of centimeter-size, or in very small platelets of few-micron thickness and lateral dimensions of a few tens of microns.

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This disparity of size estimates affects the estimated void fractions and permeabilities in the case where the clad debris size would be in the range which could effectively fill the voids between fuel particles. For much smaller clad particles, the particles will probably become dislodged and are ineffective in reducing the permeability. For much larger clad particles, the fuel particle size will be the determining factor in the effective permeability. The calculations reported below (Table) consider only the cases where the clad particles are larger or smaller than the size which would fill the voids between fuel particles.

The thermal effect of the cladding debris mixed in with the fuel debris can be assessed by noting that its presence increases the height of the fuel debris by about 30%, and that the average power per unit volume decreases correspondingly. These effects cancel in the formulae used herein if the clad debris is uniformly dispersed with unchanged void fraction, so the clad volume-fuel volume ratio does not appear explicitly in the formulae given below.

For both the intact pellets and the fractured fuel, a reasonable lower bound on void fraction was chosen as 0.3, although 0.4 is more probable. The corresponding permeabilities were calculated using the Kozeny relationship[1] (see Formulae) with an effective diameter which, for the cylindrical pellets, was based on 6 divided by the specific surface.[1]

Two configurations of debris in the core were considered. For conservative scoping calculations, the entire 93,000 kg of UO_2 was considered to be rubbleized within the core barrel with the fuel sizes as given above. Also, because the fractured fuel of 2.5 mm size can fit easily between the normal pitch of fuel rods in the undamaged lengths of fuel assemblies, this configuration was also studied. The damaged core fraction was chosen such that it exactly fills all interstitial space in the undamaged core fraction. Because of the form of the calculations, the actual condition, in which the core is cooled by unidirectional flow from bottom to top, is not considered. Instead, a much more severe situation, in which the lower core boundary is impermeable and adiabatic, is the basis of the cooling calculations performed. This form of calculation therefore includes, by implication, the condition in which a local blockage may cause the main unidirectional flow to bypass the blocked region, leading to a situation in which cooling of the local blockage requires the development of a local cellular flow regime.

The cooling calculation considers the limiting condition to exist when local dryout (vapor blanketing of a local region) occurs within the debris. The values given in the table are based on the simple two-phase version of the Hardee-Nilson formulation[2] which has been shown to be in reasonable agreement with water experiments by independent groups. In this equation, credit is not taken for the heat required to raise the water to its boiling point. All results are given for the "worst" case, where the system is at atmospheric pressure. Results at higher pressures will be more favorable for natural cooling of the debris.

An additional calculation was performed to assess the single-phase typical temperature rises which might occur with the assumed form of natural convection. This is based on the Nusselt-Rayleigh number correlation given in the collection of formulae and gives some idea of the margin which is necessary to prevent local boiling in the debris.

Although a very conservative approach has been attempted throughout the analysis, it should be emphasised that the simple formulas chosen cannot be considered as high precision predictors. Therefore, cautious application requires that fairly large error margins be allotted to the results in the table.

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References

1. R. B. Bird, W. E. Stewart, E. N. Lightfoot, <u>Transport Phenomena</u>, John Wiley & Sons, Inc., p. 199 (1960).

2. H. C. Hardee and R. H. Nilson, "Natural Convection in Porous Media with Heat Generation", <u>Nuc. Sci and Eng</u>, <u>63</u>, p. 119-132 (1977).

3. H. Kampf and G. Karsten, <u>Nucl. Appl.</u>, <u>9</u>, p. 288 (1970).

RESULTS

Case	1	2	3	4	
d (m)	.0112	.0025	.0025	.0025	.00
K (m^2)	3.84×10^{-8}	1.91×10^{-9}	6.17×10^{-9}	1.91×10^{-9}	6.1
L (m)	1.75	1.75	2.04	1.70	1.8
ε	.30	.30	.40	.30	.4
k_m (W/m·K)	2.8	2.8	2.2	2.8	2.2
p_s, d* (W/kg-UO_2)	4000	200	640	119	386
ΔT (K)	21	94	59	121	76

Notes:

Case 1: Entire core is rubblized intact pellets, with an assumed void fraction of 30%.

Case 2: Entire core is a debris bed of fractured fuel pellets with an average diameter of 2.5 mm (0.1 inch). Assumed void fraction is a conservative 30%.

Case 3: Same as Case 2, except void fraction is a nominal 40%.

Case 4: Fractured fuel pellet debris falls between intact pins until height of debris equals height of remaining pins. Void fraction in debris is 30%. The term (1-ε) is divided by the fraction of fuel in debris form to account for heat from intact pins (within which coolant cannot flow).

Case 5: Same as Case 4, except void fraction is 40%.

*Nominal decay power on April 13, 1979 was p_s = 35.8 W/kg-UO_2.

Formulae used in obtaining results presented in Table:

$$K = \frac{d^2}{180} \frac{\varepsilon^3}{(1-\varepsilon)^2} \qquad \text{(Ref. 1)}$$

$$P_d = \frac{\rho_l g K h_{fg}}{\nu_l (1 + \sqrt{\nu_v/\nu_l})^2} \cdot \frac{1}{L \cdot \rho_s (1-\varepsilon)} \qquad \text{(Ref. 2)}$$

$$\Delta T = \sqrt{\frac{16 \nu_l \alpha_l \rho (1-\varepsilon) P_s L}{g K \beta k_m}} \qquad \text{(Ref. 2)}$$

$$k_m = k_l \left(1 - \frac{(1-\varepsilon)(1-k_s/k_l)}{k_s/k_l + (1-\varepsilon)^{1/3}(1-k_s/k_l)}\right) \qquad \text{(Ref. 3)}$$

d = effective particle diameter (m)

g = gravitational acceleration (m/s^2)

h_{fg} = heat of vaporization of water (J/kg)

k_l = thermal conductivity of water (liquid) (W/m·K)

k_m = effective thermal conductivity of debris-water mixture (W/m·K)

k_s = thermal conductivity of oxide fuel (solid) (W/m·K)

L = bed depth (m)

P_s = specific power of oxide fuel (W/kg)

$P_{s,d}$ = specific power of oxide fuel at bed dryout (W/kg)

α_l = thermal diffusivity of water (m^2/s)

β = volumetric thermal expansivity (K^{-1})

ε = volume fraction of water in debris bed (void fraction)

K = permeability of water (m^2)

ν_l = kinematic viscosity of water (liquid) (m^2/s)

ν_v = kinematic viscosity of water (vapor) (m^2/s)

ρ_l = density of water (kg/m^3)

ρ_s = density of oxide fuel (kg/m^3)