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TO : Marvin M. Mann, Asst. Director for Compliance, Division of Inspection, AEC Headquarters **DATE:** May 24, 1960

FROM : V. A. Walker, Inspection Specialist, Division of Inspection, AEC Headquarters *V. A. Walker*

SUBJECT: TRANSMITTAL OF HEAT TRANSFER ANALYSIS OF WTR INCIDENT

SYMBOL : INS:VAW

The heat transfer analysis that was performed upon the subject incident is attached. This incident occured on April 3, 1960.

The method used is essentially the same as that used by W. J. Gambill of ORNL. The differences in the conclusions are enumerated in the analysis but mainly involve interpretation of the existent information. The most important difference is that he used a correlation developed by Mirshak, et. al. at SRL and reported in DP-355 whereas I used a correlation developed by Bernath and reported at the Third National Heat Transfer Conference in August, 1959. The Mirshak correlation gives a burnout heat flux of about 1.1×10^6 Btu/hr, ft^2 whereas Bernath's method yields a burnout heat flux of about 0.3×10^6 Btu/hr, ft^2. Neither correlation strictly applies, but it is my opinion that Bernath is more nearly correct.

The conversation with J. R. Cunningham of ORNL regarding his observations of the damaged fuel assembly resulted in his expressing the opinion that based on his limited visual examination, there was no evidence of a fuel failure. He stated also that the 932° F blister test would not reveal good mechanical contact but no metallurgical bonding of the clad to the fuel core alloy; M. H. Bartz, PPCo did not concur with this opinion by Cunningham. Bartz thinks that the blister test will show poor metallurgical bonding between the cladding and fuel core alloy.

M. A. Schultz, Westinghouse, is not available this week to discuss the analysis performed prior to the execution of the boiling detector calibration. I plan to visit Waltz Mill on June 1, 1960, to discuss this subject.

Schultz has not been advised of the results of the analysis that is attached.

Enclosure:
Heat Transfer Analysis

A/26

HEAT TRANSFER ANALYSIS OF WTR INCIDENT

SUMMARY

The calculations show that the fluid exiting from the hot channels of the element in position L-65 was a mixture of saturated steam and water at a quality of 6 per cent when the flow through the active core was 3500 gpm, the reactor power was 37.8 Mw and the inlet water temperature was about 115° F; i.e. the thermal-hydraulic conditions just preceeding the rapid removal of 0.4 to 0.6 per cent reactivity. The maximum operating heat flux reported to apply at this time was 4.8×10^5 Btu/hr, ft^2. Experimental data obtained by Lowdermilk, et. al. and reported in NACA-TN-4382 1/ and application of the correlation developed by Bernath 2/ indicate that burnout could be expected at a heat flux of about 3×10^5 Btu/hr, ft^2. The reduction in the coolant velocity in the hot channel caused by the local boiling and the two-phase flow was included in determining the burnout heat flux.

It is my opinion that maldistribution of flow was the main reason for the burnout of L-65 and no apparent damage to the other fuel assemblies in approximately the same environment.

METHOD OF CALCULATION

The following data were cited by the WTR staff:

Average velocity in a nominal channel = 6.2 ft/sec

Maximum heat flux = $\frac{4.8 \times 10^5 \text{ Btu}}{\text{hr, ft}^2}$

Maximum to average flux ratio, vertically = 1.75

Nominal channel thickness = 0.094 inches

Nominal channel length = 38 inches

Outside diameter innermost fuel tube = 1.625 inches

Inside diameter middle fuel tube = 1.813 inches

Cladding thickness = 0.0365 inches

1/ NACA-TN-4382, Lowdermilk, W. H., Lanzo, C. D., and Siegel, B. H. Investigation of Boiling Burnout and Flow Stability for Water Flowing in Tubes, September, 1958.

2/ L. Bernath, A Theory of Local Boiling Burnout and Its Application to Existing Data, presented at the Third National Heat Transfer Conference, August, 1959.

Meat thickness = 0.0520 inches

Assembly to assembly velocity variation, average to minimum ratio = 1.22

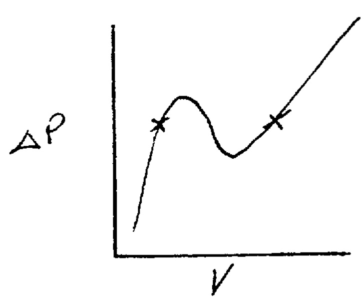
Channel to channel velocity variation, average to minimum ratio = 1.11

Primary system pressure = 100 psia

It was assumed that a vertical neutron flux profile normalized with respect to length as determined in the MTR and having a maximum to average ratio vertically of about 1.6 was applicable.

The pressure drop across the hot channel is determined and controlled by the pressure drop across an average channel. The first step is to calculate the pressure drop across an average channel using the methods and data cited in Reactor Handbook, Engineering 3/.

The velocity in the hot channel will be at least the average divided by the average to minimum ratio and if substantial local boiling occurs will be even less. According to theory and experimental measurements, there are two stable operating velocities for a constant pressure drop and heat flux. In one case, there is no local boiling but in the other, low quality steam is generated. In the latter situation for aluminum cladding, melting can be expected.



X Stable Operating Conditions

The problem becomes a calculation of the velocity for the case where steam is formed. A velocity is assumed and the wall temperature profile along the length of the channel is calculated. The correlation used to calculate the heat transfer coefficient is:

$$\frac{hDe}{K} = 0.023 \, Re^{0.8} \, Pr^{1/3}$$

3/ AECD-3646, The Reactor Handbook, Volume 2, Engineering, May, 1955.

where h = heat transfer coefficient, Btu/hr, ft^2 ^oF;
De = hydraulic diameter, ft;
K = thermal conductivity, Btu/hr, ft^2 ^oF/ft;
Re = Reynolds number dimensionless;
Pr = Prandtl modulus, dimensionless.

All the physical properties are evaluated at the film temperature.

In the case under study, it was found that nucleate boiling began about 18-inches from the top of the fuel core alloy. The next step involves determining the location at which the bulk water temperature reaches the saturation temperature. It was found that 6-inches above the bottom of the fuel core alloy that bulk boiling began. Over about one foot of length local boiling was occuring; the average heat flux over this length was determined to be about 4.1×10^5 Btu/hr, ft^2.

In local boiling, the pressure drop is related to the isothermal pressure drop, according to J. B. Reynolds, 4/ by the following expressions:

$$\frac{\Delta P_{LB}}{\Delta Po} = \frac{1}{a V} \sinh a V$$

$V = 4q'' L/G' \, DeCp \, (\Delta t_{sub,o})$;

$a = 4.6 \times 10^{-6} q'' + 1.2$;

q'' = heat flux, Btu/hr, ft^2;

L = length in local boiling, ft;

G' = mass velocity, lbs/hr, ft^2;

De = hydraulic diameter, ft;

Cp = specific heat, Btu/lb, ^oF;

$\Delta t_{sub,o}$ = bulk water subcooling at point where local boiling begins, ^oF;

ΔP_{LB} = local boiling pressure drop;

ΔP_o = single phase pressure drop.

4/ ANL-5178, J. B. Reynolds Local Boiling Pressure Drop, March, 1954.

This ratio was about 70 for the case under study.

The two phase pressure drop was determined using the data cited in the Reactor Handbook, Engineering, page 73 [3]. The pressure drop resulting from acceleration of the fluid was calculated from the method cited in the latter Handbook.

The effect of the buoyancy of the bubbles and the steam was calculated and found to be small; this additional pressure drop was subsequently ignored.

The individual pressure drops were summed and compared with that available as determined from the average channel. The entire procedure was repeated until reasonable correspondence was obtained.

A velocity of about 3-3/4 ft/sec was calculated using the method outlined.

The burnout heat flux is calculated by Bernath's method using the following correlations:

$$T_{w,Bo} = 57 \ln P - 54 \left(\frac{P}{P+15} \right) - V/4$$

$$h_{Bo} \doteq 10{,}890 \left(\frac{De}{De+Di} \right) + \frac{48V}{De^{0.6}}$$

$$Q/A\,\Big)_{B.O.} = h_{BO} \left\{ T_{w,BO} - T_B \right\}$$

where $T_{w,Bo}$ = wall temperature at burnout, $^{\circ}$C;

P = absolute pressure, psia;

V = velocity, ft/sec;

h_{BO} = heat transfer coefficient at burnout, PCU/hr, ft^2, $^{\circ}$F;

De = hydraulic diameter, ft;

Di = heated perimeter divided by π, ft;

$Q/A\,\Big)_{B.O.}$ = burnout heat flux, PCU/hr, ft^2.

Using Bernath's correlations, a velocity of 3-3/4 ft/sec and a bulk water temperature equal to the saturation temperature at 100 psia (330° F) a burnout heat flux of 3.2×10^5 Btu/hr, ft^2 was calculated. If the velocity were raised to 6.2 ft/sec and the bulk water temperature decreased accordingly, the calculated burnout heat flux is about 8.7×10^5 Btu/hr, ft^2.

DISCUSSION

There appears to be several questionable areas in this analysis.

J. B. Reynolds data were extrapolated; the highest heat flux he examined was about 3.0×10^5 Btu/hr, ft^2 and his data were extrapolated to about 4.0×10^5 Btu/hr, ft^2. It is not known if this extrapolation is conservative or not.

Bernath's correlation for burnout was applied at zero ° F subcooling. He examined 0° F subcooling but at high pressures (2000 psia) and concluded the correlation was satisfactory; it may or may not be at 100 psia.

Lowdermilk's data were obtained with thin tubes of about 0.1 inch diameter with water flowing upward at a pressure of about 15 psia. The quality of the steam exiting from the tube was probably considerably higher than 6 per cent, but he does not cite these data. In my opinion, Lowdermilk's work gives an indication of what can be expected but does not duplicate the situation under study.

The use of a curve relating neutron flux to length from the MTR may be criticized, but it represents the vertical neutron flux profile more precisely than the assumption that the profile is a chopped cosine.

If the flow was poorly distributed and there are data supporting this, then it seems that burnout of the fuel element did occur.

W. J. Gambill in his analysis of this accident used Mirshaks [5/] correlation. But to do this the range of varibles must be extended beyond that studied by Mirshak. The most important of these is the subcooling; Mirshak did not study bulk boiling and the minimum subcooling was about 8° F. In my opinion, this correlation does not apply.

5/ DP-355, Mirshak, S., Purant, W. S., and Towell, R. H. Heat Flux at Burnout, February, 1959.

Gambill also applied the hydrodynamic instability criterion discussed by Bonilla [6]. This is the ratio of the Grashoff number to the Von Karman number:

$$Gr = \frac{D^3 \rho^2 g \, \beta \Delta t}{\mu^2}$$

and

$$Ka = \frac{\Delta P_f \, g_c \, D \rho}{N \, \mu^2}$$

where Gr = Grashoff number, dimensionless;

D = hydraulic diameter, ft;

ρ = fluid density, lb/ft^3;

g = gravitational constant, ft/hr^2;

β = coefficient of volumetric thermal expansion, $^\circ F^{-1}$;

t = average bulk temperature rise $\frac{(t_2 - t_1)}{2}$, $^\circ F$;

μ = fluid viscosity, lb/ft, hr;

Ka = Von Karman number, dimensionless;

ΔP_f = frictional pressure drop, lb/ft^2;

N = length of channel ft.

According to Bonilla, downflow should be stable if this ratio is much less than one. However, a brief examination of the moduli indicates that the criterion can only be applied for single phase flow. Hence, this criterion does not apply for the WTR situation at failure.

[6] C. F. Bonilla, Nuclear Engineering, McGraw-Hill, page 322, 1957.