OAK RIDGE NATIONAL LABORATORY

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UNION CARBIDE NUCLEAR COMPANY

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Post Office Box X

Oak Ridge, Tennessee

<p>ORNL</p> <p>CENTRAL FILES NUMBER</p> <p>58-4-53</p>
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External Transmittal Authorized

COPY NO. 112

DATE: April 15, 1958

SUBJECT: HRT Dome Wall Temperature

TO: Distribution

FROM: H. C. Claiborne

SUMMARY

Maximum HRT dome wall temperatures for reactor powers up to 10 Mw were calculated for both an insulated and uninsulated dome. Temperatures exceeding 315°C in the fuel solution flowing through the HRT dome section can cause phase separation which results in excessive corrosion rates.

The results, based on very conservative assumptions, indicated wall temperatures exceeding 315°C could occur in the insulated dome when operating the reactor at 10 Mw.

Using the same conservative assumptions, the analysis of the uninsulated dome indicated wall and bellows temperatures below 300°C.

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HRT DOME WALL TEMPERATURES

Introduction

Temperatures greater than 315°C are to be avoided in the HRT fuel solution since phase separation can occur and the resulting dense phase causes severe corrosion rates and operation difficulties. A possible point of high temperature during 10 Mw operation of the HRT is at the inner surface of the HRT Dome Wall.

The HRT dome contains a 347 stainless steel bellows that is part of the transition joint connecting the zircaloy core exit pipe with the external stainless steel piping (see Fig. 1). Fuel solution is fed into the dome section by a bypass line that connects into the main circulating stream near the core inlet. Fuel solution from the bypass line flows through a drilled hole in the dome flange into the annular space between the bellows and the dome wall. On the other side of the bellows, D₂O from the blanket flows through the annular space between the bellows and the core exit pipe. The temperature rise of the fuel solution and the dome wall temperature are a function of the operating power, the neutron flux and the flow rate. The heat input to the dome fuel solution comes primarily from decay betas, fission, and heat transfer from the dome wall. Heat generation in the dome wall is due to decay and fission gammas from both the fuel in the core exit pipe and in the dome, and capture gammas in the stainless steel.

Maximum dome wall temperatures were calculated using conservative assumptions for both an insulated HRT dome and an uninsulated one.

Flow Regime

Any analysis of flow problems is, of course, dependent on whether the flow is turbulent or laminar. The flow regime is dictated by the Reynolds number, DG/μ . Using the conventional equivalent diameter $2(R_2 - R_1)$ for an annulus and expressing in terms of the mass flow rate, the Reynolds number is

$$Re = \frac{2w}{\pi(R_2 + R_1)\mu}$$

Because of the convolutions of the bellows, D_1 varies from 8-1/8 in. to 6-1/8 in. The effect, however, on the Reynolds number is small, so an average is used. For $D_2 = 8-5/8$ in., $D_1 = 7-1/8$ in. and $\mu = 0.35$ lb/hr ft, $Re = 2.77 w$.

The flow rate through the HRT dome during initial operations was bracketed between 45 and 1880 lb/hr.² The lower value represents the minimum possible flow rate and is based on the bypass thermocouple response time. The higher rate is based on pressure drop measurements across the core. These flow rates give Reynolds numbers between 125, which is definitely laminar, and 5200, the approximate limit of the transition zone.

In the interest of conservatism the flow regime was assumed laminar even for the highest flow rate of 1880#/hr.

Idealized System

In order to analyze the thermal behavior of the HRT dome with a reasonable expenditure of effort, it is necessary to consider an idealized system.

Construction of the idealized system is based on the following postulates, which are generally conservative:

1. The parallel plates approximation is permissible since the average annular spacing is reasonably small compared to the radius.
2. The variable spacing between the bellows and the dome wall may be represented by an equivalent distance.
3. No heat is transferred through the bellows wall.
4. Uniform flux ($q/A = \text{constant}$) exists at a heat transfer surface.
5. The physical properties are not a function of temperature.
6. For the case of the uninsulated dome, the variable wall thickness may be represented by an equivalent thickness.
7. Fully developed and stable laminar velocity profiles always exist.
8. The neutron flux throughout the dome is uniform.

Laminar Flow between Parallel Plates Containing
A Volume Heat Source

The differential equation describing the case of laminar flow between parallel plates containing a volume heat source (see Fig. 2) is

$$\frac{\partial^2 t}{\partial y^2} = \frac{c_p}{k_f} \left(\frac{\partial t}{\partial x} \right) u - \frac{Q_f}{k_f} \quad (1)$$

where the local velocity is,

$$u = \frac{3U}{2} \left(1 - \frac{4y^2}{d^2} \right) \quad (2)$$

For uniform flux and a position far downstream (no entrance effects, a conservative postulate), $\frac{\partial t}{\partial x} = \frac{dt}{dx}$. With the dome wall perfectly insulated, all heat generated in the wall must transfer into the fuel solution. A heat balance gives

$$U_p \, cd \, dz \, dt = k_f \left(\frac{dt}{dy} \right)_2 dz \, dx + Q_d \, d \, dz \, dx = q_2/A_2 \, dz \, dx + Q_d \, d \, dz \, dx \quad (3)$$

$$\text{and} \quad \rho c \frac{dt}{dx} = \frac{1}{U} \left(\frac{q_2}{A_2 \, d} + Q_d \right) \quad (4)$$

Combining equations (1), (2) and (4),

$$\frac{d^2 t}{dy^2} = \frac{3}{2k_f} \left(\frac{q_2}{A_2 \, d} + Q_d \right) \left(1 - \frac{4y^2}{d^2} \right) - \frac{Q_d}{k_f} \quad (5)$$

The boundary conditions are:

$$\begin{aligned} \text{At } y &= -\frac{d}{2}, \quad \frac{dt}{dy} = 0 \\ \text{At } y &= \frac{d}{2}, \quad \frac{dt}{dy} = \frac{q_2}{k_f A_2} \end{aligned}$$

Integrating equation (5) and applying the boundary conditions,

$$t - C = \left(\frac{3q_2}{4 k_f A_2 \, d} + \frac{Q_d}{4 k_f} \right) y^2 - \left(\frac{q_2}{2k_f A_2 \, d^3} + \frac{Q_d}{2k_f \, d^2} \right) y^4 + \frac{q_2}{2k_f A_2} y \quad (6)$$

where C is an arbitrary constant depending on the temperature at an arbitrary point.

At any point along the wall,

$$t_2 - t_m = t_2 - \frac{\int_{-b/2}^{b/2} u \, dy}{b/2} \quad (7)$$

where t_2 is obtained from equation (6) on setting $y = b/2$, and t_m is the mixed mean fluid temperature. Combining equations (2), (6) and (7), and integrating,

$$t_2 - t_m = \frac{13 q_2 d}{70\pi k_f R_2 L} + \frac{27}{2240} \frac{Q_d d^2}{k_f} \quad (8)$$

For the stipulated conditions, the maximum temperature occurs at the dome exit on the inner surface of the dome wall. To determine the mixed mean fluid temperature at the dome exit, the temperature rises in the bypass line (from decay betas) and in the dome (from beta and fission energy and heat transfer from the wall) must be added to the core inlet temperature (t_i).

$$\text{exit } t_m = t_i + \frac{Q_b T_b + Q_d T_d}{c_p} + \frac{q_2}{wc} \quad (9)$$

Combining equations (8) and (9),

$$\text{Max. } t_2 - t_i = \frac{13 q_2 d}{70\pi k_f R_2 L} + \frac{27 Q_d d^2}{2240 k_f} + \frac{Q_b T_b + Q_d T_d}{c_p} + \frac{q_2}{wc} \quad (10)$$

Temperatures in Uninsulated Dome Wall

The differential equation for the temperature distribution in the dome wall is

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dt}{dr} \right) - Q_s \quad (11)$$

where the volume heat source, Q_s , is a function of the radial distance r .

Actually Q_s should be essentially exponential in form since gamma photons entering the wall attenuate exponentially. To simplify the analysis, a linear form is used which will not cause significant error.

It is assumed that the capture gammas born in the dome wall result in a uniform volumetric heat source and the gammas (from the fuel solution) entering the wall result in a volumetric heat source that varies linearly with r from a maximum at R_2 to zero at R_3 . Therefore,

$$Q_s = a(R_3 - r) + q_c/V_s \quad (12)$$

The constant "a" is a function of the total energy generated in the dome wall and is evaluated in the following manner.

$$q_t = \int_{R_2}^{R_3} 2\pi r \left[a(R_3 - r) + \frac{q_c}{V_s} \right] dr \quad (13)$$

Integrating and solving for a,

$$a = \frac{q_t - \frac{\pi L q_c}{V_s} (R_3^2 - R_2^2)}{2\pi L \left[\frac{R_3(R_3^2 - R_2^2)}{2} - \frac{(R_3^3 - R_2^3)}{3} \right]} \quad (14)$$

From equation (12),

$$Q_s = aR_3 - ar + \frac{q_c}{V_s} = -ar + k \quad (15)$$

$$\text{where } K = aR_3 + \frac{q_c}{V_s} \quad (16)$$

The boundary conditions associated with equation (9) are:

$$\text{At } r = R_2, k_s \left(\frac{dt}{dr} \right) = \frac{Q_2}{A_2}$$

$$\text{At } r = R_3, -k_s \left(\frac{dt}{dr} \right) = \frac{q_3}{A_3} = h_3 (t_3 - t_a)$$

Combining equations (9) and (13), integrating and applying the first boundary condition,

$$t_3 - t_2 = \frac{a(R_3^3 - R_2^3)}{9 k_s} - \frac{K(R_3^2 - R_2^2)}{4 k_s} + \left[\frac{q_2}{2\pi L k_s} - \frac{aR_2^3}{3 k_s} + \frac{KR_2^2}{2 k_s} \right] \ln \frac{R_3}{R_2} \quad (17)$$

From the second boundary condition,

$$t_3 = \frac{q_3}{A_3 h_3} + t_a = \frac{q_t - q_2}{2\pi L R_3 h_3} + t_a \quad (18)$$

Combining equations (8) and (18),

$$t_3 - t_2 = \frac{q_t - q_2}{2\pi L R_3 h_3} + t_a - t_m - \frac{13}{35} \frac{q_2 d}{2k_f \pi R_2 L} - \frac{27}{2240} \frac{Q_d d^2}{k_f} \quad (19)$$

Since the value of the heat transfer coefficient at the outside of the dome will depend on the magnitude of the temperature, a solution in terms of temperature differences is not possible for this case as for the insulated dome. In calculating the value of q_2 , an average t_m must be used. A reasonable approximation to avoid undue complication is to use an average value of t_m . Therefore,

$$t_{m_{av.}} = t_i + \frac{Q_b T_b}{c_p} + \frac{Q_d T_d}{2c_p} + \frac{q_2}{2wc} \quad (20)$$

Solving for q_2 by equating equations (17) and (19) and substituting equation (20),

$$q_2 = \left[\frac{q_t}{2\pi L R_3 h_3} + \Psi - \frac{27 Q_d d^2}{2240 k_f} - \frac{a(R_3^3 - R_2^3)}{9 k_s} + \frac{K(R_3^3 - R_2^2)}{4 k_s} \right. \\ \left. + \left(\frac{a R_2^3}{3 k_s} - \frac{K R_2^2}{2 k_s} \right) \ln \frac{R_2}{R_2} \right] \left[\frac{1}{\frac{\ln R_3/R_2}{2\pi L k_s} + \frac{1}{2wc} + \frac{13d}{70\pi k_f R_2 L} + \frac{1}{2\pi L R_3 h_3}} \right] \quad (21)$$

$$\text{where } \Psi = t_a - t_i - \frac{Q_b T_b}{c_p} - \frac{Q_f T_f}{2c_p}$$

Note that in the derivation of equation (21), it was assumed that heat is transferred from the wall into the fuel solution. If a minus value of q_2 is computed from equation (21) (which actually occurred for this system), it simply means that heat is transferred into the wall and the equations are still valid when the algebraic value of q_2 is used.

For the solution of equation (21), it is necessary to know the value of the heat transfer coefficient, h_3 , on the outside of the dome wall. This coefficient is a combined radiation and natural convection heat transfer coefficient, which is a function of the surface temperature. Consequently, an iterative method of solution is required, i.e., guess the surface temperature, compute h_3 , calculate q_2 , compute the wall temperature to check the guess, and continue until agreement is obtained.

The maximum dome wall temperature is calculated from equation (10) using the value of q_2 calculated from equation (21).

For a minus q_2 (heat transferred from the fuel solution), the maximum system temperature occurs at the exit on the bellows surface. The bellows surface temperature, t_1 , is obtained from equation (6) on setting $y = -\frac{d}{2}$, and $t_1 - t_m$ is given by equations (7) and by (8) when t_2 is replaced by t_1 .

$$t_1 - t_m = - \frac{9 q_2 d}{140\pi k_f R_2 L} + \frac{27 Q_d d^2}{2240 k_f} \quad (22)$$

Combining equations (9) and (21),

$$\text{max. } t_1 - t_i = \frac{-9 q_2 d}{140\pi k_f R_2 L} + \frac{27 Q_f d^2}{2240 k_f} + \frac{q_2}{wc} + \frac{(Q_b T_b + Q_d T_d)}{cp} \quad (23)$$

Note that the algebraic value of q_2 must be used in equation (23).

Calculation of Parameters Used in Temperature Equations

The method of calculating the parameters used in the temperature solutions derived in the previous sections are developed in this section and the constants used in the application to the HRT are listed.

Capture Gammas in Dome Wall

Gamma photons are liberated in the dome wall from thermal neutron capture in the components of 347 stainless steel. The composition of 347 stainless is approximately 71.2% Fe, 18% Cr, 10.0% Ni and 0.8% Nb. The energy and number of gamma photons per capture for these components are listed in Table I, which is based on the data of Mittleman and Liedkte.⁶

Table I

CAPTURE GAMMAS FROM 347 STAINLESS STEEL

<u>Energy, Mev</u> <u>Component</u>	<u>Number of gammas/capture</u>					<u>Cross Section</u> <u>at 280°C,</u> <u>b.</u>
	1.0	2.0	4.0	6.0	8.0	
Fe	0	0.10	0.24	0.22	0.50	1.6
Cr	0.37	0.16	0.12	0.18	0.69	2.0
Ni	0	0	0.14	0.30	0.72	3.0
Nb	0	0	0.54	0.14	0	0.65

The total energy release per neutron capture in a unit volume is
 $1.6 \times 10^{-13} \sum_i n_i E_i N_i \sigma_i \phi$ for the listed analysis and tabulated values.

Assuming that all capture gamma energy is absorbed in the dome wall,

$$q_c = 17.6 \times 10^{-4} \times 3.413 \times 28,320 \times 10^{-14} \phi V_s = 1.70 \times 10^{-8} \phi V_s \quad (24)$$

Complete gamma absorption, of course, only applies to an infinite body.

Actually, a 2-1/2 in. thick steel slab approaches infinite thickness as far as probability of escape is concerned.

Fission Energy Released in Fuel Solution

Taking $\sigma(U^{235}) = 350$ b. and the critical concentration as 10 g/liter, the power density from fission alone in the dome section is

$$\frac{350 \times 10 \times 0.6023 \times 10^{-3} \phi}{235 \times 3.1 \times 10^{10}} = 2.89 \times 10^{-13} \phi \quad (25)$$

It is assumed that $\phi = 10^{11}$ for 10-Mw operation. At other powers, ϕ is reduced in proportion.

Beta and Gamma Energy from Fission Product Decay

In an operating reactor system, the average rate of energy release may be represented to a fair approximation by the integrated Kay-Wigner equation.³ For long-time operation (a few weeks of operation effectively approaches infinite operating time),

$$\text{Energy release in watts} = 5.9 \times 10^{-3} P \theta^{0.2} \quad (26)$$

where θ is the time after shutdown or removal from the reactor in days.

The total energy release from the entire reactor system fuel inventory over any time interval is obtained by integrating equation (26). Putting θ in hours and converting from watt-days to Btu/hr,

$$E = \frac{5.9 \times 10^{-4} P \times 24 \times 3.413}{0.8 \times 24^{0.8} T} \left(\theta_2^{0.8} - \theta_1^{0.8} \right) = \frac{0.0475 P (\theta_2^{0.8} - \theta_1^{0.8})}{T} \quad (27)$$

Of this total energy, about 47% is gamma energy and 53% beta energy.

Retention Times

The retention time in any part of the system is

$$T = \frac{V\rho}{w} \quad (28)$$

Using $\rho = 52 \text{ lb/ft}^3$, $V_d = 0.138 \text{ ft}^3$ or 3.9 liters.⁽²⁾ and $V_b = 0.0201 \text{ ft}^3$, the retention times in the dome section and bypass line are

$$T_d = \frac{7.160}{w} \quad \text{and} \quad T_b = \frac{1.045}{w} \quad (29)$$

The estimated time for the core fuel solution to go from the center of the HRT core to the core inlet is 14 sec.⁽²⁾ For a 13.3-ft/sec velocity (400 gpm through a 3.5-I.D. pipe) in the core exit pipe, the retention time in the dome section is 0.75 sec. The time for flow from the HRT core center to the exit pipe is about 6 sec.

Gamma Energy to Dome Wall from Fuel Solution

Gamma energy to the dome wall comes from fuel solution in the bellows section and in the core exit pipe. The major contribution is from decay gammas; a small amount results from prompt fission. All contributions are calculated by equations (25) and (27). It is assumed that all gamma energy reaching the dome wall is absorbed and that the gamma emission is from essentially collimated sources emitting in a radial direction. Using a core system volume of 500 liters and assuming 3% of fission energy is gamma energy, the total gamma energy released in the passage between the bellows and the dome wall is

$$E_d = \frac{0.47 \times 0.0475P \times 3.9}{T_d \times 500} \left[\left(\frac{14}{3600} + T_b + T_d \right)^{0.8} - \left(\frac{14}{3600} + T_b \right)^{0.8} \right] + 0.03 \times 2.89 \times 10^{-13} \phi \times 3.9 \times 10^3 \times 3.413 \quad (30)$$

Assuming that one-half of this energy enters the dome wall unattenuated and the other attenuates through the material located between the source and the opposite dome wall, the attenuated energy input to the dome wall is

$$q_d = \frac{E_d}{2} (1 + f_d) \quad (31)$$

where f_d is the attenuation factor.

Similarly for the core exit pipe (volume = 1.89 liters),

$$E_x = \frac{0.47 \times 0.0475P \times 3600 \times 1.89}{0.75 \times 500} \left[\left(\frac{6.75}{3600} \right)^{0.8} - \left(\frac{6}{3600} \right)^{0.8} \right] \quad (32)$$

$$+ 0.03 \times 2.89 \times 10^{-13} \phi \times 1.89 \times 10^3 \times 3.413$$

Since all this energy must be attenuated through the material between core pipe source and the dome wall, the energy reaching the dome wall is

$$q_x = f_x E_x \quad (33)$$

The total gamma energy to the dome wall is

$$q_t = q_c + q_d + q_x \quad (34)$$

For the system considered, the attenuation factors can be only roughly estimated without unwarranted difficulty. Assuming the gamma photon energy averages 0.7 mev,

$$\mu_{\text{steel}}^{(1)} = 7.9 \times 0.072 = 0.569$$

$$\mu_{\text{D}_2\text{O}}^{(1)} = 0.83 \times 0.084 = 0.0697$$

The core pipe gammas pass through 0.85 in. of steel and about 7 cm of fuel solution. The number of relaxation lengths are

$$(\mu x)_{\text{total}} = 2.54 \times 0.569 \times 0.85 + 0.0697 \times 7 = 1.716$$

The system buildup factor was estimated to be 2.77 by averaging the energy absorption buildup factors for a collimated source¹ for steel and water on an electron percentage basis.

$$f_x = 2.77 e^{-1.716} = 0.498 \quad (35)$$

For the dome fuel solution gammas that attenuate, the number of relaxation lengths are about twice that for the core pipe source.

Similarly,

$$f_d = 4.39 e^{-3.432} = 0.142 \quad (36)$$

Volume Heat Source Terms

The volume heat source terms used in the analysis are the source in the dome wall (Q_s) and the sources in the fuel solution flowing through the bypass line (Q_b) and through the dome section (Q_d).

Q_s , which is a function of radial distance, is defined by equation (12).

In calculating the fuel solution heat source terms, only the beta energy is considered; the gamma energy contribution is very small. Utilizing equation (27),

$$Q_b = \frac{0.53 \times 0.0475 P \times 28.32}{500 T_b} \left[\left(\frac{14}{3600} + T_b \right)^{0.8} - \left(\frac{14}{3600} \right)^{0.8} \right] \quad (37)$$

and

$$Q_d = \frac{0.53 \times 0.0475 P \times 28.32}{500 T_d} \left[\left(\frac{14}{3600} + T_b + T_d \right)^{0.8} - \left(\frac{14}{3600} + T_b \right)^{0.8} \right] \quad (38)$$

Heat Transfer Coefficient

For the case of no insulation on the HRT dome, the heat transfer coefficient, h_3 , on the outer wall consists of a natural convection contribution and a radiation contribution. The natural convection coefficients for long vertical cylinders in air are roughly correlated⁷ by

$$h_{\text{conv.}} = 0.5 \left(\frac{t_3 - t_a}{24 R_3} \right)^{0.25} \quad (39)$$

The radiation coefficient may be approximated⁴ by

$$h_{\text{rad.}} = \frac{0.173 \epsilon}{t_3 - t_a} \left[\left(\frac{460 + t_3}{100} \right)^4 - \left(\frac{460 + t_a}{100} \right)^4 \right] \quad (40)$$

where t_a is the temperature of the ambient air and surroundings and ϵ is the emissivity of the surface.

$$h_3 = h_{\text{conv.}} + h_{\text{rad.}} \quad (41)$$

Summary of Physical Properties and Pertinent Constants

$$\rho = 52 \text{ lb/ft}^3, \quad c = 1.15 \frac{\text{Btu}}{\text{lb}^\circ\text{F}}, \quad k_f = 0.32 \text{ Btu/ft hr}^\circ\text{F}, \quad k_s = 10 \text{ Btu/ft hr}^\circ\text{F},$$

$$V_s = 0.532 \text{ ft}^3, \quad V_d = 0.138 \text{ ft}^3, \quad V_b = 0.0201 \text{ ft}^3,$$

$$V_x = 0.0667 \text{ ft}^3, \quad d = 0.0672 \text{ ft}, \quad R_1 = 0.292 \text{ ft}, \quad R_2 = 0.359 \text{ ft}$$

$$R_3 = 0.546 \text{ ft}, \quad t_a = 90^\circ\text{F}, \quad \epsilon = 0.6, \quad L = 1 \text{ ft}, \quad \text{exit core}$$

$$\text{pipe velocity} = 13.3 \text{ ft/sec}, \quad \text{average core fuel cycle time} = 14 \text{ sec.}$$

Results and Discussion

Some pertinent results of the thermal analysis of the insulated HRT dome are tabulated in Table II and shown graphically in Figure 3. The results shown are for 10 Mw, to correct to other power levels, multiply by the power ratio since the ordinate ($\max t_2 - t_1$) is independent of the core inlet temperature and directly proportional to reactor power. The flow rate ranges from the minimum possible (45 lb/hr) to the probable maximum (1880 lb/hr). In all probability the actual flow rate is at least several times the minimum possible value. A 10^{11} thermal neutron flux at 10 Mw as an upper limit represents an educated guess. Any reasonable method of calculating the dome neutron flux cannot be done with any confidence in the accuracy. It is believed that the dome flux is probably closer to 10^{10} than 10^{11} . Obviously (see Figure 3), fluxes below 10^{10} are of no concern from the viewpoint of maximum surface temperature.

Figure 3 shows that even for zero neutron flux and optimum flow rate, the lowest maximum surface temperature obtainable is 320°C for a 260°C core inlet temperature and 10-Mw operation. Acceptance of this result without more careful analysis dictates the removal of the insulation for 10-Mw operation. Actually, these results are quite conservative and it is quite possible that the maximum surface temperature would not exceed 315°C. It must be remembered that the postulation of no entrance effects, stable laminar flow even at the high flow rates, complete absorption of gamma energy in the dome wall and collimated plane sources are very conservative.

The most conservative postulate probably is the neglect of entrance effects, i.e., using the far downstream solution ($L/D = \infty$) rather than an entrance solution for the equivalent L/D (~ 15) of the idealized system. Examination of j-factor plots⁵ as a function of L/D for laminar flow leads to a rough estimate of a heat transfer coefficient for $L/D = 15$ that is about a factor of two higher than for $L/D = \infty$. Applying the correction to $t_2 - t_m$ (inversely proportional to the heat transfer coefficient) reduces max. $t_2 - t_1$ to 52°C for a 10^{11} flux and a flow rate of only 200 lb/hr. For a 260°C core inlet temperature, this gives a maximum surface temperature of 312°C . At flow rates greater than 800 lb/hr, turbulence will exist and larger reduction in $t_2 - t_m$ can occur. Thus, max. $t_2 - t_1$ would show a sharp decrease at the onset of turbulence and continue to decrease slightly with increasing flow rate rather than slightly increasing as shown in Figure 3. The slight increase as shown, incidentally, is a result of an increase in the rate of energy release (fission product decay) with decreasing retention time, without an increase in the heat transfer coefficient as would occur for turbulent flow.

As a general result of the foregoing discussion, one may conclude that it is quite possible that the maximum surface temperature in the HRT would not exceed 315°C for power levels up to 10 Mw.

Any conclusion as to the necessity for removal of the insulation from the HRT dome is now academic since the insulation already had been removed by the time this memorandum was written. In weighing the advantages and disadvantages of removal, it was deemed better to remove the insulation. The only apparent disadvantage was the increased heat load to the cell space coolers, which seem adequate to handle the increased capacity.

During the initial operation of the HRT at power, the maximum power reached was about 1.5 Mw. Even at the minimum possible flow rate, the maximum temperature above the core inlet is only 18°C according to Figure 3.

In view of the conservatism of the analysis, it can be concluded that damagingly high temperatures could not have existed in the dome, provided that there was no extreme condition of channeling of the flow due to poor flow distribution and/or accumulation of uranium containing solids.

The results of the analysis of the uninsulated HRT dome for a neutron flux of 10^{11} and a 260°C core inlet temperature are shown in Figure 4. These results are not proportional to power and not independent of the core inlet temperature as in the insulated case. For relatively small deviations from a 260°C core inlet temperature, the results are still applicable without significant error.

It is evident from Figure 4 that removal of the insulation will keep the maximum surface temperature of the inner dome wall at around the core inlet temperature, slightly above at the low flow rates and slightly below at higher flow rates. In this case heat is transferred from the dome fuel solution into and through the dome wall. For this condition the maximum surface temperature occurs on the bellows surface. Less confidence can be placed on the accuracy of the calculated bellows surface temperature than on the temperature of the dome wall since a large deviation between the idealized system and the actual system exists at this point. However, in view of the general conservatism of the analysis, the bellows temperatures shown in Figure 4 may be considered the probable upper limit.

TABLE II

Temperatures in Insulated HRT Dome

Flow rate, lb/hr	Temp. rise, °C		Temp. diff., °C		Wall heat generation, watts		
	bypass	dome	$t_2 - t_m$	max. $t_2 - t_1$	From cap. γ 's	From dome fuel, γ 's	From core fuel, γ 's
neutron flux = 10^{11} n/cm ² sec.							
45	5.8	62.4	57.4	125.6	265	378	202
100	2.9	30.9	61.6	95.4	265	437	202
200	1.5	16.9	65.3	83.7	265	491	202
400	0.8	9.0	69.0	78.8	265	544	202
800	0.4	4.8	72.3	77.5	265	596	202
1880	0.2	2.2	75.9	78.3	265	642	202
neutron flux = 10^{10} n/cm ² sec							
45	5.8	49.8	41.2	96.8	26.5	376	201
100	2.9	25.3	45.3	73.5	26.5	435	201
200	1.5	14.0	49.1	64.6	26.5	489	201
400	0.8	7.9	52.7	61.4	26.5	542	201
800	0.4	4.5	56.5	61.4	26.5	594	201
1880	0.2	2.2	59.7	62.1	26.5	640	201

Figure 2: Bellows Section of HRT Dome

Figure 3: Idealized Model of HRT Dome

MAXIMUM HRT DOME WALL TEMPERATURE
FOR INSULATED DOME

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Figure 3

Nomenclature

A	heat transfer area, ft^2
a	constant defined by equation (14), Btu/hr ft^4
c	heat capacity, $\text{Btu/lb } ^\circ\text{F}$
d	equivalent thickness between dome wall and bellows, ft
E	Gamma and/or beta energy, Btu/hr
f	attenuation factor, dimensionless
G	mass flow rate, lb/hr ft^2
h	heat transfer coefficient, $\text{Btu/hr ft}^2 ^\circ\text{F}$
k	thermal conductivity, $\text{Btu/hr ft } ^\circ\text{F}$
K	parameter defined by equation (16), Btu/hr ft^3
L	Length of bellows section, ft
P	reactor power, watts
Q	volumetric heat source, Btu/hr ft^3
q	heat flow rate, Btu/hr
q_c	heat generation from capture gammas in dome wall, Btu/hr
q_t	heat generation rate in dome wall from all gammas, Btu/hr
q_x	heat generation from core exit pipe gammas, Btu/hr
R	radius to a surface, ft
r	radial distance to any point, ft
t	temperature, $^\circ\text{F}$
T	retention time, hr

U	average velocity, ft/sec
u	velocity at any point, ft/sec
V	volume, ft ³
w	flow rate, lb/hr
x	coordinate distance, ft
y	coordinate distance, ft
z	coordinate distance, ft
ρ	density, lb/ft ³
ϕ	thermal neutron flux, neut./cm ² sec
μ	viscosity, lb/ft hr

Subscripts:

a	refers to ambient air and surroundings
b	refers to bypass line
d	refers to annulus between dome wall and bellow
f	refers to fuel solution
m	refers to mixed mean
s	refers to dome wall
x	refers to exit core pipe
1	refers to equivalent bellows surface
2	refers to inner dome wall
3	refers to equivalent outer dome wall

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