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Date: July 15, 1955

Subject: Some Heat Removal Considerations of the HRT Pressure Vessel During Operation

To: W. R. Gall

From: R. E. Aven

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Summary

By the use of a modified form of the Nusselt equation for free convection it is possible to estimate the difference between the average blanket temperature and the temperature of the inside surface of the pressure vessel as a function of heat flux from this surface. Using this along with the temperature distribution equation across the stainless steel cladding and carbon steel pressure vessel, it is possible to calculate the temperature at any point in the pressure vessel. The resulting temperature profiles are presented in Figure 1 for 1, 5, and 10 Mw power levels.

Curves relating stress with heat removal rates from the outside surface of the pressure vessel for various power levels are given in Figure 2. The heat removal rate from the outside surface is presented in Figure 3 as a function of reactor power level. From Figures 2 and 3 it is possible to estimate the total tangential stress as a function of the power level. This is shown in Figure 4.

The temperature drop $(\Delta T)_f$, across the blanket film and the total tangential stress, σ_t , in the wall of the pressure vessel are given below for a pure D_2O blanket and for a 312.3 gms./liter, blanket solution of $UO_2SO_4-D_2O$.

P_o, Mw	$(\Delta T)_f$ for D_2O	$(\Delta T)_f$ for $UO_2SO_4-D_2O$	σ_t for D_2O	σ_t for $UO_2SO_4-D_2O$
5	14°F	16°F	12,400 psi	12,600 psi
10	26°F	34°F	13,600 psi	12,500 psi

Introduction

During reactor operation, the heat generated in the HRT pressure vessel is removed both by radiating heat to the blast shield and by conducting heat into the blanket solution. At the higher power levels ($> 5 Mw$) the major portion of this heat is removed by the blanket solution. One purpose of this paper then

is to provide a temperature profile across the pressure vessel wall at various power levels (Figure 1). To determine this, estimations are included of:

1. The heat transfer coefficients across the blanket film at the inside surface of the pressure vessel as a function of temperature drop across the blanket film.
2. The total heat generation rate in the pressure vessel, including the cladding.
3. The heat flux into the blanket for various power levels.
4. Temperature distribution across stainless steel cladding and carbon steel vessel wall.

Another purpose is to present the total tangential stress in the pressure vessel wall as a function of reactor power. (Figure 4)

Estimates of the temperature drop across the blanket film have been made for a $\text{UO}_2\text{SO}_4\text{-D}_2\text{O}$ blanket solution (300 gms U/liter). These values are useful in fixing the blanket operating temperature so as to prevent phase separation of the uranyl sulfate solution.

Temperature Profile

In order to determine the effects radiation cooling will have on the pressure vessel, the heat removal rate from the outside surface should be known as a function of outside surface temperature. To estimate this the following equations are used. [1] , [3]

For the heat lost by radiation

$$\left(\frac{q}{A}\right)_{\text{rad.}} = \frac{0.173}{\left(\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1\right)} \left[\left(\frac{T_b + 460}{100}\right)^4 - \left(\frac{T_o + 460}{100}\right)^4 \right] \quad (1)$$

For the heat lost by natural convection in the annulus

$$\left(\frac{q}{A}\right)_{\text{conv}} = 0.3 \left(\frac{T_b - T_o}{2}\right)^{1.25} \quad (2)$$

For the total heat lost

$$\left(\frac{q}{A}\right)_{r=b} = \left(\frac{q}{A}\right)_{\text{rad}} + \left(\frac{q}{A}\right)_{\text{conv}} \quad (3)$$

where T_b = temperature of outside surface of pressure vessel

$\left(\frac{q}{A}\right)$ = heat removal rate, Btu/(hr-ft²)

T_o = temperature of inside surface of blast shield

In computing the heat lost from the outside surface of the pressure vessel, the following conditions are assumed.

1. All heat is transferred by radiation and convection. The conduction of heat across the air gap is negligible.
2. Average temperature of inside surface of blast shield is 160-170°F.
3. ϵ_1 = emissivity of carbon steel pressure vessel = 0.8
4. ϵ_2 = emissivity of stainless steel blast shield = 0.8

At steady state operation the total heat generated in the blast shield and cladding must be removed as fast as it is formed. From a knowledge of T_b , the heat removal rate from the outside surface, $\left(\frac{q}{A}\right)_{r=b}$, may be found. The difference between this value and the total heat generation rate in the pressure vessel is the average heat removal rate by the HRT blanket solution. Let

R = inside radius of pressure vessel = 30" $\approx$ 2.500 ft.

a = inside radius of carbon steel shell = 30.5" $\approx$ 2.5417 ft

b = outside radius of pressure vessel = 34.5" $\approx$ 2.8750 ft

T_R = temperature of inside surface of pressure vessel

T_a = temperature of interface between carbon steel shell and stainless steel cladding

T_b = temperature of outside surface of pressure vessel

To estimate the total heat production in the pressure vessel (including cladding)

the following assumptions are made:

1. The heat generation properties of the stainless steel cladding are the same as the carbon steel pressure shell.
2. Heat generation constants are directly proportional to reactor power.

The following equations are used: [1]

$$T(r) = - \frac{H_1 e^{-m_1(r-R)}}{k m_1^3} \left[\frac{m_1 r+2}{r} \right] - \frac{H_2 e^{-m_2(r-R)}}{k m_2^3} \left[\frac{m_2 r+2}{r} \right] - \frac{H_3 e^{-m_3(r-R)}}{k m_3^3} \left[\frac{m_3 r+2}{r} \right] - \frac{C_1}{r^2} + C_2 \quad \dots (4)$$

$$\frac{dT(r)}{dr} = \frac{H_1 e^{-m_1(r-R)}}{k m_1^3 r^2} (m_1^2 r^2 + 2m_1 r + 2) + \frac{H_2 e^{-m_2(r-R)}}{k m_2^3 r^2} (m_2^2 r^2 + 2m_2 r + 2) + \frac{H_3 e^{-m_3(r-R)}}{k m_3^3 r^2} (m_3^2 r^2 + 2m_3 r + 2) + \frac{C_1}{r^2} \quad \dots (5)$$

$$\left(\frac{q}{A} \right)_{r=b} = k \left(\frac{dT}{dr} \right)_{r=b} \quad (6)$$

$$\left(\frac{q}{A} \right)_{r=R} = k \left(\frac{dT}{dr} \right)_{r=R} \quad (7)$$

where H_1 = heat generation constant = $6.188 \times 10^3 P_o$ Btu/hr ft³
 H_2 = heat generation constant = $9.282 \times 10^3 P_o$ Btu/hr ft³
 H_3 = heat generation constant = $-7.426 \times 10^3 P_o$ Btu/hr ft³
 P_o = reactor power, Mw
 m_1 = 7.876 ft^{-1}
 m_2 = 17.386 ft^{-1}
 m_3 = 48.146 ft^{-1}
 k = thermal conductivity of pressure vessel = $25 \text{ Btu/hr ft } ^\circ\text{F}$

C_1, C_2 = arbitrary constants

r = radius, ft.

The arbitrary constants C_1 and C_2 may be solved from the boundary conditions:

$$T(r=a) = T_a \quad (8)$$

$$T(r=b) = T_b \quad (9)$$

Solving for C_1 and C_2 :

$$C_1 = 21.925 (T_b - T_a) - 77.553 P_o \quad (10)$$

$$C_2 = T_b + 7.6262 (T_b - T_a) - 26.747 P_o \quad (11)$$

Solving equation (5) for the present case

$$\left(\frac{dT}{dr} \right)_{r=b} = 1.8232 P_o + 0.12098 C_1 \quad (12)$$

$$\left(\frac{dT}{dr} \right)_{r=R} = 50.820 P_o + 0.16000 C_1 \quad (13)$$

The total heat, Q , generated in a spherical sector of the pressure vessel with 1 ft² outside surface is

$$Q = \frac{R^2}{b^2} \left(\frac{q}{A} \right)_{r=R} - \left(\frac{q}{A} \right)_{r=b} \quad (14)$$

Solving for Q for the HRT

$$Q = 915 P_o, \text{ Btu/hr} \quad (15)$$

Equation (15) represents the total heat generation rate in a spherical sector of the pressure vessel (including cladding) with 1 ft² of outside surface.

In order to determine the temperature distribution across the stainless cladding, the thermal conductivity of stainless steel must be considered. The value of k is 11.2 Btu/hr ft °F for the range 570 °F to 600 °F. For this case the arbitrary constants C_1 and C_2 are solved in terms of T_a and T_R .

$$C_1 = 152.50 (T_a - T_R) - 607.408 P_o \quad (16)$$

$$C_2 = T_a + 60.00 (T_a - T_R) - 230.570 P_o \quad (17)$$

The rate at which heat is transferred to the blanket solution from the inside surface of the pressure vessel is given by the difference between the total heat generated and the heat removed, by the cooling system, from the outside surface. This can be represented by

$$\left(\frac{q}{A}\right)_{r=R} = \frac{Q - \left(\frac{q}{A}\right)_{r=b}}{R^2/b^2}$$

or

$$\left(\frac{q}{A}\right)_{r=R} = \frac{915 P_o - \left(\frac{q}{A}\right)_{r=b}}{0.756} \quad (18)$$

This heat must be transferred across the blanket film at the inside surface of the pressure vessel. The temperature drop across this film is needed to determine the temperature profile of the pressure vessel wall. It will also be needed to determine if there is a possibility of phase separation at the wall, should the blanket contain uranyl sulfate.

Since the area available to flow in the blanket annulus, is large, the average linear velocity through the blanket is very small. For this reason the heat transfer coefficient is assumed to depend on natural convection only. To determine this the Nusselt equation for free convection is written as a function of the product of the Grashof and Prandtl numbers [4].

$$N_u = c (Gr \times Pr)^d$$

or

$$\frac{h_c L}{k} = c \left[\left(\frac{g \beta (\Delta T)_f L^3 \rho^2}{\mu^2} \right) \left(\frac{C_p \mu}{k} \right) \right]^d$$

$$\frac{h_c L}{k} = c \left[\frac{g\beta(\Delta T)_f L^3 \rho^2 C_p}{\mu k} \right]^d \quad (19)$$

Solving for h_c

$$h_c = \frac{ck}{L} \left[\frac{g\beta(\Delta T)_f L^3 \rho^2 C_p}{\mu k} \right]^d \quad (20)$$

where

h_c = free convection heat transfer coefficient

g = gravitational constant

$\beta = \frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right) =$ coefficient of thermal expansion of the blanket solution.

$(\Delta T)_f$ = temperature drop across the blanket film.

L = vertical length of heated surface.

k = thermal conductivity of blanket solution.

μ = viscosity of blanket solution

C_p = heat capacity of blanket solution

ρ = density of blanket solution

c, d = constants

Assuming the blanket to be D_2O at $280^\circ C$ ($536^\circ F$), the following physical properties are used:

At $536^\circ F$:

$$\begin{aligned} \rho &= 51.88 \text{ lbs/ft}^3 & [5], [2] \\ \mu &= 0.266 \text{ lbs/hr-ft} & [5], [2] \\ \beta &= 0.00115^\circ F^{-1} \text{ (estimated from curve of } \rho \text{ vs } T), & [5] \\ k &= 0.337 \text{ Btu/hr ft } ^\circ F, & [6], [2] \\ C_p &= 1.238 \text{ Btu/lb } ^\circ F & [2], [6] \\ \left(\frac{g\beta\rho^2 C_p}{\mu k} \right) &= 20.27 \times 10^9 \text{ ft}^3/^\circ F \end{aligned}$$

For values of $\left[\frac{g\beta(\Delta T)_f L^3 \rho^2 c_p}{\mu k} \right] > 10^9$, Brown and Marco [4] give the following values for c and d:

$$d = 1/3$$

$$c = 0.15 \text{ (for spherical shape)}$$

Equation (20) reduces to

$$h_c = 0.15 k \left[\frac{g\beta(\Delta T)_f \rho^2 c_p}{\mu k} \right]^{1/3} \quad (21)$$

Solving equation (21) for conditions in the blanket at 536°F

$$h_c = 130 (\Delta T)_f^{1/3} \quad (22)$$

The heat flux from the inside surface of the pressure vessel may be expressed

$$\left(\frac{q}{A} \right)_{r=R} = h_c (\Delta T)_f \quad (23)$$

Combining equations (22) and (23) and solving for $(\Delta T)_f$

$$(\Delta T)_f = 0.026 \left[\left(\frac{q}{A} \right)_{r=R} \right]^{3/4} \quad (24)$$

The procedure for determining the temperature profile across the pressure vessel and blast shield walls is the following:

1. Assume a reasonable value for the temperature of the outside surface of the pressure vessel, for the desired power level, P_o .
2. From equations (1), (2) and (3) estimate $\left(\frac{q}{A} \right)_{r=b}$
3. From equation (18) calculate $\left(\frac{q}{A} \right)_{r=R}$
4. From equation (24) compute the temperature drop, $(\Delta T)_f$, across the D_2O blanket film.
5. From the temperature of the blanket solution and $(\Delta T)_f$ the value of T_R is fixed.
6. From equation (7) determine $\left(\frac{dT}{dr} \right)_{r=R}$
7. From equation (13) determine C_1 .

8. From equation (16) determine $(T_a - T_R)$. This fixes T_a , since T_R is known from step 5 above.
9. Determine T_b in a similar manner from equations (6), (12) and (10). This value should agree with the assumed value in step 1. If not, assume a new value and repeat the process. (Since $\left(\frac{q}{A}\right)_{r=b}$ is an approximation only, one needs not be too precise in determining T_b .)
10. When surface temperatures are established, the temperature profile in the pressure vessel wall can be found from equations (4), (10) and (11) for the carbon steel and equations (4), (16) and (17) for the stainless steel cladding.

Assuming an average blanket temperature of 536°F the temperature profile has been estimated and plotted for HRT power levels of 1 Mw, 5 Mw and 10 Mw. (See Figure 1).

Tangential Stress in Pressure Vessel

It may prove interesting to estimate the total stress in the pressure vessel wall as a function of reactor power. This has been done assuming a D_2O blanket temperature of 536°F and an internal pressure of 2000 psia. In order to do this Figure 2 was prepared showing the total stress as a function of heat removal rate from the outside surface, $\left(\frac{q}{A}\right)_{r=b}$, for several power levels. This was prepared in a manner similar to that for Figure (2) in CF-55-3-119 [1] *.

By using the first 9 steps of the procedure listed for determining temperature profile, Table I was prepared showing outside surface heat removals expected

* It may be noticed that the total stress in the vessel wall as given in Figure 2 is lower by ~ 2000 psi than the values given in CF-55-3-119. This is because a system pressure of 2000 psia was assumed here rather than the design pressure of 2500 psia assumed in preparing CF-55-3-119. If the stress in the vessel wall is desired for a 2500 psia system then 2000 psi should be added to the values read from figures in this paper.

from the cooling system at several different power levels.

Table I

Heat Removal from Outside Surface of Pressure Vessel
vs. HRT Power Levels

$P_o, \text{ Mw}$	$\left(\frac{q}{A}\right)_{r=b}, \frac{\text{Btu}}{\text{hr. ft}^2}$
0.1	1050
1.0	1100
2.0	1160
3.0	1220
5.0	1300
10.0	1560
18.0	1960

The values given in Table I are plotted in Figure 3 giving approximately a straight line relationship.

From Figures (2) and (3) the total stress in the vessel wall can be found for any power level. Figure 4 shows the total stress plotted versus the reactor power level.

Temperature Drop Across Blanket Film for $\text{UO}_2\text{SO}_4\text{-D}_2\text{O}$ Blanket Solutions

Calculations made in the preceding section of this paper have been based on a D_2O blanket at a pressure of 2000 psia and an average temperature of 536°F . In this case the only interest in the temperature drop across the blanket film is to determine the temperature level existing in the pressure vessel wall. Actually this temperature level will vary at different points of the vessel wall. This is due to the variations of the natural convection heat transfer coefficient at different levels inside the vessel and the variation in the thickness of the vessel.

At temperatures of $\sim 280^\circ\text{C}$ (536°F) and above, $\text{UO}_2\text{SO}_4\text{-D}_2\text{O}$ solutions, (300 gms U/liter), separate into two liquid phases, one of which is very corrosive. If $\text{UO}_2\text{SO}_4\text{-D}_2\text{O}$ blankets are used, it is preferable to keep the solution

below this temperature so that no phase separation takes place. The temperature drop across the blanket film is important then in determining the best average operating temperature of the blanket.

Since the temperature drop across the blanket film is more critical in the case of the uranyl sulfate solutions, it may be wise to use more conservative values for the constant c of equation (20), and to establish reasonable limits on the heat transfer coefficient and temperature drop equations. The value of c as used for the D_2O blanket was that given by Brown and Marco [4] for heat transfer from the outside of a spherical surface. The value, therefore, is probably a little optimistic for the case under consideration here, which is heat being transferred from the inside surface of a spherical vessel. To establish more conservative limits on the heat transfer coefficients the following values of the constant c are used: [9]

1. For the upper limit, $c = 0.13$, (constant for a vertical plate).
2. For the lower limit, $c = 0.07$, (constant for a horizontal plate facing downward.)

Equation (20) becomes

$$\text{For the upper limit} \quad h_c = 0.13 k \left[\frac{g\beta(\Delta T)_f \rho^2 c_p}{\mu k} \right]^{1/3} \quad (25)$$

$$\text{For the lower limit:} \quad h_c = 0.07 k \left[\frac{g\beta(\Delta T)_f \rho^2 c_p}{\mu k} \right]^{1/3} \quad (26)$$

Upper and lower limits on the natural convection heat transfer coefficient equations have been estimated for blanket concentrations of 200 gm U/liter and 300 gms U/liter at operating temperature. Physical properties for these concentrations are listed in Table II.

Table II

Physical Properties of $\text{UO}_2\text{SO}_4\text{-D}_2\text{O}$ Solutions (280°C)

Concentration of Blanket, gms U/liter	200	300
Density, ρ , lbs/ft ³ [7]	71.67	80.35
Viscosity, μ , lbs/hr-ft [7]	0.363	0.460
Coefficient of thermal expansion, β , $^\circ\text{F}^{-1}$	0.000839	0.000748
Heat capacity, C_p , Btu/lb $^\circ\text{F}$ [8]	0.966	0.872
Thermal conductivity, k , Btu/hr ft $^\circ\text{F}$ (assumed same as water)	0.337	0.337
$\left[\frac{g\beta\rho^2 C_p}{\mu k} \right]$, ft ³ / $^\circ\text{F}$	14.19×10^9	11.32×10^9

Solving equations (25) and (26) for h_c

For a blanket concentration of 200 gms U/liter:

$$\text{Upper limit equation: } h_c = 106 (\Delta T)_f^{1/3} \quad (27)$$

$$\text{Lower limit equation: } h_c = 57 (\Delta T)_f^{1/3} \quad (28)$$

For a blanket concentration of 300 gms U/liter:

$$\text{Upper limit equation: } h_c = 99 (\Delta T)_f^{1/3} \quad (29)$$

$$\text{Lower limit equation: } h_c = 53 (\Delta T)_f^{1/3} \quad (30)$$

Combining equations (23) with (27), (28), (29) and (30) respectively and solving for $(\Delta T)_f$, the following limiting equations may be written for the temperature drop across the blanket film:

For a blanket concentration of 200 gms U/liter

$$\text{Lower limit for } (\Delta T)_f: \quad (\Delta T)_f = 0.030 \left[\left(\frac{q}{A} \right)_{r=R} \right]^{3/4} \quad (31)$$

$$\text{Upper limit for } (\Delta T)_f: \quad (\Delta T)_f = 0.048 \left[\left(\frac{q}{A} \right)_{r=R} \right]^{3/4} \quad (32)$$

For a blanket concentration of 300 gms U/liter

$$\text{Lower limit of } (\Delta T)_f : \quad (\Delta T)_f = 0.032 \left[\left(\frac{q}{A} \right)_{r=R} \right]^{3/4} \quad (33)$$

$$\text{Upper limit of } (\Delta T)_f : \quad (\Delta T)_f = 0.051 \left[\left(\frac{q}{A} \right)_{r=R} \right]^{3/4} \quad (34)$$

Average heat transfer coefficients and temperature drops across the blanket film may be taken as the average of values calculated from the upper and lower limit equations given for each concentration. However, in order to determine if phase separation may occur at a given power level, it is recommended that the equations predicting the higher temperature drops (equations (32) and (34) be used.

Heat Generation in Pressure Vessel Wall when $\text{UO}_2\text{SO}_4\text{-D}_2\text{O}$ Blanket is Used

The heat generation rate in the pressure vessel is dependent upon the type blanket which is employed. Values given for the heat generation constants of equations (4) and (5) are for a pure D_2O blanket and do not hold for a blanket solution containing uranyl sulfate. New heat generation constants are therefore needed to predict temperature drops across the blanket film for uranyl sulfate blankets.

Curves have been prepared by A. L. Gaines, showing the total heat production rate (at 5 Mw HRT power) versus pressure vessel thickness for a pure D_2O blanket and for a blanket containing 312.3 gms U/liter. These curves have been based upon the UNIVAC calculations of neutron flux distributions, from which primary and secondary γ -fluxes in the wall were obtained. In the case of the $\text{UO}_2\text{SO}_4\text{-D}_2\text{O}$ blanket the reactor power is divided between the core and blanket as follows:

Core	-	3.515 Mw
Blanket	-	<u>1.485 Mw</u>
Total		5.000 Mw

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The total heat production rate for the 312.3 gm U/liter blanket can be approximated by the equation

$$H(r) = H e^{-m(r-R)} \quad (35)$$

Equation (35) could better approximate actual conditions in the vessel wall by considering more exponential terms, however one term is sufficient for the present case. The constants H and m are estimated to give values at least as great as or slightly greater than the actual heat generation rates. They are

$$m = 8.388 \text{ ft}^{-1}$$

$$H = 3.06 \times 10^4 \text{ Btu/hr ft}^3 \text{ at 5 Mw total power}$$

As before, assume the heat generation rate to be directly proportional to power to give

$$H = 6.12 \times 10^3 P_o \text{ Btu/hr ft}^3$$

Using equation (35) as the heat generation term, equation (5) becomes

$$\frac{dT(r)}{dr} = \frac{H e^{-m(r-R)}}{km^3 r^2} (m^2 r^2 + 2mr + 2) + \frac{C_1}{r^2} \quad (36)$$

Equation (36) can be solved for conditions at the inside surface ($r=R$) and the outside surface ($r=b$) of the pressure vessel.

$$\left(\frac{dT}{dr}\right)_{r=R} = 32.122 P_o + 0.16 C_1 \quad (37)$$

At the outside surface:

$$\left(\frac{dT}{dr}\right)_{r=b} = 1.3674 P_o + 0.12098 C_1 \quad (38)$$

Solving for Q from equations (6), (7), (14), (37) and (38)

$$Q = 573 P_o \frac{\text{Btu}}{\text{hr. (spherical sector of 1 ft}^2 \text{ outside surface)}} \quad \dots (39)$$

The heat flux into the blanket solution from the inside surface of the pressure vessel then is

$$\left(\frac{q}{A}\right)_{r=R} = \frac{573 P_o - \left(\frac{q}{A}\right)_{r=b}}{0.756} \quad (40)$$

The heat removal rate from the outside surface and the total stress in the pressure vessel may be estimated from Figures (3) and (4). (This is true only if the general form of the temperature distribution in the vessel wall for the UO_2SO_4 - D_2O blanket can be assumed the same as that for the D_2O blanket) To do this:

1. Estimate the power level of the reactor with D_2O blanket which will give the same total heat generation in the wall as that given by the desired power level of the reactor with the UO_2SO_4 - D_2O blanket. This can be done from equations (15) and (39) to give

$$P_o(D_2O \text{ Bl.}) = \frac{573}{915} P_o(UO_2SO_4-D_2O \text{ Bl.}) = 0.626 P_o(UO_2SO_4-D_2O \text{ Bl.})$$

2. From $P_o(D_2O \text{ Bl.})$ and Figures (3) and (4), values for the outside heat removal, $\left(\frac{q}{A}\right)_{r=b}$, and tangential stress, σ_t , may be read. (The heat removal rate from the outside surface and the total tangential stress are plotted for the UO_2SO_4 - D_2O blanket solution, as dashed lines on Figures (3) and (4) respectively).

Table III gives estimated values for heat fluxes, stress, temperature drops and recommended maximum exit blanket temperatures for the HRT with UO_2SO_4 blanket solutions at several power levels.

Table III

Values for Various Total Power Levels in the HRT
with 312.3 gms U/liter in Blanket

Power Level	Heat Removal from Outside Surface	Heat Flux Into Blanket Solution from Inside Surface	Temperature Drop Across Blanket Film	Tangential Stress in Pressure Vessel	Recommended Maximum Exit Blanket Temperatures
Mw	$\left(\frac{q}{A}\right)_{r=b}, \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2}$	$\left(\frac{q}{A}\right)_{r=R}, \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2}$	$(\Delta T)_f, ^\circ\text{F}$	σ_t, psi	$^\circ\text{C}$
5	1210	2190	16	12,500	270
10	1370	5770	34	12,300	260
15	1530	9350	49	13,200	250
20	1690	12900	62	14,900	240

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Fig. 1. Temperature Profile Across Pressure Vessel Wall (For D₂O Blanket)

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Fig. 2. Maximum Tangential Total Stress in Pressure Vessel Wall vs. Heat Removal From the Outside Surface (D₂O Blanket Assumed)

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Fig. 3. Heat Removal Rate Radiated from Outside Surface of Pressure Vessel vs Power Level of HRT

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Fig. 4. Maximum Total Tangential Stress in Pressure Vessel Wall vs HRT Power Level.