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Effect of Uranium-Bearing Scale Deposits on HRE-2 Core Wall Temperature, Heat Flux and Patch Temperature

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ABSTRACT

Calculations are presented to show the effect of uranium-bearing scale deposits on the HRE-2 core wall temperature, heat flux, and the temperature of patches proposed for sealing the holes of the HRE-2 core vessel. Flow behavior in the HRE-2 core mockup with simulated patches installed and simulated corrosion pits drilled in the vessel wall was determined.

A plausible mechanism was advanced to account for hot spots due to sedimentation of solids on metal surfaces projecting from the core wall. Patch designs with reduced metal projections from the core wall are presented.

1.0 Introduction

Plans for modification of the HRE-2 core vessel include reversal of the flow direction through the core, removal of six top screens in the diffuser section and sealing two holes in the core tank wall with Zircaloy patches. The expected improvement in core wall cooling and mechanical scrubbing of the wall has been described previously[1].

This report gives the results of additional flow tests and calculations to show the effect of uranium-bearing scale deposition on the core wall temperature, heat flux and patch temperature. Flow tests were made to determine the flow behavior in the vicinity of the proposed core wall patches, the extent to which particulate solids would settle on the patches during circulation, and the extent to which mud-like solids would be removed from the patches during circulation at the HRE-2 flow rate. Calculations were made to determine (1) the patch temperatures for 5 MW, two-region reactor operation with no uranium-bearing scale deposition, (2) core wall temperature and heat flux for uniform deposition of uranium-bearing scale on the core wall, and (3) the effect of local deposits of uranium-bearing scale in core wall pits, and on projections and crevices around the core wall patches.

2.0 Core Flow Tests

Tests were performed to determine the flow conditions around the hole patch located 15° below the equator of the HRE-2 core. In addition, tests were performed to determine the extent to which particulate material (sand) would settle on the patches during circulation, and the extent to which mudlike material (East Tennessee red clay) would be removed from the patches by circulation.

The tests showed no tendency for particulate material to accumulate around the patches. However, the mudlike material was not completely removed from any of four patches tested even after 2 hours of circulation at 450 gpm. Figure 1 shows diagrams of the mud left around the patches at the completion of the tests. The different types of accumulation, and the lack of reproducibility, suggest that a flush mounted patch is highly desirable.

To test for accumulation in core wall pits, 60 simulated pits varying from 1/16-in. to 1/4-in. in diameter were drilled in the core wall, spaced 30° apart in horizontal angle and at five elevations from the intersection of the 90° cone and the sphere up to 30° north of the equator. Sand was placed in the holes, and after 3 hours of water circulation the pits were examined for sand. There was a small amount of sand piled up at the bottom of each of the pits.

During the course of these tests, some asymmetrical flow behavior was observed in the northern hemisphere of the vessel even after all efforts had been made to square the core vessel and inlet nozzle.

The result of this flow asymmetry, if it should occur in HRE-2, would be to raise the maximum fluid temperature in the vicinity of the

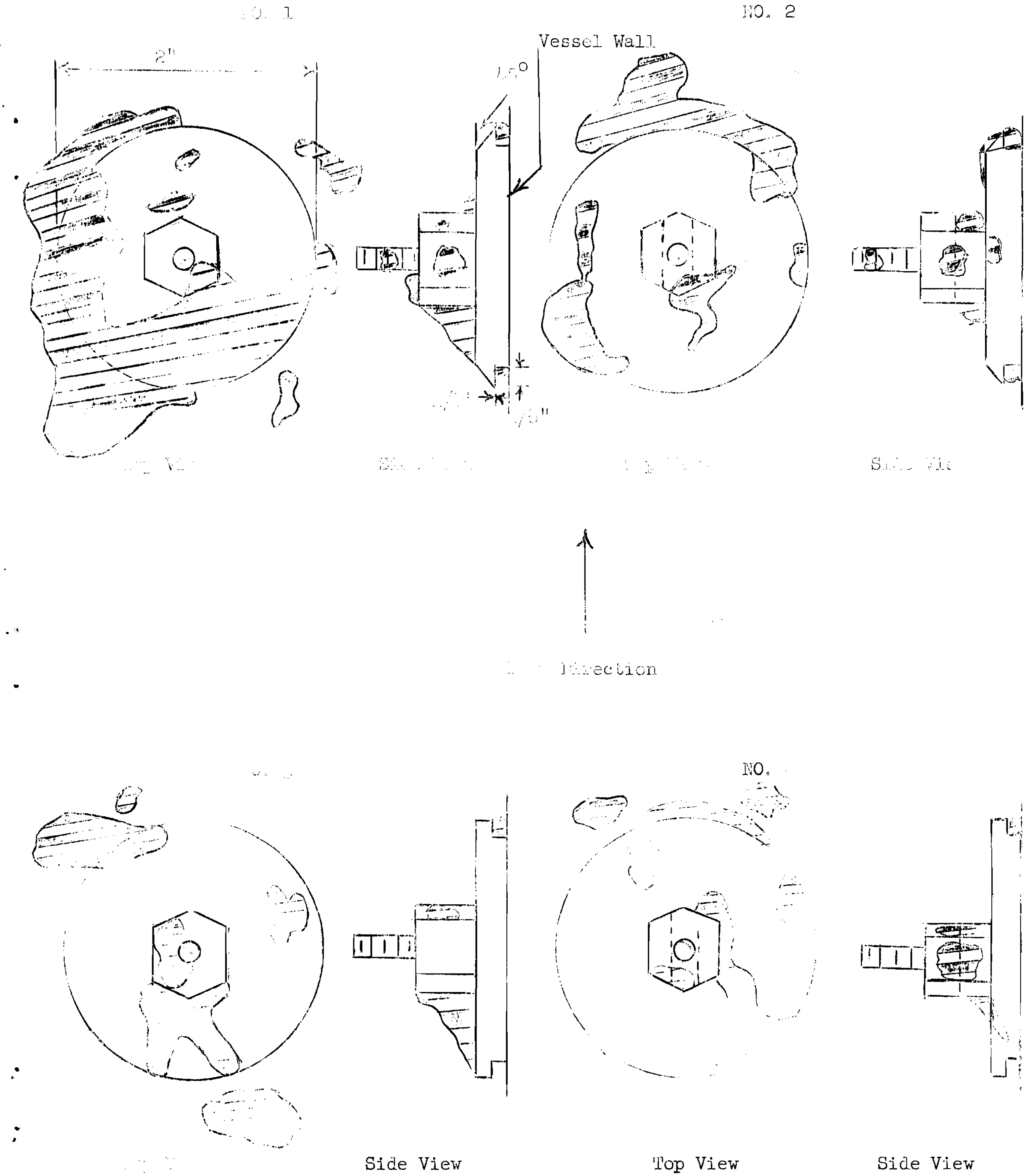

FIGURE 1
[illegible] Simulated Patch [illegible]
[illegible]

Mud

wall to about 574°F (301°C) rather than to the 570°F (299°C) reported previously[1]. The maximum wall temperature would be 300°C with the blanket at 250°C and with no scale deposition on the core wall.

The effect of minor perturbations of asymmetrical geometry on this flow situation will be studied further.

3.0 Core Patch Temperature in Absence of Uranium-Bearing Scale Deposits

It is proposed to seal the two holes in the HRE-2 core tank with Zircaloy patches or plugs. Figure 2 shows a design which involves holding a patch to the core wall by means of a toggle bolt[2]. An annealed gold gasket compressed by bolt tension provides a seal at the core wall. A conical seat in the patch allows the bolt head to provide a seal around the bolt. Means for remotely installing this type patch have been developed.

Figure 3 illustrates an alternate design which reduces the extent of metal projections into the core. In this design the plug is seated on the core wall without a gasket. The bolt head is cemented or soldered to the Zircaloy bolt, and can be removed after the patch is installed.* Tools for reaming the hole, installing the flush patch and removing the bolt head have not been tested.

The flush patch design (Figure 3) is more suited for sealing the upper hole in the HRE-2 core tank; primarily because this hole is of reasonably regular shape and is in a surface of simple curvature. These factors indicate a high probability of success in reaming the existing hole to a known shape and size which is required for proper installation of the flush patch. In the case of the lower hole in the HRE-2 core, the gasketed patch is better suited for proper installation because of the compound curvature of the surface at this location, the variable wall thickness near the hole, and the irregular shape of the hole.

Gamma heat generated in the patches will be transferred to the core and blanket fluids. The temperature attained in and around the patches will depend on the local core and blanket fluid heat transfer coefficients, and fluid temperatures. Following are results of calculations of the patch temperature for various cooling effects for no uranium-bearing scale deposits on or around the patches.

If the HRE-2 core is descaled, the core wall patches should be free of uranium-bearing scale during the initial operation of the reactor after modification. Under these conditions, no excessive temperatures will be attained in and around the patches at a reactor power of 5 MW. As indicated in a previous section, the fuel temperature in contact with the upper patch will be about 572°F (300°C), moving at a velocity of approximately 2 ft/sec, and a heat transfer coefficient of at least 1000 Btu/hr ft^2 $^\circ$F will be applicable. The rates of heat removal from the lower patch should be greater than the upper one as the fuel temperature will be perhaps 10 to 20°F lower, and the average heat transfer coefficient for the patch surface will be higher owing to a higher fuel velocity across the patch. The lower patch is in the impingement zone of the entering jet.

*Two methods for removing the bolt head after installation are being considered by E. C. Hise, Engineering Development Section; (1) shearing the cement bond between bolt head and bolt, after the cement is weakened by heating in boiling water for 24 hrs; (2) dissolution of carbon steel bolt head in dilute nitric acid.

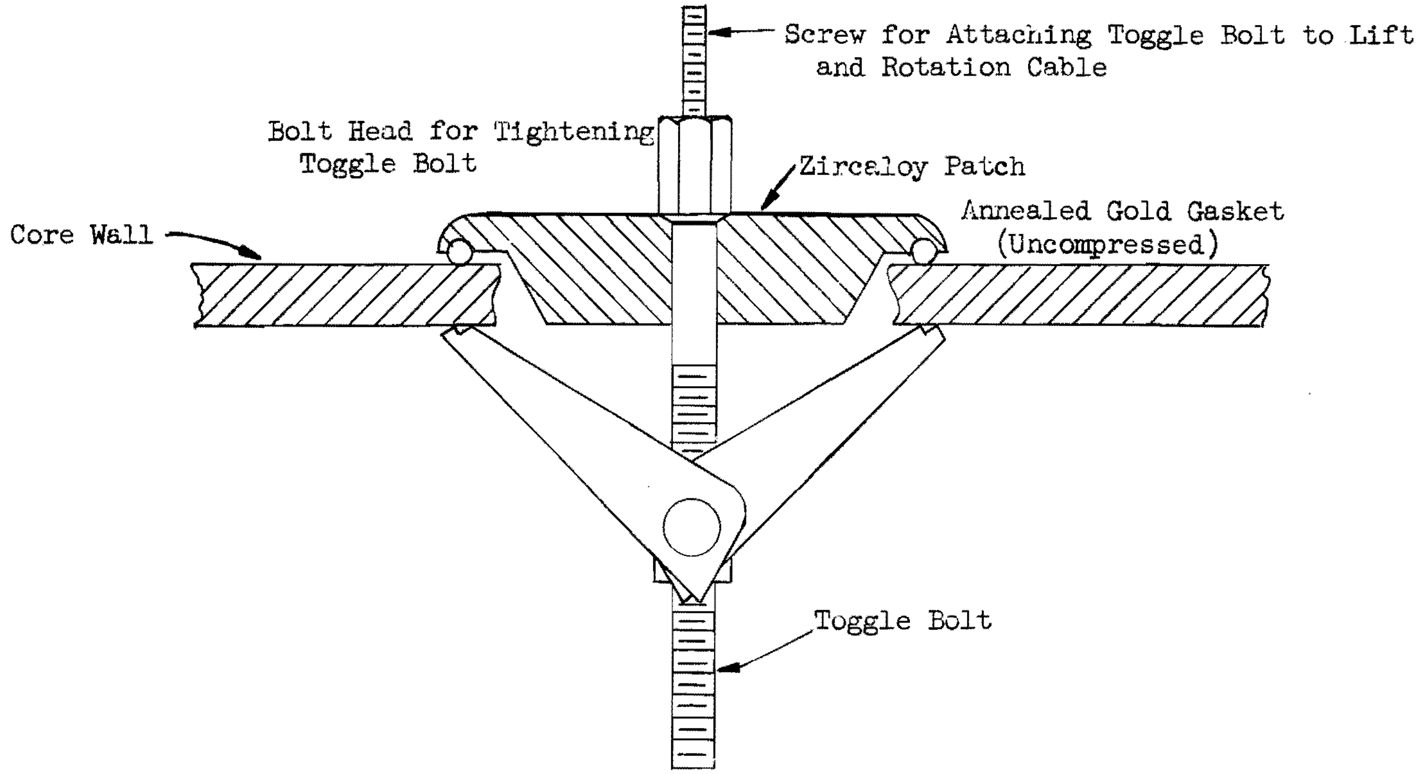

Figure 2

Zircaloy Patch with Gold Gasket for Seal

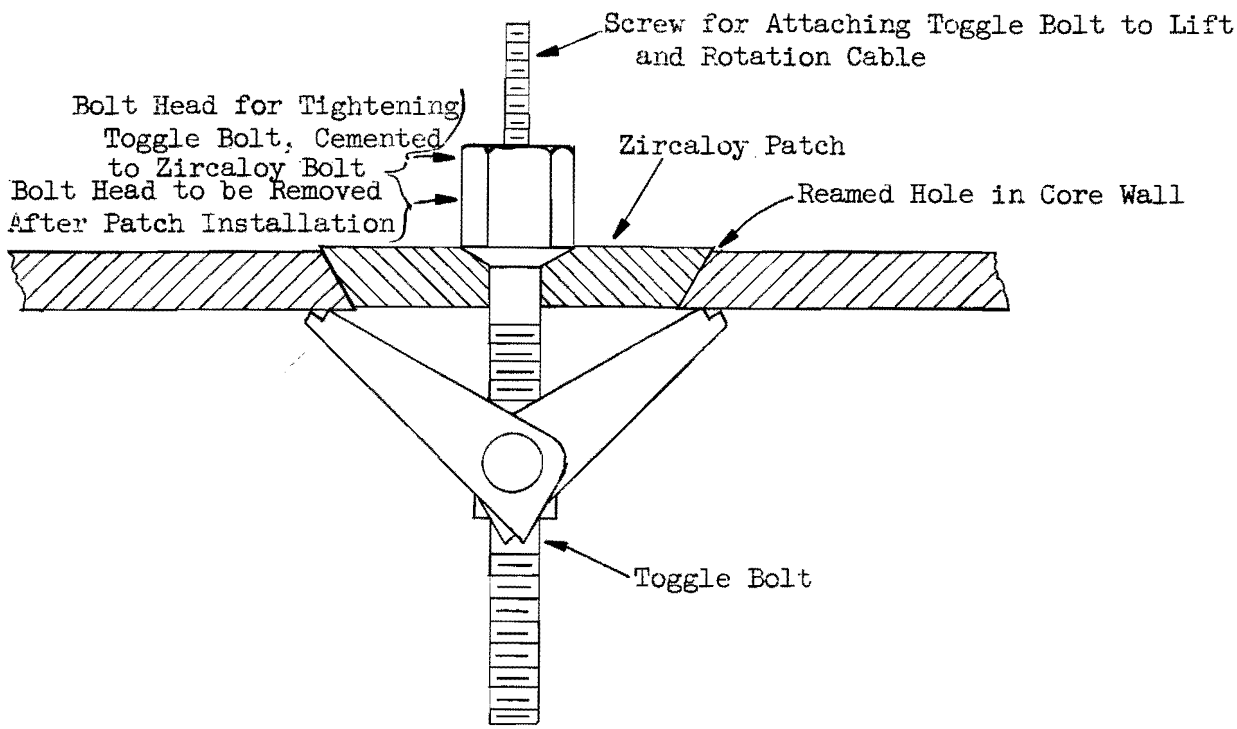

Figure 3

Zircaloy Patch with Core Wall Hole Reamed to Form Patch Seat

Table I gives calculated patch temperatures for the two designs shown in Figures 2 and 3. The temperatures were calculated on the basis of an infinite slab of Zircaloy with 3 watts/cc gamma heat generated in the metal. Results are presented for the case of blanket cooling due to blanket fluid at 482°F (250°C) with an average heat transfer coefficient of 600 Btu/hr ft^2 °F, and for the case of no blanket cooling. Appendix A gives a summary of the heat transfer relationships used in the calculations.

For both patch designs and with the blanket fluid at 482°F, all the heat generated in the patches and some heat from the fuel is transferred to the blanket fluid. The average patch surface temperature on the core side was calculated to be 574°F (301°C) and 568°F (298°C) for the core projection and flush patch designs, respectively. Even with no cooling on the blanket side, the core side patch temperature was calculated to be no greater than 592°F (311°C) and 586°F (307°C) for the two designs.

For the patch design involving a bolt head projecting into core fluid, the bolt head surface temperature was calculated by assuming a slab thickness equal to that of the patch plus the bolt head. This value is an upper limit, and the actual temperature will be lower than this temperature because of cooling on the cylindrical surface of the bolt head. The maximum metal temperature was calculated on the basis of the patch plus bolt head thickness. With blanket cooling the maximum temperature of 607°F (319°C) occurs near the base of the bolt head; and with no blanket cooling, the maximum temperature of 803°F (429°C) occurs on the blanket-side patch surface. For the flush patch design, there will be no bolt head to add extra metal to the patch thickness, and the bolt head and maximum metal temperatures are identical to the patch surface temperatures.

4.0 Effect of Uniformly Deposited Uranium-Bearing Corrosion Scale on Core Wall Temperature and Core Wall Heat Flux

Calculations were made to estimate the temperature of the core wall as a function of deposited zirconium scale which contains uranium. The primary assumptions are that there is no lateral conduction of heat and that the power density in the scale uranium expressed as Kw/gm U^{235} is the same as it is in the fuel solution next to the wall at 5 MW, about 1.67 Kw/gm U^{235}. The gamma heat generation in the scale is not considered and wall gamma heating is fixed at 3 watts/cc. It is assumed boiling starts at the liquid saturation temperature. Appendix A includes a summary of the heat transfer equations used in these calculations.

The results of these calculations are shown in Figures 4, 5 and 6 as the metal-scale interface temperature versus the mils of zirconium corroded. The results for a film having a ratio of 0.1 for gm U/gm Zr are shown in Figure 4. The upper curve is for the case where the system is pressurized so boiling does not occur; the middle curve has the blanket pressurized and the core at 1500 psia, and the lower curve is for the case where the blanket and core are at 1500 psia. It is seen that at 1500 psia boiling begins on the core side when the scale thickness corresponds to the corrosion of 6 mils of Zircaloy. The interface temperature is 620°F (326°C), about 24°F above the saturation temperature, and is very close to the second liquid phase formation temperature for HRE-2 solutions. As thicker scales are developed, the core wall

Table I

Estimated Zircaloy Patch Temperatures for HRE-2 Operating at 5 Mw, Two-Region Reactor (No Uranium-Bearing Scale on Patch Surface)

Patch Type	t_{PC} Avg. Patch Surface Temperature Core Side-°F		t_{PB} Avg. Patch Surface Temperature Blanket Side-°F		Maximum Metal Temperature-°F		Surface Temp. Core Side-°F		q'_C Average Core Side Flux-Btu/hr-ft²-°F		q'_B Average Blanket Side Heat Flux-Btu/hr-ft²-°F	
	(a)[3]	(b)[4]	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Core Projection[1] (Fig. 2)	574	592	511	641	607	803	592	607	-2200	+15,100	+17,300	0
Flush[2] (Fig. 3)	568	586	513	604	568	604	568	586	-9000	+ 9060	+18,060	0

[1]Equivalent slab thickness 5/8-in.

[2]Equivalent slab thickness 3/8-in.

[3]Blanket at 482°F (250°C), heat transfer coefficient - 600 Btu/hr-ft²-°F.

[4]No blanket cooling.

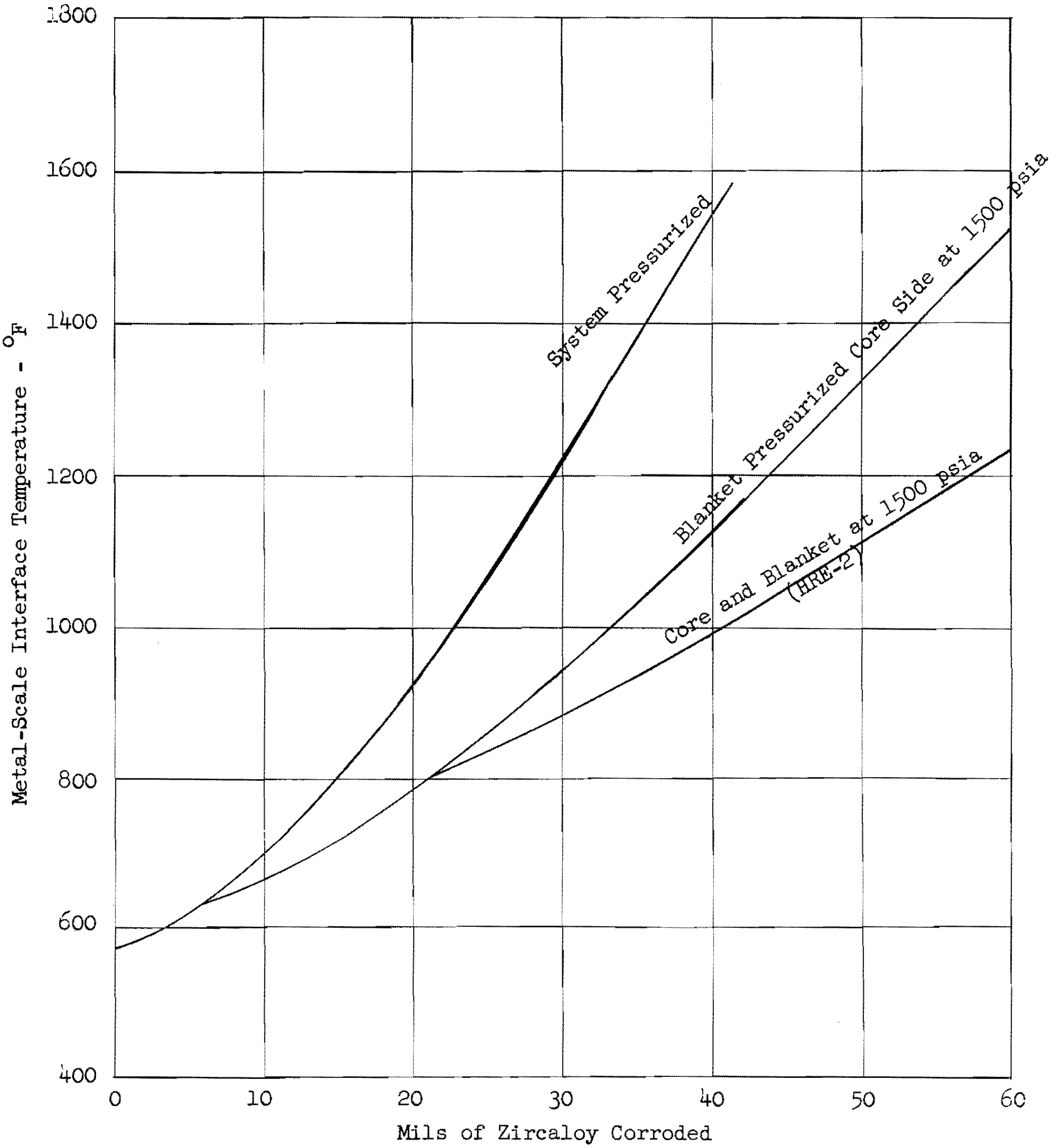

Figure 4

Metal-Scale Interface Temperature vs. Mils of Zircaloy Corroded.
Uranium Concentration, 0.1 g U/g Zr.

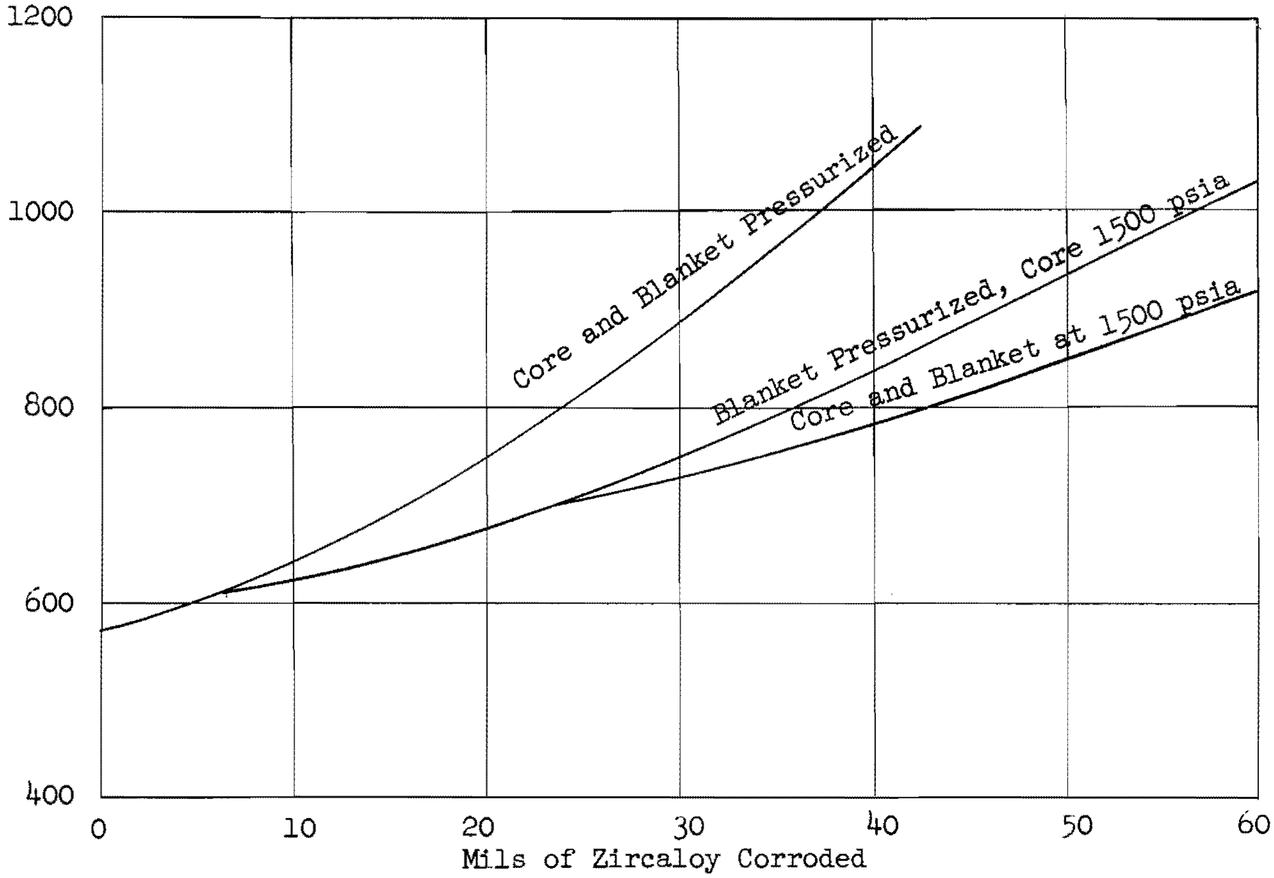

Figure 5

Metal-Scale Interface Temperature vs. Mils of Zircaloy Corroded.
Uranium Concentration, 0.05 g U/g Zr.

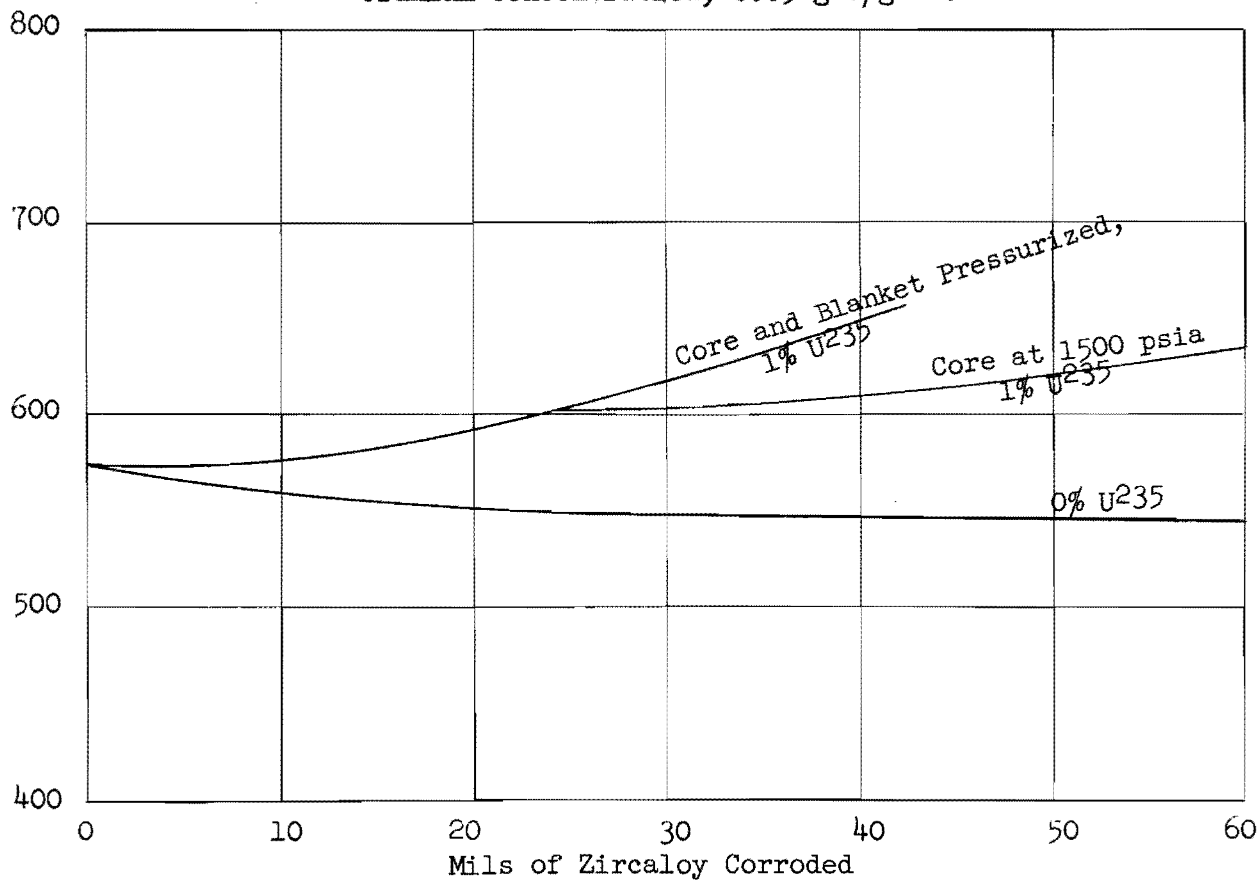

Figure 6

Metal-Scale Interface Temperature vs. Mils of Zircaloy Corroded.

temperature continues to climb until the blanket starts to boil when the scale thickness corresponds to the corrosion of about 20 mils of Zircaloy. The core wall temperature continues to climb, although at a lesser rate, with continued scale deposition. When the scale is the equivalent of 60 mils Zircaloy, the core wall temperature is at 1220°F. The actual scale thickness under these conditions is calculated to be 110 mils thick and has a concentration of 407 mg uranium/cc or 113 mg uranium/cm^2.

Figure 5 is a plot of the core wall temperature versus Zircaloy corroded for a uranium to Zircaloy weight ratio of 0.05. (This curve may also be considered as the temperatures of the core wall for the same scale as in Figure 4 but with the reactor at 2.5 Mw operation since the gamma heating in the core wall does not represent a great contribution to the heating.) Boiling begins when the core wall temperature is at 610°F and when the scale is equivalent to about 7 mils of Zircaloy. When the scale is about 25 mils thick, boiling begins on the blanket side. A 60 mil tightly adhering scale results in a core wall temperature of 910°F when the system is at 1500 psia.

Figure 6 shows the metal-scale interface temperature when the weight ratio of uranium to Zircaloy is 0.01 and zero. With a 1% scale, boiling occurs on the core side at a scale equivalent of 25 mils if Zircaloy corroded and the blanket does not boil even for a 60 mil thick scale.

The uranium-free scale acts as an insulator and actually helps in attaining a lower metal wall temperature.

Figure 7 gives the temperature of the scale-solution interface at which sustained boiling is established as a function of system pressure. This temperature is about 3.5°F above the saturation temperature of the liquid (ignoring effect of dissolved gas). Based on the Jens-Lottes nucleate boiling correlation[3], the temperature of the scale-solution interface increases as the one-fourth power of the heat flux. The surface temperature in excess of the saturation temperature will not exceed 10°F unless the core side heat flux rises above 10^6 Btu/hr-ft^2.

It is evident from these graphs that barring large amounts of deposition, the solution-scale interface temperature may be controlled by limiting the system pressure. The temperature within any scale present in the core will be controlled by the size or thickness of the scale and by the uranium concentration within the scale.

The boiling heat flux on the core side is plotted in Figure 8 for the case when both sides of the core wall are boiling. The peak boiling heat flux for the HRE-2 revised core flow is estimated to range from 0.45×10^6 to 1.7×10^6 Btu/ft^2-hr depending upon the correlation used (see Appendix B). The scales considered in these calculations do not produce a heat flux greater than 0.375×10^6 Btu/ft^2-hr. However, the factors which limit the uranium content of the deposited scales have not been clearly elucidated, and there exists the possibility that scale deposition is autocatalytic and leads to scales containing more than 10% uranium. If scales of the magnitude considered in the present calculations and containing significantly higher than 10% uranium, there exists the high probability that the core side heat flux can exceed the peak values.

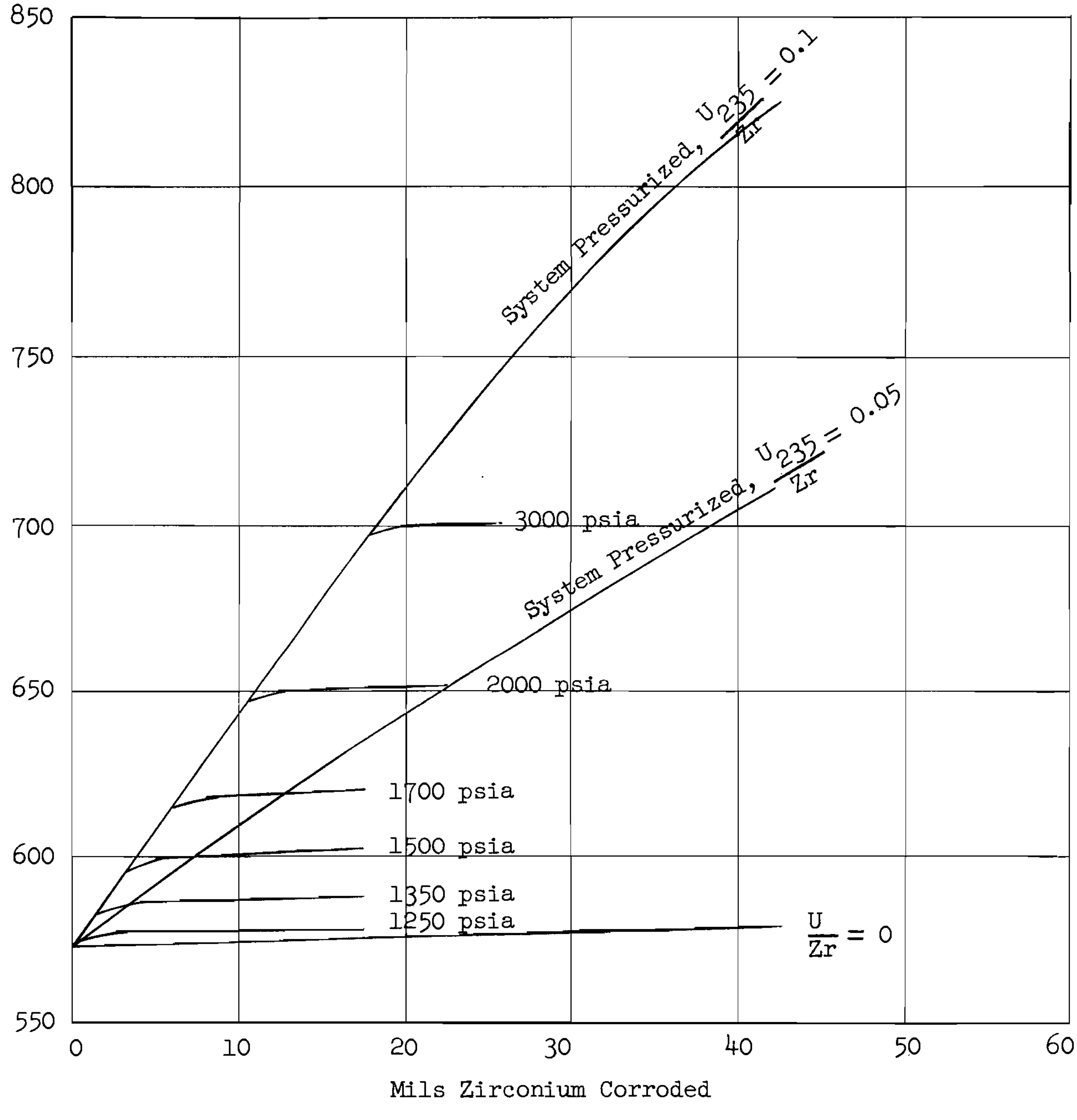

Figure 7

Solution-Scale Interface Temperature as a Function of Mils Zr Corroded and of System Pressure

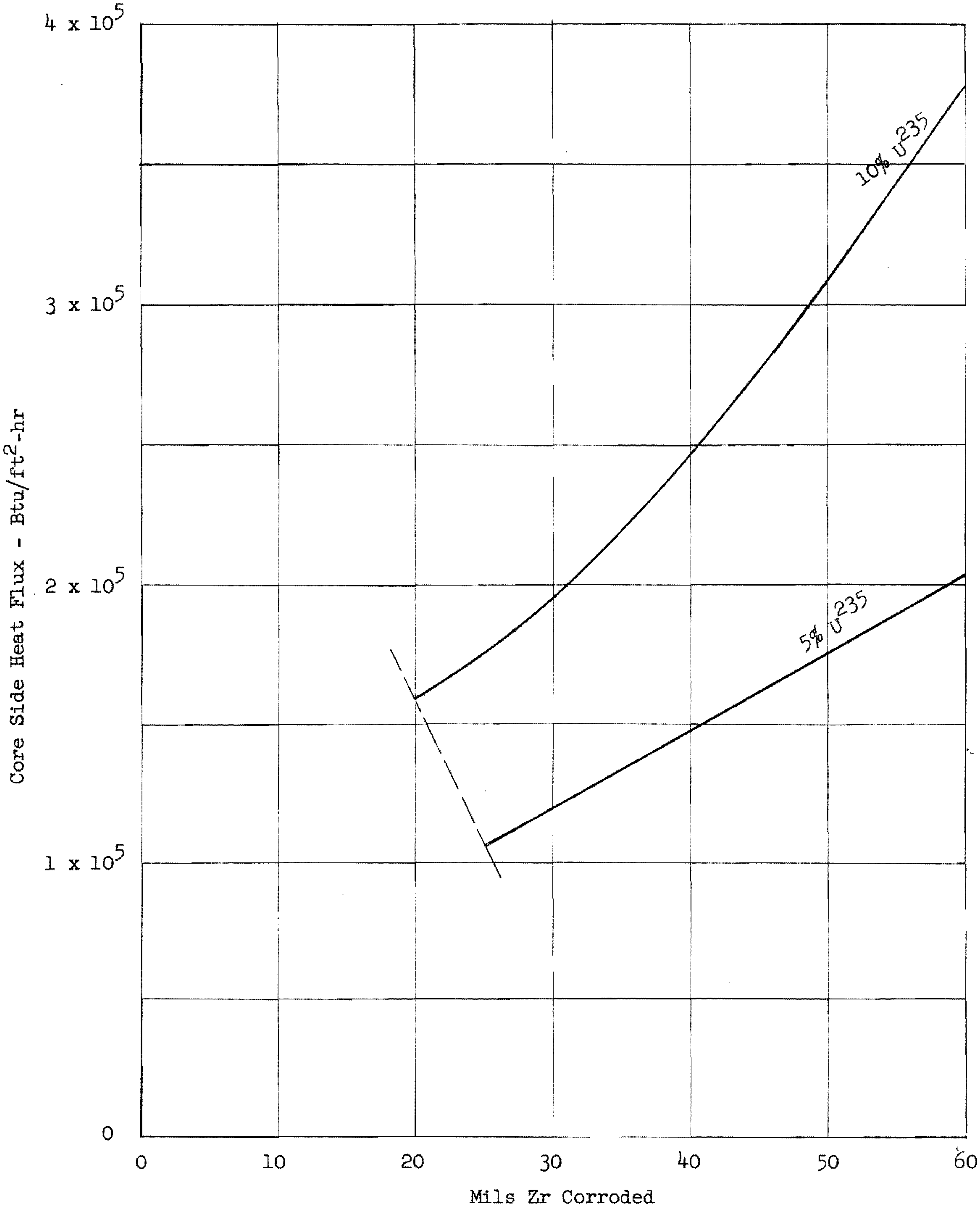

Figure 8

Core Side Boiling Heat Flux vs. Zr Corroded with U^{235} Adsorbed in Zr Scale

5.0 Possible Influence of Sedimented Solids and System Pressure Upon the Formation of Loosened Screens and Vented Core Vessels

Photographs made during forward flow tests of the full geometric scale model of the HRE-2 have shown that gross deposits of solids greater than about 0.5 mm (0.0016 ft) and smaller than the diameter of the holes in the diffuser plates (0.0313 ft) may settle on the walls in the southern hemisphere of the core vessel if these solids have a specific gravity of about 3 gms/cc and if they are permitted to circulate in the high pressure system. These wall regions are highly susceptible to flow reversals because of the large diffusion angle. In addition, the bulk velocity of the fluid in the central region of the cones where there is no separation is low enough so that the separated fluid has almost no velocity at all. As a consequence, the solids deposited will be cooled almost entirely by natural convection. The natural convection forces act against the reversed fluid slowing it down even further.

If the particle surface reaches the saturation temperature, water will be evaporated. When the system pressure is high enough, the second liquid phase forms initially[4], and then solids precipitate from the solution when the second phase temperature is 20° to 30°C above the light phase temperatures. Thus the solution may leave its uranium behind within the solid. This process would be enhanced once the second phase forms due to its higher consistency and preferred wetting properties on oxide surfaces[5].

When the system pressure is low enough to prevent the formation of second liquid phase the concentrated solution always remains on the surface of the particle since its vapor pressure is substantially the same as the bulk solution. Further, the concentrated solution always has the same ratio of uranium to total acid thereby making the solution more stable as the concentration increases. Hence, it would be more difficult to form solids without evaporating all of the water from the solution when the system pressure does not permit the formation of a heavy liquid phase.

Calculations were made to determine the temperature rise of the solid particle surface based on natural convection cooling coefficients[6] and the heat generation within the particle according to the equation.

$$\left(\frac{\Delta T}{D_o}\right)^{1.25} = \frac{E_s}{3.18\left[\frac{\rho_L{}^2\, B_L\, g}{\mu_L{}^2}\left(\frac{C\mu}{k}\right)_L\right]^{0.25}}$$

where

ΔT	Temperature of surface above liquid temperature
ρ_L	Density of liquid
D_o	Diameter of particle
μ_L	Viscosity of liquid
B_L	Coefficient of expansion of liquid
g	Gravitational acceleration

$\left(\frac{C\,\mu}{k}\right)_L$ Prandtl number of liquid

E_s Heat generation rate in solid particle

The results of these calculations are shown in Figure 9 as the temperature rise of the surface above ambient fluid as a function of uranium concentration in the solid and particle diameter. The calculations are made for the reactor power level at 2.5 Mw where the instabilities are pronounced at high pressures, assuming the particles are located near the core wall. If the ambient fluid is at 500°F (260°C), an additional 96°F will bring the particles to boiling with the system pressure at 1500 psia. This temperature will be attained by a particle containing 450 mg U^{235}/cc and having a diameter of 0.014 ft (4.3 mm). An agglomerate of particles will arrive at boiling condition at either a lower uranium concentration or a lower power density. The calculations confirm the plausibility of the stated mechanism. Once deposition occurs, the heat flux will increase,further deposition will occur and the surface temperature becomes hotter until a screen ligament is melted out, a pit is formed, or a hole is produced.

The above discussion may be considered a supplement to the comments of R. N. Lyon and C. S. Morgan[7], and McDuffie and Marshall[4]. The additional factors discussed here are that (1) Accumulation of large sedimented particles in regions of flow separation and low velocity will be cooled by natural convection at best. (2) These particles and accumulations will be larger than those supported in the flow near the wall and the temperature difference from particle (or agglomerate) surface to bulk fluid will be sufficient to cause boiling.

The type of events postulated above for sedimented particles can also occur in loose scales covering the core vessel.

6.0 Effect of Local Deposits of Uranium-Bearing Scale on Core Wall Temperature and Patch Temperature

In the previous section a mechanism was described whereby flow separation in the vicinity of abrupt projections or recessions in the core wall would possibly support solids, and autocatalytically bring about increased uranium deposition at these locations. The HRE-2 core wall possibly contains pits which could serve as such local deposition sites.

Table II shows the calculated metal wall temperature and core side heat flux for wall pits of various depths filled with scale containing 10 to 20% uranium having a density of 3.5 g/cc. Boiling at 1500 psia on the core and blanket sides of the scale-filled pit was assumed. Infinite slab heat conduction relationships were used in the calculations. The actual metal temperature would be somewhat lower than that calculated owing to lateral conduction. (See Appendix B for a summary of the equations used in the calculation.)

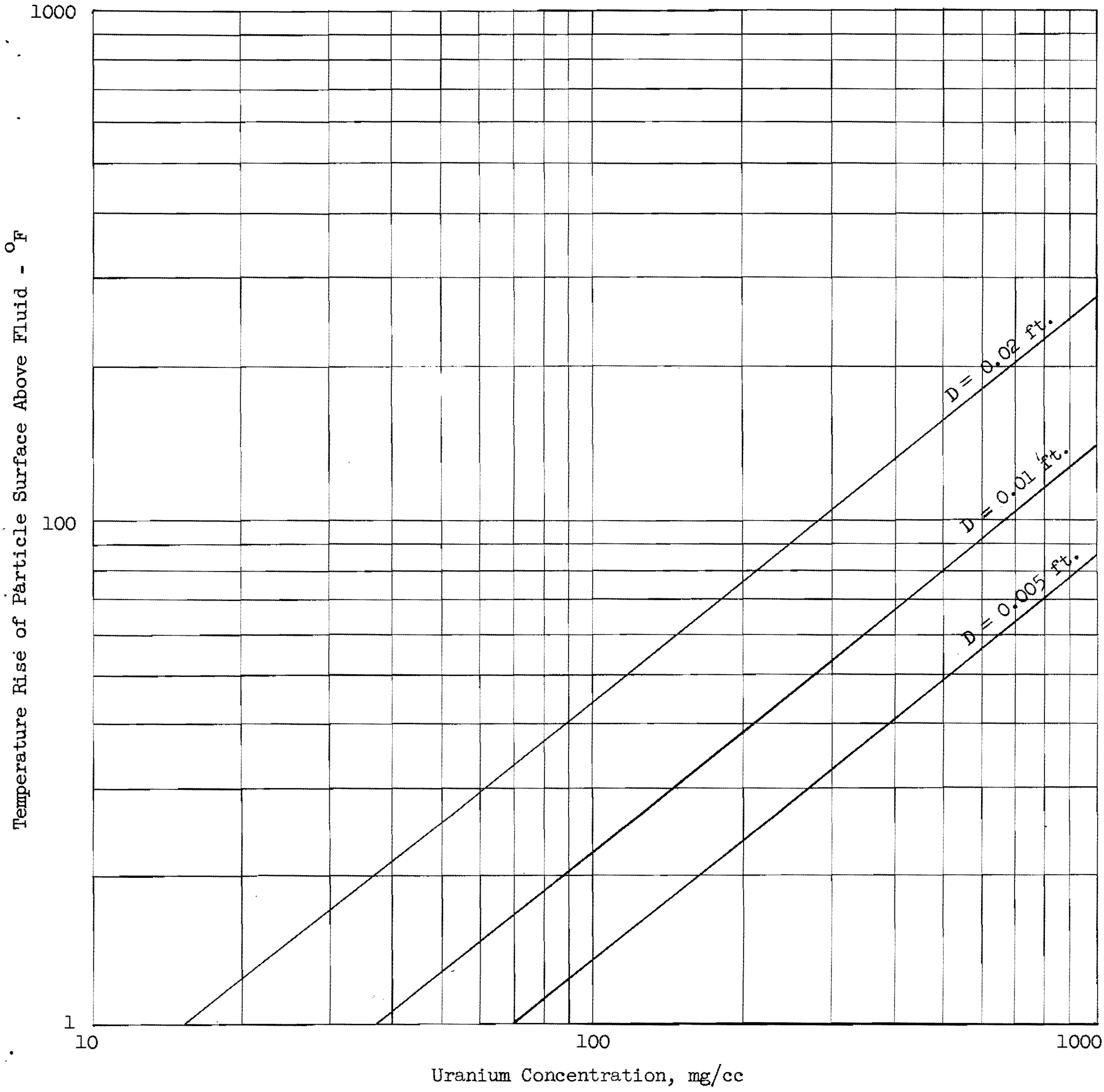

Figure 9

Temperature Rise of Particle Surface Above Ambient Liquid With Natural Convection Cooling, 2.5 Mw Power, No Boiling

Table II

Estimated Metal Temperature for Uranium-Bearing Scale-Filled Pits in HRE-2 Core Wall

Pit Depth in.	Metal Wall Thickness in.	Metal Temp. °F (10% U)	Metal Temp. °F (20% U)	Scale Surface Temp. °F (10% U)	Scale Surface Temp. °F (20% U)	Core Wall Heat Flux Btu/hr ft² (10% U)	Core Wall Heat Flux Btu/hr ft² (20% U)
1/32	9/32	697	802	603	604	113,800	225,800
1/16	1/4	865	1129	604	605	196,000	386,000
1/8	3/16	1080	1562	605	607	340,000	674,000
1/4	1/16	960	1331	606	608	602,000	1,200,000

Although the calculated metal temperatures for pits filled with 10 or 20% uranium scale do not rise to the melting temperature, and the core side heat flux is not greater than the peak nucleate boiling heat flux (0.45 to $1.7 \cdot 10^6$ Btu/hr ft^2) it is quite possible that the wall pits could lead to further damage to the HRE-2 core. To cause direct melting, though, scales containing greater than 20% uranium will be required.

The two designs for a patch to be installed in the two holes of the HRE-2 core tank involve ledges and crevices which would be susceptible for buildup or deposition of scale. Likely places for such deposition around the patch are the recess around the base of the bolt head, the recess between the patch lip and the core tank wall in the core-projection design, and the ledge or recess which will be created by not achieving exactly flush seating in the flush-patch design. As in the case of the wall pits, significant overheating of the patch can occur if uranium-bearing scale is deposited in these locations.

Estimated maximum thickness of scale which could form in crevices and on projections at the patch locations are:

1. Core projection patch
   Bolt head crevice, 1/64-in.
   Gasket recess, 1/32-in. to 1/16-in.

2. Flush patch
   Bolt head crevice, 1/64-in.
   Gasket recess, 1/32-in. to 1/16-in.

Calculations were made to determine the fuel-scale and scale-metal interface temperatures for scale containing 10 and 20% uranium by weight having a density of 3.5 g/cc. It was assumed that the fuel in contact with the scale and the blanket fluid opposite the scale were boiling at 1500 psia (596°F). These calculations were also based on infinite slabs of material having thicknesses of the local deposit, hence the actual metal temperatures will be less than the calculated values because of lateral conduction from the local deposit. Table III gives the calculated temperatures for scale thicknesses which cover the range of interest. Include also are calculations for a 1/8-in. thick scale to show the effect of a deposit which is thicker than those expected.

Table III

Estimated Zircaloy Patch Temperatures for HRE-2 Operating at 5 Mw, Two-Region Reactor With Local Deposits Containing 10 and 20% Uranium

Patch Type	Scale Location	Metal Thickness in.	Scale Thickness in.	Metal Temp., °F (10% U)	Metal Temp., °F (20% U)	Scale Surface Temp., °F (10% U)	Scale Surface Temp., °F (20% U)	Core Side Heat Flux Btu/hr-ft^2 (10% U)	Core Side Heat Flux Btu/hr-ft^2 (20% U)
Core Projection (Fig. 2)	Bolt Head Crevice	5/8	1/64	644	684	602	603	73,400	140,000
Core Projection (Fig. 2)	Gasket Recess	5/16	1/32	702	803	603	604	118,000	232,000
Core Projection (Fig. 2)	Gasket Recess	5/16	1/16	898	1192	604	605	205,000	402,000
Core Projection (Fig. 2)	Gasket Recess	5/16	1/8	1335	2058	605	607	367,000	726,000
Flush (Fig. 3)	Bolt Head Crevice	5/16	1/64	634	668	602	603	65,500	128,000
Flush (Fig. 3)	Patch Ledge (or Recess)	5/16	1/32	702	803	603	604	118,000	232,000
Flush (Fig. 3)	Patch Ledge (or Recess)	5/16	1/16	898	1192	604	605	205,000	402,000

The scale surface temperature was calculated to be only a few degrees in excess of the saturation temperature (602 to 607°F). The core side heat flux from the thickest scale considered likely to deposit (1/16-in.) was approximately 4×10^5 Btu/hr-ft^2, which is below the expected peak nucleate heat flux for the HRE-2 conditions. Failure of the patches, either the flush- or core-projection type, by direct melting is not indicated for scales containing less than 20% uranium.

The results for a 1/8-in. thick deposit show the high metal temperature (1335 to 2058°F) and core wall heat flux (0.367 to 0.726×10^6 Btu/hr-ft^2) which can be realized for this condition.

7.0 Conclusions

Following are conclusions based on the flow tests and calculations described in the present report:

1. There was a negligible tendency for accumulation of particulate solids on a simulated HRE-2 core patch. Mudlike deposits were not readily removed from the simulated patch at a water flow of 450 gpm. The maximum fuel temperature in the revised HRE-2 core was calculated to be 574°F (301°C) at 5 Mw, two-region reactor operation.

2. In the absence of uranium-bearing scale deposits on the core wall patch, the temperature of the patch surface on the core side was calculated to be no greater than 574°F (301°C) for the blanket at 482°F (250°C), and 592°F (311°C) with no cooling on the blanket side. The core side heat flux from the patch surface will be no greater than approximately 15,000 Btu/hr-ft^2. Because the lower patch is in the impingement zone of the entering jet, this patch will be cooled better than the upper one.

3. Calculations showed that a uniform deposit of scale containing 10% (wt) uranium corresponding to corrosion of up to 60 mils of Zircaloy will produce metal temperatures no greater than 1500°F if nucleate boiling occurs on the core side at 1500 psia. The resulting core side heat flux is less than the expected peak nucleate heat flux for the HRE-2 operating conditions.

4. Another statement is presented which explains possible influences of sedimented solids and system pressure on the formation of hot spots on the wall and screens of the HRE-2 core vessel. Because these hot spots are most likely to occur in regions of flow separation and on horizontal surfaces where solids can be supported, it is recommended that a flush patch be installed to seal the upper hole in the HRE-2 core vessel. A gasketed patch with a minimum of surfaces projecting into the core is recommended for installation at the lower hole of the reactor.

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CGL:FNP:job

Appendix A

Peak Nucleate Heat Flux for HRE-2 and Revised HRE-2

When estimating the core wall temperature of the HRE-2 with scale deposits, it may be necessary to know the boiling heat flux at which the transition from nucleate to film boiling occurs. This transition occurs at the "peak flux." At a higher flux, the wall temperature rises disproportionately and usually exceeds the melting point of the material constituting the heat transfer surface[8].

Empirical and theoretical relationships permit the evaluation of the peak flux for pool boiling and for forced convection in channels less than 1 in. thick. Neither of these cases applies directly to the HRE-2 core, but estimates are made in an attempt to evaluate the peak flux at the condition of highest ambient wall temperature for the HRE-2 core.

The pool boiling estimates are based on the theoretical work of Zuber and Tribus[9] and upon the work of Addoms[10]. The Zuber-Tribus correlation is

$$\phi_p = 0.16\, L\, \rho_v \left[\sigma\, g g_c\, \frac{\rho_L - \rho_v}{\rho_v^2} \right]^{0.25} \left[\frac{\rho_L}{\rho_L + \rho_v} \right]^{0.5} \qquad (1)$$

where

L	Latent heat of vaporization at saturation pressure
ρ_v	Density of the vapor
ρ_L	Density of the liquid
σ	The surface tension of the liquid-vapor interface
g	Gravitational field acceleration
g_c	Force-mass conversion factor
ϕ_p	Peak flux for pool boiling.

For water at 1500 psi and fluid temperature of 304°C, the value of ϕ_p is 1.6×10^6 Btu/ft^2-hr.

The empirical correlation of Addoms is:

$$\phi_p = L\, \rho_v \left[g \left(\frac{k}{\rho c}\right)_L \right]^{1/3} f\left(\frac{\rho_L - \rho_v}{\rho_v}\right) \qquad (2)$$

where $f\left(\frac{\rho_L - \rho_v}{\rho_v}\right)$ is an empirical function

and $\left(\frac{k}{\rho c}\right)_L$ is the molecular thermal diffusivity of the liquid.

The value for ϕ_p according to the Addoms correlation is 1.8 x 10^6 Btu/ft^2-hr.

The two calculations for the peak flux in pool boiling agree essentially, as shown in Fig. A-1.

The empirical relationships used to evaluate the forced convection peak flux are those of Jens and Lottes[3] and of Zenkevich[11]. According to Jens and Lottes, at a pressure of 1500 psia,

$$\phi_p = 0.62 \left[\frac{G}{10^6}\right]^{0.385} \left[T_{sat} - T_L\right]^{0.22} \qquad (3)$$

G = Mass velocity in lbm/ft^2-hr

$T_{sat}-T_L$ = ^oF temperature difference between bulk fluid and saturation.

ϕ_p = Peak heat flux $\frac{BTU}{ft^2\text{-hr}}$

At fluid velocities below 5 ft/sec, the above equation is an extrapolation.

A second estimate of the peak flux is based on the most recent and complete work of Zenkevich. The empirical equation for the peak nucleate boiling flux is

$$\phi_p = 396 \left[T_{sat} - T_L\right]^{0.33} \left[\frac{\rho_L - \rho_v}{\rho_L}\right]^{1.8} \left[G\right]^{0.5} \qquad (4)$$

Equation (4) is applicable from velocities of 1 ft/sec (at 1500 psia) and $T_{sat}-T_L > 18^oF$.

Equations 3 and 4 are plotted in Figure A-1 as ϕ_p versus velocity for 1500 psia and 304^oC liquid temperature and are compared with the pool boiling values of Equations 1 and 2. From these curves, it is estimated that the value of the peak flux at the hottest fluid region of the revised HRE-2 flow is between 0.5 and 1.7 x 10^6 Btu/ft^2-hr. For the HRE-2 with screens burned, the peak flux near the equator may have been as low as 2 x 10^5 Btu/ft^2-hr.

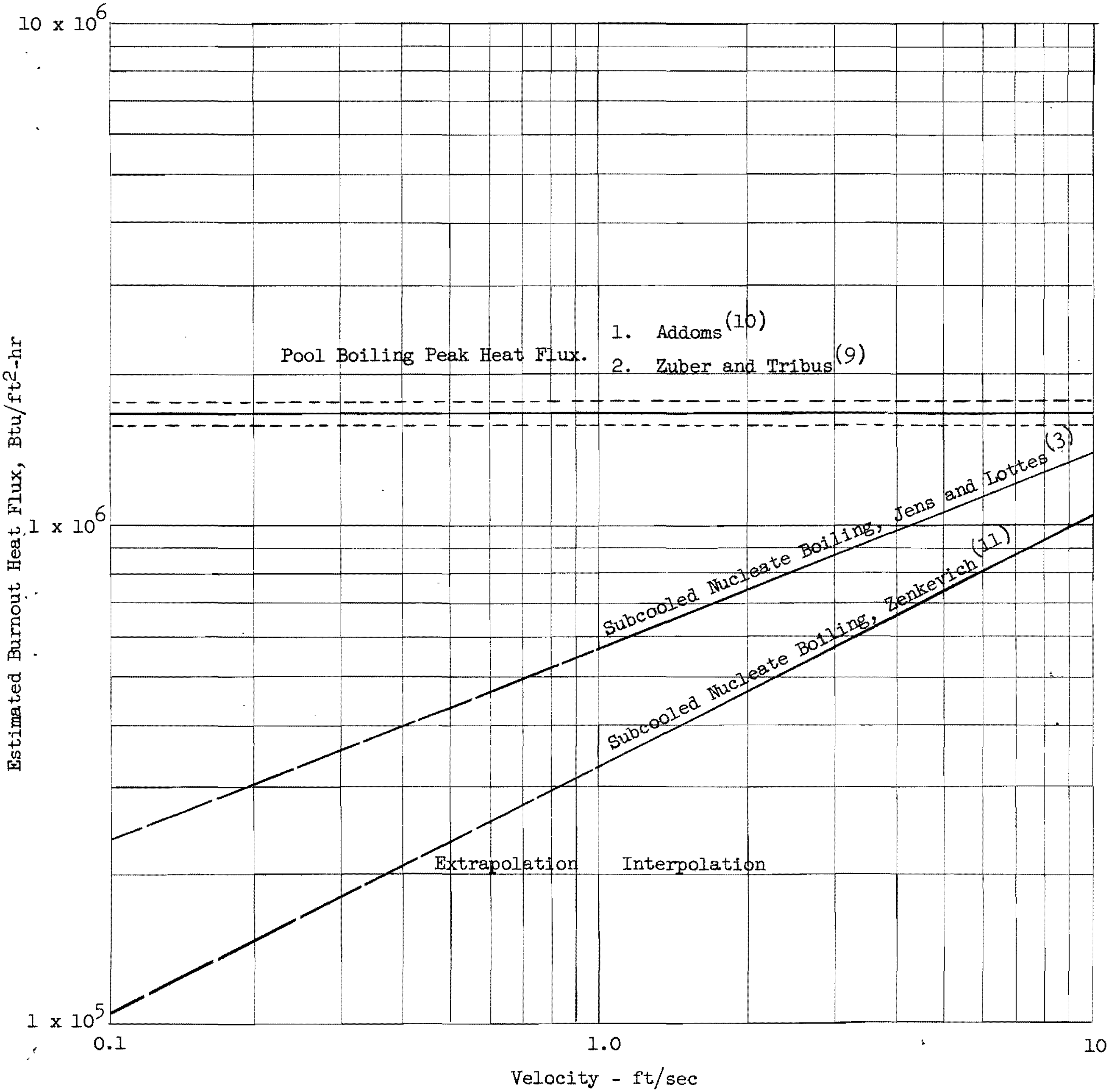

Figure A-1

Estimated Peak Heat Flux as a Function of Velocity for D_2O at 1500 psia, 16°F Subcooling

Appendix B

Summary of Heat Transfer Relationships Used for Calculation of Core Wall Temperature, Core Side Heat Flux and Patch Surface Temperature

1. Core Wall Temperature with Uniform Deposit of Uranium-Bearing Scale (see Figures 4-8)

A. Core and blanket pressurized

$$t_s = \frac{t_b + h_c(t_c + \Delta t_{VHS})\left[\frac{1}{h_b} + \frac{L_s}{k_s} + \frac{L_w}{k_w}\right] + E_w L_w\left[\frac{1}{h_b} + \frac{L_w}{2k_w}\right] + E_s L_s\left[\frac{1}{h_b} + \frac{L_s}{2k_s} + \frac{L_w}{k_w}\right]}{1 + \frac{h_c}{h_b} + h_b\left[\frac{L_w}{k_w} + \frac{L_s}{k_s}\right]}$$

$$t_{wc} = \frac{t_b h_b\left[\frac{1}{h_c} + \frac{L_s}{k_s}\right] + E_w L_w\left[\frac{1}{h_c} + \frac{L_s}{k_s}\right]\left[1 + \frac{h_b L_w}{2k_w}\right] + E_s L_s\left[\frac{1}{h_c} + \frac{L_s}{2k_s}\right]\left[1 + \frac{h_b L_w}{k_w}\right] + \left[t_c + \Delta T_{VHS}\right]\left[1 + \frac{h_b L_w}{k_w}\right]}{1 + \frac{h_b}{h_c} + h_b\left[\frac{L_w}{k_w} + \frac{L_s}{k_s}\right]}$$

t_b = Blanket coolant temperature = 482°F

t_c = Fuel temperature 573.8°F

Δt_{VHS} = Adiabatic temperature rise of wall above t_c = 7.2°F

t_s = Interface temperature between scale and fuel solution

E_w = Energy deposition rate in wall $3\ \frac{w}{cc} \approx 0.29 \times 10^6$ Btu/hr-ft^2

L_w = Thickness of Zircaloy wall = 0.026 ft

L_s = Scale thickness = 1.402×10^{-3} M

M = No. of mils (0.001 in.) of Zircaloy corroded

k_w = Core wall conductivity, 8.0 $\frac{\text{Btu-ft}}{\text{ft}^2\text{-hr-}^\circ\text{F}}$

k_s = Conductivity of corrosion scale 1.1 $\frac{\text{Btu-ft}}{\text{ft}^2\text{-hr-}^\circ\text{F}}$

h_b = Blanket side forced convection coefficient = 600 $\frac{Btu}{ft^2\text{-}hr\text{-}^oF}$

h_c = Core side forced convection coefficient = 1000 $\frac{Btu}{ft^2\text{-}hr\text{-}^oF}$

E_s = Energy deposition rate in scale = $1.6 \times 10^5\ U_s\ \frac{Btu}{ft^2\text{-}hr}$

U_s = Concentration of uranium in scale mg/cc

$$U_s = \frac{\rho_{Zr}}{\rho_{ZrO_2}} \cdot \frac{W_{Zr}}{W_{ZrO_2}} \cdot X$$

ρ_{Zr} = Specific gravity of Zircaloy = 7.5

ρ_{ZrO_2} = Specific gravity of ZrO_2 = 5.5

W_{Zr} = Molecular weight of Zr = 91

W_{ZrO_2} = Molecular weight of ZrO_2 = 123

X = Weight ratio of uranium to Zircaloy

B. Boiling on core side only at 1500 psi

$$t_s = t_{sat} + \frac{1.9}{e^{P/900}} q_c^{1/4} \qquad \text{(Reference 3)}$$

q_c = Core side heat flux, Btu-ft^2-hr

t_{sat} = Saturation temperature of liquid, 596^{o}F

$$t_{wc} = t_b + E_w L_w \left[\frac{1}{h_b} + \frac{L_w}{2k_w}\right] + E_s L_s \left[\frac{1}{h_b} + \frac{L_w}{k_w}\right] - q_c \left[\frac{1}{h_b} + \frac{L_w}{k_w}\right]$$

where q_c is calculated from

$$\frac{1.9}{e^{P/900}} q_c^{1/4} + \left[\frac{1}{h_b} + \frac{L_w}{k_w} + \frac{L_s}{k_s}\right] q_c = t_b + E_w L_w \left[\frac{1}{h_b} + \frac{L_w}{k_w}\right] + E_s L_s \left[\frac{1}{h_b} + \frac{L_w}{k_w} + \frac{L_s}{2k_s}\right] - t_{sat}$$

C. Nucleate boiling on core and blanket side (1500 psi)

$$t_{cw} - t_{sat} = \frac{\left[E_s L_s + E_w L_w\right] \frac{L_s}{2k_s}}{1 + \frac{k_w L_s}{k_s L_w}}$$

and

$$q_c = E_s L_s + \frac{k_w}{L_w}\left[\frac{E_w L_w^2}{2k_s} - (t_{cw} - t_{sat})\right]$$

$$t_s = t_c$$

2. Patch Surface Temperature, No Uranium-Bearing Scale Deposit (See Table I)

$$t_{pc} = \frac{\frac{t_b h_b}{h_c} + E_w L_w\left[\frac{1}{h_c} + \frac{L_b L_w}{2h_c k_w}\right] + (t_c + \Delta t_{VHS})\left[1 + \frac{h_b L_w}{k_w}\right]}{1 + \frac{h_b}{h_c} + \frac{h_b L_w}{k_w}}$$

$$t_{pb} = \frac{t_b\left[\frac{h_b}{h_c} + \frac{h_b L_w}{k_w}\right] + E_w L_w\left[\frac{1}{h_c} + \frac{L_w}{2k_w}\right] + t_c + \Delta t_{VHS}}{1 + \frac{h_b}{h_c} + \frac{h_b L_w}{k_w}}$$

$$q'_c = h_c\left[t_{pc} - t_c - \Delta t_{VHS}\right]$$

$$q'_b = h_b\left[t_{pb} - t_b\right]$$

where

t_{pc} = Patch surface temperature on core side, ^{o}F

t_{pb} = Patch surface temperature on blanket side, ^{o}F

q'_c = Heat flux on core side, Btu/hr-ft^2-^{o}F

q'_b = Heat flux on blanket side, Btu/hr-ft^2-^{o}F

Other notation and data same as calculation 1a.

3. Metal Wall-Scale Interface for Wall Pit Filled with Uranium-Bearing Scale (See Table II)

$$t_{wc} = \frac{t_{sat}\left[\frac{L_w}{k_w} + \frac{L_s}{k_s}\right] + \frac{L_s L_w}{2k_s k_w}\left[E_w L_w + E_s L_s\right]}{\frac{L_w}{k_w} + \frac{L_s}{k_s}}$$

$$q'_b = \frac{E_w L_w\left[\frac{L_w}{2k_w} + \frac{L_s}{k_s}\right] + \frac{E_s L_s^2}{2k_s}}{\frac{L_w}{k_w} + \frac{L_s}{k_s}}$$

$$q'_c = \frac{\frac{E_w L_w^2}{2k_w} + E_s L_s\left[\frac{L_w}{k_w} + \frac{L_s}{2k_s}\right]}{\frac{L_w}{k_w} + \frac{L_s}{k_s}}$$

where

t_{sat} = 596°F (1500 psia)

E_s = 5.6×10^7 Btu/hr-cu ft for 10% U

11.2×10^7 Btu/hr-cu ft for 20% U

L_w = Metal wall thicknesses given in Table II

L_s = Scale thickness given in table II

Other notation and data same as calculation 1a.

4. Metal Wall-Scale Interface for Deposits of Uranium-Bearing Scale on Patch (See Table III)

Same equations and data used in calculation 3.

Values of L_w, L_s given in Table III.

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