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Possibility of Interconnecting the
HRT Pressurizers with an Open Pipe

Summary

Calculations show that the transfer of solids from the core to the blanket side of the HRT is improbable when the two pressurizers are connected with an open pipe.

Introduction

An open pipe connection between the two HRT pressurizers has a number of advantages. The pressure balancing system between the core and the blanket can be eliminated, the dump valves need not be throttled during the dumping operation, and no maintenance is required for the rupture discs and the rest of the balancing system. The disadvantage is that the open pipe allows the possibility of mass transfer of uranium and other soluble solids from the core to the blanket. Also there may be a continual transfer of water vapor from one pressurizer to the other due to the differences of the purged rates to the two pressurizers and the possible different rate of heat losses between the two pressurizers. This transfer can be compensated however, by operating the heaters of one pressurizer at a higher temperature than those of the other pressurizer. (3)

Mass Transfer During a Normal Dump

During normal operations only water probably would be transferred from one pressurizer to the other pressurizer. During a quick dump, or the dumping of only one of the reactor systems, pressure differences would be produced greater than those required to break the rupture discs, which then would allow mass transfer. Normal dumping operations, however, would allow shutting the reactor down without breaking the rupture discs. For the

open pipe connection, mass transfer with solids may be possible for this operation and therefore this situation was studied.

The normal dumping operation may be divided into three periods; the delay period, the venting period, and the dumping period. During the delay period the steam valve is closed and the fuel is allowed to continue to circulate. This takes two minutes and the entire fuel solution in the reactor approaches the average temperature of 280°C .⁽¹⁾

During the venting period, the pressure drops from the initial value of 1700 psia to 990 psia in two minutes. It was assumed that the venting took place through one vent line with a valve of C_v of 0.34. Vapor passing through the vent line during this time is generated from the liquid in the pressurizers. Details of this calculation are shown in Appendix A. Due to fission energy, the fuel solution will heat from 280°C to 283°C as shown in Appendix B.

After the delay and the venting periods, the fuel and the blanket solutions are actually dumped. Venting still continues through the single vent line and the circulating pump continues to run until no more solution passes through it whereupon it stops. It is assumed because of the heat generation, heat losses, and heat stored in the systems that there is no heat generation or loss in these systems. The final small amount of overpressure is removed and the fuel and blanket solutions boil and evaporate as well as the liquid in the pressurizers. Slightly over three minutes are required to drain the core solution from the reactor, and the pressure drops from 990 to 724 psi as shown in Appendix C. There is a slight amount of mass transfer from the core to the blanket, and then from the blanket to the core during this period. The amount of vapor transferred is shown in Figure 1, and the details of

those calculations are shown in Appendix D.

It can be seen that the amount of vapor transferred during the dumping operation is small and it is very doubtful if any solids would be carried over to the blanket by entrainment. However there were a number of idealizing assumptions made in the calculations. Thermodynamic equilibrium was assumed at all-times, and it was assumed that the valves were opened instantaneously. In actual practice a slight delay is encountered and it is doubtful if two valves open at exactly the same time. The effects of heat generation, storage, and losses are difficult to estimate and were ignored. The dump rates used are those measured during the natural uranium runs of the HRT and could be slightly in error which would affect the results.

Two other methods were used, therefore, to gain an indication of the amount and rate of the mass transfer from the fuel system to the blanket system during the dumping operation. Haubenreich⁽³⁾ found that the greatest pressure difference of the core over the blanket during a dump was about 55 psi. The average pressure during this time was about 1000 psia. Two seconds after the actual dump started, it was found in one of the dump tests that the pressure difference of the fuel over the blanket reached a maximum. It was assumed for the purposes of these calculations that the pressure of the fuel system was initially 1025 psia and that of the blanket system was initially 970 psia. As shown in Appendix E, about 2.8 cu ft, which is equivalent to 6.3 lbs of vapor, is transferred from the core to the blanket in order to bring the entire reactor system back to equilibrium. If it is assumed that two seconds are required to transfer this vapor, the average rate of transfer would be about 3.2 lb per sec. In Appendix F, it was assumed that the pressures were the same and the flow rate was calculated from an estimation of the flow resistance in the piping connecting the two

pressurizers. It was found that the initial flow rate from the core to the blanket would be about 8.4 lb per sec, but this would rapidly decrease. Therefore, it appears that the mass transfer of uranium or other dissolved solids from the core to the blanket is not probable for normal operation.

Conclusions

The calculations show that the transfer of uranium or other dissolved solids from the fuel system to the blanket is not probable. Therefore it is believed that the HRT could be operated without the presence of rupture discs between the pressurizers.

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Appendix A

Venting Period of the HRT Dumping Operation

Since the HRT vent valves flow rates were determined,⁽²⁾ the valve trims have been replaced. The C_v of the new vent valves is 0.34 compared to a C_v of 0.07 for the old vent valves.⁽³⁾ The flow rate through the new vent valve is then $0.34/0.07$ or 4.857 times that through the old valves. Figure 2 shows the flow rate through a new vent valve 100% open.

It is assumed for venting the HRT pressurizers when connected with an open pipe that the vent stream passes through one vent line with the valve 100% open. A mass balance, a volume balance, an energy balance, and an equation of state were used for these calculations. These equations are as follows:

Mass Balance

$$m_f + m_g = M_o - m_v : \quad \text{where } m_v = \sum_0^M (\overline{w}_{vent})_i \Delta t_i$$

Volume Balance

$$m_f + v_f + m_g + v_g = V$$

Energy Balance

$$m_f h_f + m_g h_g = H_o - H_v - Q_{loss} : \quad \text{where } H_v = \sum_0^M (\overline{w}_{vent} h_g)_i \Delta t_i$$

Equation of State

$$\begin{array}{ll} h_f = f(p) & h_g = f(p) \\ v_f = f(p) & v_g = f(p) \end{array} \quad \text{For saturated steam}$$

It can be seen that there are four equations and four variables; m_f , m_g , p , and t . These equations were solved by trial and error by first assuming a time increment Δt and then calculating the other variables until the four equations were satisfied.

The volume of the HRT pressurizer system is as follows: ⁽⁴⁾

Liquid volume in two pressurizers	66.6 liters	2.350 ft ³
Vapor volume in pressurizers	159 liters	<u>5.615 ft³</u>
Total volume V		7.965 ft ³

The HRT pressurizer system is initially at 1700 psia. ⁽³⁾ From this information and that in the steam tables, ⁽⁵⁾ the initial mass in the HRT pressurizers is

Liquid mass	2.350/0.0243	96.71 lbs
Steam mass	5.615/0.2354	<u>23.85 lbs</u>
Total mass, M ₀		120.56 lbs

The initial enthalpy in the HRT pressurizers is

Liquid enthalpy	96.71 x 636.3	61,540 Btu
Steam enthalpy	23.85 x 1155.9	<u>27,570 Btu</u>
Total enthalpy, H ₀		89,110 Btu

The rate of heat loss from the two pressurizers has been estimated by Michelson to be 13.2 kw or 12.52 Btu per second. ⁽⁴⁾

Using this information, the pressure drop during the venting of the HRT pressurizers has been calculated and the results are shown in Figure 3.

Appendix B

Temperature Rise of the Fuel Solution During the Venting Period

The HRT will not become subcritical during the normal dumping operation until approximately at the end of the delay period. (The delay period is two minutes long.)⁽¹⁾ During this time, the entire fuel system will approach the equilibrium temperature of 280°C.⁽⁶⁾

After the delay period when the reactor has gone subcritical, the temperature of the fuel solution will rise due to the fission product energy. The fission product energy was estimated by passing a straight line of the same slope as obtained by Hill⁽⁹⁾ when plotted on log-log plot through the point where the HRT becomes subcritical as shown in Figure 4. The equation of the power curve after the reactor has gone subcritical is then

$$\ln P = -0.2295 \ln t + 6.59$$

where P is power in kw and t is time in sec.

The heat capacity of the fuel solution in the HRT is 1069 Btu/°F⁽⁶⁾, and the heat capacity of the fuel heat exchanger is 2910 Btu/°F⁽⁸⁾. This makes the total heat capacity of the HRT fuel system 3979 Btu/°F or 4198 kw-sec/°F. The temperature change to the fuel with time is given by the equation

$$\int_{536}^T dT = \frac{1}{4198} \int_{120}^t P dt$$

Combining these equations

$$\int_{536}^T dT = \frac{730}{4198} \int_{120}^t \frac{dt}{t^{0.2295}}$$

Integrating,

$$T = 0.2258 t^{0.7705} + 526.9$$

The results of this equation are shown in Figure 5. The fuel temperature at the end of the vent period is 542.3°F.

Appendix C

Dumping Period of the HRT Dumping Operation

It is assumed that there is no heat gain or loss from the fuel and the blanket systems during the dumping period. Although heat is generated by the fuel and there is heat which is stored in the walls of the systems, heat is also lost from these systems to the reactor cell. Since these factors tend to compensate each other and they are hard to estimate, they are ignored.

The dumping period may be divided again into three parts:

1. Initial pressure to the fuel saturation pressure.
2. Fuel saturation pressure to the blanket saturation pressure.
3. Blanket saturation pressure to end of dump operation.

The pressure decreases from 990 psia to 978 psia, the fuel saturation pressure, during the first part. Venting rates were obtained from Appendix A and the flow rates through the dump lines were obtained from information gathered by Haubenreich. (3) Water evaporates only from the pressurizers and not from the fuel and blanket during this period of dumping.

The equations used for these calculations are as follows:

Mass balance

$$m_{f,P} + m_g = M_o - W_{Vent} \Delta t$$

Volume balance

$$m_{f,P} v_{f,P} + m_g v_g = V + K' \Delta t; \text{ where } K' = v_{ff} W_{f,dump} + v_{fb} W_{b,dump}$$

Energy balance

$$m_{fP} h_{fP} + m_g h_g = H_o - H_v - \frac{144p}{J} K' \Delta t$$

where $H_v = \frac{W_{vent} h_g}{J} \Delta t$

Combining these equations

$$(M_o - W_{vent} \Delta t) v_{fp} + m_g v_g = V + K' \Delta t$$

$$(M_o - W_{vent} \Delta t) h_{fp} + m_g h_g = H_o - H_v - \frac{144p}{J} K' \Delta t$$

Solving these equations simultaneously using the steam tables⁽⁵⁾ for the equation of state, Δt is 0.41 seconds.

During the second part of the dumping period, the pressure drops from 978 psia to 931 psia, which is the saturation pressure of the blanket. As before the venting rates were obtained from Appendix A, and the dump rates were obtained from information gathered by Haubenreich.⁽³⁾ Water will be evaporating from the fuel and the pressurizers, but not from the blanket during this part of the dumping period.

The equations used for these calculations are as follows:

Mass balance

$$m_f + m_g = M_o - K \Delta t; \quad \text{where } K = W_{vent} + W_{f,dump}$$

Volume balance

$$m_f v_f + m_g v_g = V + \overline{v_{fb}} \overline{W_{b,dump}} \Delta t$$

Energy balance

$$m_f h_f + m_g h_g = H_o - H \Delta t - \frac{144p \overline{v_{fb}} \overline{W_{b,dump}}}{J} \Delta t ;$$

$$\text{where } H = \overline{h_g W_{vent}} + \overline{h_f W_{f,dump}}$$

Combining these equations

$$(M_o - K \Delta t) v_f + m_g v_{fg} = V + H \Delta t$$

$$(M_o - K \Delta t) h_f + m_g h_{fg} = H_o - H \Delta t - \frac{144p \overline{v_{fb}} \overline{W_{b,dump}}}{J} \Delta t$$

Solving these equations simultaneously using the steam tables⁽⁵⁾ for the equation of state, Δt is 11.1 seconds.

For the third and final part of the dumping period, the liquid in the fuel system, the blanket systems, and the pressurizers and the vapor are all in equilibrium. Again, the venting rates were obtained from Appendix A, and the dump rates were obtained from information gathered by Haubenreich.

The equations used for these calculations are as follows:

Mass balance

$$m_f + m_g = M_o - K\Delta t ; \text{ where } K = W_{\text{vent}} + W_{f,\text{dump}} + W_{b,\text{dump}}$$

Volume balance

$$m_f v_f + m_g v_g = V$$

Energy balance

$$m_g h_f + m_g h_g = H_o - H\Delta t; \text{ where } H = (W_{f,\text{dump}} + W_{b,\text{dump}}) h_f + W_{\text{vent}} h_g$$

Combining these equations

$$(M_o - K\Delta t) v_f + m_g v_{fg} = V$$

$$(M_o - K\Delta t) h_f + m_g h_{fg} = H_o - H\Delta t$$

Calculations were made down to the point where the fuel was drained from the reactor. Further calculations for this situation are immaterial as there probably is no more entrained liquid which can enter the blanket from the fuel side of the reactor. The pressure versus time for the dumping operation is shown in Figure 6.

Appendix D

Estimation of Mass Transfer from Fuel to Blanket During Dumping Period

The ratio rate of vapor formation in the HRT high pressure fuel system to the total rate during the dumping period is assumed to be proportional to the ratio of the mass of fuel liquid to the total liquid at any time. The effects of the dissolution of the dissolved hydrogen and oxygen in the fuel have been neglected. Using the calculations of Appendix C, the total vapor in the HRT high pressure system at any time was calculated. From this the total vapor formed during dumping was computed by adding the amount of vapor removed through the vent valve to the difference between the vapor in the high pressure system at any time and that before dumping. The amount of this vapor formed from the fuel was then calculated using the assumptions mentioned above. The following table is a summary of these calculations.

Time	Vapor in High Pressure System	Excess Vapor Over Initial Amount	Vapor Removed Through Vent Valve	Total Vapor Formed	Vapor Formed by Fuel
min:sec	lbs	lbs	lbs	lbs	lbs
0	13.57	0	0	0	0
0:00.41	13.71	0.14	0.05	0.19	0.17
0:11.55	21.08	7.51	1.46	8.97	1.96
0:42.21	41.47	27.90	5.17	33.07	6.81
1:37.49	73.27	59.70	11.50	71.20	14.09
2:10.50	88.77	75.20	14.74	89.94	17.12
2:53.26	104.32	90.75	19.06	109.81	19.70
3:04.43	107.66	94.09	21.34	114.20	19.87

The amount of vapor in the high pressure fuel system was then calculated by calculating the volume of liquid in this system at any time. The remaining volume was assumed to vapor and its mass was obtained by dividing this volume by the specific volume of the vapor at this pressure. Subtracting this value from the vapor formed by the fuel is assumed to be the mass transferred from the fuel to the blanket. The results of these calculations are summarized in the following table:

Time	Pressure	Mass of Liquid Fuel (Appendix C)	Sp. Vol. ⁽³⁾ of Liquid	Volume Liquid	Volume Vapor	Spec. Vol. ⁽⁵⁾ of Vapor	Mass of Vapor in High-Pressure Fuel System	Vapor transferred from fuel to Blanket
min:sec	psia	lbs	cu ft/lb	cu ft	cu ft	cu ft/lb	lb	lb
0	990	752.1	0.0215	16.17	0	-	0	0
0:00.41	978	750.5	0.0215	16.14	0.03	0.4568	0.07	0.10
0:11.55	931	703.4	0.0213	14.99	1.18	0.4823	2.45	-0.48
0:42.21	900	576.5	0.0212	12.22	3.95	0.5006	7.89	-1.08
1:37.49	840	548.0	0.0210	7.31	8.86	0.5396	16.42	-2.33
2:10.50	800	213.0	0.0209	4.45	11.72	0.5687	20.61	-2.91
2:53.26	740	39.6	0.0207	0.82	15.35	0.6180	24.85	-5.15
3:04.43	724	0	-	0	16.17	0.6336	25.52	-5.65

Figure 1 shows a plot of the vapor transferred from the fuel to the blanket.

Appendix E

Mass Transfer Required to Bring Fuel and Blanket Systems to Equilibrium

In these calculations, it is assumed that the pressure of the fuel system is 1025 psia and the pressure of the blanket system is 970 psia two seconds after the initiation of the dumping period. This makes a pressure difference of 55 psi which is the greatest amount of the core over the blanket system found by Haubenreich. (3) The initial conditions are assumed to be at saturation at the respective pressures. The amount of material found at the initiation of this mass transfer is assumed to be that found by the previous appendices two seconds after the initiation of the dumping period. The following is a summary of the initial conditions.

	<u>Fuel System</u>	<u>Blanket System</u>
Mass, lbs	794	2874
Volume, cu ft	20.15	64.61
Enthalpy, Btu	437,000	1,549,800

The equations for the fuel system after equilibrium has been reached are as follows:

Mass balance

$$m_{cf} + m_{cg} = 794.0$$

Volume balance

$$m_{cf} v_f + m_{cg} v_g = 20.15 + Z$$

Energy balance

$$m_{cf} h_f + m_{cg} h_g = 437,700 - \frac{144p Z}{J}$$

The equations for the blanket system after equilibrium has been reached are as follows:

Mass balance

$$m_{bf} + m_{bg} = 2873.9$$

Volume balance

$$m_{bf} v_f + m_{bg} v_g = 64.61 - Z$$

Energy balance

$$m_{bf} h_f + m_{bg} h_g = 1,549,800 + \frac{144p Z}{J}$$

Specific volumes and enthalpies are a function of the pressure since saturation conditions are assumed. Therefore there are six equations and six unknowns.

Solving these equations simultaneously, it was found that the final pressure is 981 psia and the volume of vapor transferred from the fuel to the blanket is 2.80 cu ft. Assuming the specific volume of the vapor to that at the average pressure of the fuel during the transfer (0.4442 cu ft per lb). The mass of vapor transferred during this period is 6.30 lbs. If two seconds are required to transfer this vapor, the average rate of transfer is then 3.15 lb per sec.

Appendix F

Estimation of Flow from the Fuel to Blanket when Pressure Difference is 55 psi

The conditions assumed for this situation are the same as those for the initial conditions in Appendix E. Resistance of flow through the line connecting the HRT pressures including the inlet and outlet losses (without the rupture disc or holder) in velocity heads is estimated to be 4.50. Therefore the rate of flow through the connecting line is

$$\Delta p = \frac{4.50 V^2}{(144)(v_g)(2g_c)} = \frac{4.50 V^2}{(144)(0.4456)(64.34)} = 55$$

or

$$V = \sqrt{\frac{144 \times 64.34 \times 0.4456 \times 55}{4.50}} = 224.5 \text{ ft/sec}$$

The inside diameter of this line is 1.750 in., and its inside area is then 0.01670 sq ft. Assuming the specific volume to be that at the average pressure, the flow rate from the core to the blanket is then

$$w = \frac{224.5 \times 0.01670}{0.4456} = 8.42 \text{ lb/sec}$$

Table of Nomenclature

C_v	Vent valve coefficient
H	Heat leaving with fluid leaving system, Btu/sec.
H_o	Initial enthalpy of system, Btu
H_v	Heat leaving with fluid passing through vent valve, Btu/sec
h_f	Liquid enthalpy, Btu/lb
$h_{f,P}$	Pressurizer liquid enthalpy, Btu/lb
$h_{f,g}$	Enthalpy of vaporization, Btu/lb
h_g	Vapor enthalpy, Btu/lb
J	Energy conversion factor, 778 ft-lb/Btu
K	Mass of fluid leaving system, lb/sec
K'	Volume of liquid leaving high pressure system, cu ft/sec
m_{bf}	Liquid in blanket system, lb
m_{bg}	Vapor in blanket system, lb
m_{cf}	Liquid in fuel system, lb
m_{cg}	Vapor in fuel system, lb
m_f	Liquid in system, lb
$m_{f,P}$	Liquid in pressurizers, lb
m_g	Vapor in system, lb
p	Pressure, psia
$\bar{p}$	Average pressure, psia
P	Power, kw
Q_{loss}	Rate of heat loss from system, Btu/sec
T	Temperature, °F or °C
t	Time, sec
V	Volume of system, cu ft

v_f	Liquid specific volume, cu ft/lb
v_{fb}	Blanket liquid specific volume, cu ft/lb
v_{ff}	Fuel specific volume, cu ft/lb
v_{fg}	Volume of vaporization, cu ft/lb
$v_{f,p}$	Pressurizer liquid specific volume, cu ft/lb
v_g	Vapor specific volume, cu ft/lb
$w_{b,dump}$	Blanket dump rate, lbs/sec
$w_{f,dump}$	Fuel dump rate, lbs/sec
w_{vent}	Vent rate, lbs/sec
Z	Volume displaced by system due to change in conditions, cu ft

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FIGURE 1
MASS OF MATERIAL TRANSFERRED FROM
FUEL TO BLANKET

FIGURE 3
PRESSURE DURING VENT
PERIOD

GMPL-DR-DWG.-28939
UNCLASSIFIED

FIGURE 5
HRT FUEL TEMPERATURE AFTER
CLOSURE OF STEAM VALVE

0-25