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Maintaining High Pressure System of the HRR at Temperature After Dump

Summary:

It has been suggested by Kasten and others[1] that the HRR be shut down by partially dumping the fuel solution and allowing the remaining fission product decay heat to keep the high pressure system at temperature during shutdown. An investigation of the technical feasibility of this suggestion is the subject of this report.

The results of this preliminary study indicate that such an idea is feasible if the high pressure system is kept at an equilibrium temperature in the range 350-390°F during shutdown. A fuel solution holdup of 9,600-11,900 liters (7.7-9.5 kg) is required. A minimum of 9.5 Kg will make the reactor go critical at 390°F; about 8.7 Kg at 350°F. Most of the fuel solution will be in the return pipes to the reactor. The possibility of an incident which will transfer fuel to the reactor and establish a new critical geometry with a smaller fluid and fissionable material inventory is extremely remote. A detailed nuclear study is required, however, to select the safest equilibrium temperature.

For initial design of the HRR, an equilibrium temperature of 190°C (374°F) is selected. A fuel holdup of about 11,000 liters (8.8 Kg) is required (critical mass, 9.3 Kg). The maximum heat demand on the system two days after shutdown is about 240 Kw; 207 Kw direct heat losses and 33 Kw evaporation requirements for gas dilution. A D_2O make up of 6800 liters is required during a two day shutdown to maintain constant fuel concentration. With a gas dilution to 5 mole percent D_2, and subsequent venting, there should be no explosion hazard. Removal of heat in excess of the requirements for venting and heat losses can be accomplished by controlled boiling at a lower pressure in one or more of the heat exchangers.

Introduction:

If the HRR is to be subcritical for all conceivable situations during shutdown, some limitation on fissionable material holdup in the high pressure system is required. A nuclear study of this problem has not been made. For the purposes of this initial study, it is assumed that if the holdup of fissionable material is less than required for reactor criticality at the holdup temperature, the system can be considered adequately safe. The question of technical feasibility then becomes that of determining if the amount of fuel solution holdup required to make up heat losses and venting requirements is consistent with restrictions on fissionable material inventory.

Heat Losses:

Heat losses from the high pressure system of the HRR are due to natural convection and radiation from the reactor, piping, pressurizer and heat exchangers. The piping, pressurizer, and heat exchangers are insulated (90% effective). In the final design, the reactor may be covered by a blast shield, but it is assumed that cooling of a blast shield will produce the same net loss from the reactor vessel as combined natural convection and radiation. An ambient air temperature of 150°F (610°R) around the system is assumed. In the final design, space coolers or cooling coils in the concrete walls may be required to maintain this temperature. Unless the air velocity is markedly increased, this will not alter the convection coefficients.

The average heat transfer coefficient for natural convection from large pipes is obtained by assuming the upper half cylinder to be a horizontal plate facing upward and the lower half cylinder a horizontal plate facing downward. This yields about the same average coefficient as obtained by assuming half cylinders taken about a vertical axis to be short vertical plates. This coefficient obtained by this method is somewhat higher than obtained from empirical equations which correlate pipe diameter to the natural convection loss. However, these equations are not considered accurate for very large pipe diameters.

The natural convection coefficient for the reactor sphere is obtained by assuming the upper hemisphere a horizontal plate facing upward and the lower hemisphere a horizontal plate facing downward. This yields a slightly larger coefficient than obtained assuming hemispheres taken about a vertical axis to be long vertical plates.

The heat transfer coefficient for losses by radiation from the high pressure system can be expressed as:[2]

$$hr = \frac{0.173\epsilon\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]}{T_1 - T_2}$$

hr = radiation heat transfer coefficient, B/hr ft^2 $^\circ$F

ϵ = emissivity of hot surface

T_1 = temperature of hot surface, $^\circ$R

T_2 = temperature of enclosure (ambient), $^\circ$R

The emissivity of Type 347 stainless steel piping in the temperature range 300-500°F is estimated on the basis of data given by McAdams[3] to be 0.50. The emissivity of the carbon steel reactor vessel is purposely made high since cooling of the outside wall is desired. A value of 0.8 is used. A value of 0.6 is used for the carbon steel shells and drums on the heat exchangers.

The average heat transfer coefficient for losses by natural convection can be expressed as:[4]

$$h_c = 0.29\,(T_1 - T_2)^{0.25}$$

h_c = natural convection heat transfer coefficient, B/hr ft^2 $^\circ$F

T_1 and T_2 = defined previously

On the basis of these equations the following heat transfer coefficients are obtained:

Wall Temp. °F	Natural Convection (hc)	Radiation (hr) Reactor	Piping	Heat Exchanger
300	1.02	1.81	1.13	1.36
350	1.09	2.03	1.27	1.52
400	1.16	2.27	1.42	1.70
450	1.21	2.52	1.58	1.90
482	1.24	2.71	1.69	2.03

The total heat loss, Q(B/hr), from any component of the high pressure system can be expressed as:

$$Q = (hc + hr)A\,(T_1 - T_2)$$

where A = area of hot surface, ft^2

The following areas represent the best estimate now available for the high pressure system. The reactor pressurizer is included in the piping area.

Reactor	520 ft^2
Piping	2300 ft^2
Heat Exchangers (6)	3100 ft^2

The total heat loss from the high pressure system with the piping and heat exchangers insulated is estimated to be:

Wall Temp. °F	Reactor B/hr x10^5	Piping B/hr(10%) x10^5	Heat Exch. B/hr(10%) x10^5	Total Heat Loss KW
300	2.21	0.72	1.10	118
350	3.24	1.06	1.61	174
400	4.16	1.50	2.20	239
450	5.82	1.88	2.87	310
482	6.81	2.18	3.34	360

Decay Heat:

The amount of available decay heat in the HRR fuel solution after shutdown from the shortest contemplated operating cycle of two weeks, and after shutdown from an infinite time at full power, is:*

Time After Shutdown	Decay Heat (MW)	
	Two Wks.	Infinite
10 sec.	18.4	20.5
100 sec.	11.0	13.0
1000 sec.	6.0	8.1
1 hour	4.3	6.3
1 day	1.4	3.4
2 days	1.0	2.9
4 days	0.8	2.5

Gas Production:

The gas production rate (v^1) in a reactor operating at a power level of P_c MW is:[5]

$$v^1 = 3.5 \times 10^3 P_c \qquad ccD_2(STP)/sec.$$

This gas production is due primarily to fission product recoils (G = 1.67 molecules/100 ev.). After reactor shutdown the gas production is due mostly to betas and gammas (G = 0.45 molecules/100 ev). Therefore, the gas production rate (v) due to a decay power level of P_d MW after reactor shutdown is:

$$v = 940 P_d \qquad cc\ D_2\ (STP)/sec.$$

$$= 9.22 \times 10^{-5} P_d \text{ lb-moles } D_2/sec.$$

The radiolytic gases are coming off in stoichiometric proportions.

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* Data supplied by D. R. Gilfillan.

Gas Dilution:

According to the best available estimates*, if the radiolytic gases coming from the fuel solution are diluted with vapor phase to about 5 mole percent D_2, the mixture should be nonexplosive. In order to maintain this dilution rate and purge the radiolytic gases from the high pressure system at all times, it is necessary to vaporize part of the holdup solution for venting to the dump tanks. The amount of vapor required is calculated on the basis of gas generation from decay heat after two weeks of operation at power. Since gas generation rate is directly proportional to available decay heat, the time of reactor operation is not important. Heat losses due to conduction and convection govern the choice of short-time operation as a worst condition.

Time After Shutdown	Gas Generation lb-moles D_2/sec.	Vapor Required lb/hr
	$\times 10^{-5}$	
10 sec.	169	2430
100 sec.	101	1450
1000 sec.	55	792
1 hour	40	576
1 day	12.9	186
2 days	9.2	133
	Average 0 to 2 days	250 lb/hr

The average vapor requirement of 250 lb/hr results in an average D_2O loss of 142 liters/hr or 6800 liters in a two day period. This loss is made up by condensate feed from the low pressure system. After shutdown from an infinite period of operation at full power, an average vapor rate of 506 lb/hr is required (13,800 liters D_2O in two days).

Since the heat of vaporization is highest at the lowest temperature, the heat required to supply a given amount of gas dilution vapor will be a maximum at 300°F. The percentage of available heat required for gas dilution remains about constant with time after shutdown. Therefore, as a worst condition, the heat required for gas dilution prior to reactor startup (2 days after shutdown) is:

* I. Spiewak, personal communication.

Equilibrium Temperature °F	Heat for Gas Dilution KW
300	36
350	34
400	32
450	30
482	29

Critical Mass:

The amount of fissionable material (U-235) required to make the HRR go critical is:*

Critical Temperature °F	Critical Mass g U-235/liter	Reactor Loading Kg (15,000 liters)
300	0.54	8.1
350	0.58	8.7
400	0.64	9.6
450	0.72	10.8
482	0.80	12.0

Holdup Requirements:

The decay heat available from the entire fuel solution is 1 MW (.0217 Kw/liter) after a maximum shutdown time of two days following a reactor operating period of two weeks. If decay heat from holdup in the high pressure system is to maintain a given equilibrium temperature and supply the venting heat requirements, the following minimum holdup volumes are necessary:

Equilibrium Temperature °F	Heat Required KW	Minimum Holdup liters	Fissionable Material Holdup Kg
300	154	7100	5.7
350	208	9600	7.7
400	271	12500	10.0
450	340	15600	12.5
482	389	17900	14.4

* Data supplied by D. R. Gilfillan and C. W. Nestor, Jr.

REFERENCES

(1) Kasten, P. R., "Control and Start-up of HRR", ORNL CF-56-5-124.

(2) Jakob, M., and Hawkins, G. A., Elements of Heat Transfer and Insulation, 2nd Ed., p. 185, 1950.

(3) McAdams, W. H., Heat Transmission, 3rd Ed., p. 475, 1954.

(4) Perry, J. H., Chemical Engineers Handbook, 3rd Ed., p. 474, 1950.

(5) Aven, R. E., "Internal Recombination in the HRR", ORNL CF-56-4-190.

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