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For The Atomic Energy Commission

H. F. Cansell

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SUMMARY

An introductory study of gas pressurization in the HRT has been made. This type of pressurization will probably be used in the event that vapor pressurization proves unsatisfactory. Gas pressurization has several advantages which include:

- 1) The gas pressurizer may be maintained at any desired temperature. This eliminates problems associated with the high temperature required for the production of vapor at 2000 psia.

- 2) Reactor start-up operations proceed faster.

Its disadvantages include:

- 1) Introduction into the system of a noncondensable gas.
- 2) Introduction and possible development of several new items of equipment to handle this gas.

An estimate has also been made of the D_2 concentration in the gas phase of the reactor during a dumping operation for both the gas and vapor pressurized systems. This estimate indicates that the gas phase can become highly explosive (up to 20% D_2) during the dumping operation. If possible, a delay period (after power shutdown and before the dump begins) is recommended to allow time for some of the dissolved radiolytic gases to be recombined catalytically.

INTRODUCTION

According to the present design, the high pressure system of the HRT will be pressurized with D_2O vapor. In this design, D_2O condensate is fed to heater legs connected to the pressurizer drum. Vapor is formed at $335^{\circ}C$ which maintains the pressure at 2000 psia. No heat is supplied to the stagnant leg of fuel solution which connects the vapor space of the pressurizer with the main circulating line. Several problems, however, may be associated with vapor pressurization. They include:

- 1) Entrained fuel solution may find its way into the condensate tanks

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from which the feed water to the pressurizer heater legs is taken. In this case it may be necessary to add a distillation step to the pressurizer design.

2) The concentration of uranium in the solution of the stagnant leg varies from zero at the liquid-vapor interface to the concentration of the main circulating fuel at the junction where the pressurizer leg begins. The temperature gradient varies from 335°C at the liquid-vapor interface to 300°C at the junction. The concentration and temperature gradients in between are not definitely known. The chemistry of the solution in this range may be such that precipitation of uranium will occur.

The purpose of this report then is to investigate the possibility of using gas rather than D_2O vapor to pressurize the system. Some problems associated with gas pressurization are presented along with suggested solutions.

Discussion of Gases to be Used

Several gases have been considered, the most favorable being helium, oxygen or a mixture of helium and oxygen. Nitrogen and carbon dioxide are ruled out because of undesirable nuclear or chemical properties. Air, of course, contains nitrogen and is therefore undesirable. Other gases, which may be acceptable as to their chemical properties, are ruled out because of expense or lack of experience involved in their use.

The choice between oxygen and helium may depend on the means by which pressure is attained. If a standard compressor is used the logical choice of gas will be helium or a mixture of helium with a small amount of oxygen ($\leq 10\%$). The use of an ordinary oil lubricated compressor with pure oxygen is ruled out because of the explosive hazard involved. Oxygen can be used if the pressure is attained by using the liquid form of oxygen or if a special compressor is used. If liquid oxygen is used it is stored in a container, called a liquid oxygenator, and is boiled to give the desired pressure.

Some oxygen will be needed in the gas phase of the pressurizer to insure that the fuel solution in the stagnant leg leading to the pressurizer is not deficient in dissolved oxygen. In order to establish the minimum partial pressure of oxygen needed in the gas phase, 100 ppm O_2 is assumed as the required oxygen concentration in the reactor solutions. The relation between concentration in the liquid phase and partial pressure in the gas phase is given by Henry's Law

$$p_A = K_A x_A \quad (1)$$

where p_A = partial pressure of component A in gas phase, psi

x_A = mole fraction of component A in liquid phase

K_A = Henry's Law coefficient for component A, psi/(mole fraction)

Henry's Law coefficient for oxygen at $300^\circ C$ is

$$K_{O_2} = 2.3 \times 10^5 \text{ psi/mole fraction}$$

and

$$x_{O_2} = 6.25 \times 10^{-5} \text{ mole fraction } (\approx 100 \text{ ppm } O_2)$$

The minimum oxygen partial pressure needed is found by solving equation (1) for

p_{O_2}

$$p_{O_2} = K_{O_2} x_{O_2} = 14.4 \text{ psi}$$

If gas pressurization is used large volumes of noncondensable gas will be discharged to the low pressure system in the event of a dumping operation. To minimize the amount of these noncondensable gases, it is advisable to operate the pressurizer at as high a temperature as possible consistent with maintaining a single phase of fuel solution. The advantage here is that at higher temperatures the composition of the gas phase is richer in D_2O vapor and the

percentage of ~~noncondensables~~ is consequently lower. It probably will be practical to hold the fuel solution in the stagnant leg and liquid-gas interface of the pressurizer at 300°C without danger of phase separation. At this temperature and 20000 psia pressure the composition of the gas phase is

		<u>partial pressure, psi</u>
D ₂ O vapor	70.2 mole %	1250
Noncondensables	<u>29.8</u> mole %	<u>750</u>
	100.0 mole %	2000 psia

The ~~noncondensable~~ gases may be considered ideal, while D₂O vapor is more compressible than predicted by the perfect gas law ($z_{D_2O} \approx 0.705$ where $z = \frac{PV}{nRT}$).

Since the partial pressure of the ~~noncondensable~~ gases is 750 psi, the minimum percentage of oxygen in the gas stream entering the pressurizer can now be estimated:

$$\% O_2 = \frac{14.4 \times 100}{750} = 1.9\%$$

If helium is chosen as the principal pressurizer gas then the percent oxygen in the gas feed stream is recommended to be about 5% to 10% to insure adequate oxygen in the system.

Since helium is a very light gas it has a tendency to stratify in the pressurizers. Also because of its inert chemical nature it cannot be removed from the system by chemical reaction. From this standpoint it may be advisable to consider the use of relatively pure oxygen as the pressurizing gas. Some advantages of oxygen are:

- 1) Oxygen will not stratify in the pressurizer.

- 2) Smaller pressurizer volumes required for same compression effects.
(See Table I).
- 3) Oxygen is readily available commercially and is less expensive than helium.
- 4) Can be disposed of by chemical reaction (eg. $H_2 + 1/2 O_2 \rightarrow H_2O$) before sending to the charcoal beds.
- 5) Will provide extra oxygen in solution to insure protection from corrosion.

Some of its disadvantages are:

- 1) If oxygen is not removed chemically, then the passage of large quantities of oxygen through the charcoal beds offers a greater chance for charcoal to oxidize than does helium.
- 2) Not as adaptable to use with standard compressing equipment (i.e. liquid oxygenator or special compressors must be used).
- 3) Use of pure oxygen is hazardous.

Effect of Gas Pressurization on Process

Safety calculations have been shown the need for a gaseous space in contact with the reactor solutions to accomodate surges due to liquid expansion caused by sudden reactivity additions. In this way the maximum pressure to which the system is subjected is confined within design limits.

The core vessel will probably stand an internal pressure increase up to 800 psi at operating conditions. The design pressure rise is taken as half this value or 400 psi. Associated with a 400 psi core pressure rise is the maximum permissible reactivity addition. For the HRT design (~73 liters vapor volume) the maximum pressurizer pressure increase at the time of maximum allowable core pressure was found to be 200 psi, associated with the expulsion of 5.4 liters (in ~0.1 sec.) of core fluid into the pressurizer volume.

Since the pressure surge from reactivity addition takes place over a very short time interval (~ 0.1 sec.), the compression in the pressurizer is assumed adiabatic rather than isothermal. The minimum gas spaces in the pressurizer corresponding to the various gases of interest, have been calculated for the following conditons (HRT):

$(\Delta p)_p = 200$ psi, maximum permissible pressure rise in pressurizer

$(\Delta V)_p = 5.4$ liters, volume of liquid ejected into pressurizer.

For adiabatic compression

$$pV^k = \text{constant} \quad (2)$$

where V = gas volume (1)

$$k = \frac{c_p}{c_v}$$

c = heat capacity.

For the pressurizer

$$p_o V_p^k = [p_o + (\Delta p)_p] [V_p - (\Delta V)_p]^k \quad (3)$$

Solving for V_p , the pressurizer gas volume

$$V_p = \frac{(\Delta V)_p}{1 - \left[\frac{p_o}{p_o + (\Delta p)_p} \right]^{1/k}} \quad (4)$$

where $p_o = 2000$ psia, total operating pressure.

Minimum volumes for the pressurizer have been calculated from equation (4) for various gases and are listed in Table I along with values of k .

TABLE I
MINIMUM VOLUMES FOR THE HRT PRESSURIZER

Gas	$k = \frac{c_p}{c_v}$ (300°C and 2000 psia)	Volume of Pressurizer, Liters
He	1.57	91.7
O ₂	1.35	79.2
D ₂ O	1.2 (=1.26 at 1250 psi)*	70.7
70%D ₂ O+30%He	1.35 (molar average)	79.2
70%D ₂ O+30%O ₂	1.29 (molar average)	75.8

* Values of k for D₂O are assumed the same as k for H₂O and are taken from the steam tables.

Minimum volumes recommended for the pressurizer are:

For Helium	90 liters ⇌ 3.2 ft ³
Oxygen	80 liters ⇌ 2.8 ft ³
D ₂ O vapor	71 liters ⇌ 2.5 ft ³

Effect of Pressurizer Volume in Case of Fuel Circulation

Stop and no Heat Removed from Core Solution

If the fuel circulating pump stops then the fuel solution will heat up. The temperature rise with time has been calculated by J. Hill [1] for infinite reactor operation time at 5 Mw and 10 Mw and for 1-day operation time at 5 Mw. The assumptions he made for this calculation are:

- 1) Circulation is stopped with no heat removed by the main heat exchanger.
- 2) No material is dumped to the low pressure system.

As the fuel solution temperature rises the liquid expands into the pressurizer and the compression of the gas in the pressurizer causes an

increase in total system pressure. When the pressure reaches 2800 psia the dump valves are set to open automatically and the solution is dumped to the low pressure system. The rise in pressure is a function of pressurizer gas volume and temperature of the core solution. This in turn is a function of time after a circulation stop.

The time for the pressure to reach 2800 psia vs. pressurizer volume is estimated on the following assumptions:

- 1) Only the solution in the core vessel heats up (volume of core is 300 liters)
- 2) Operating conditions before circulation stop are 2000 psia total pressure and 280°C average solution temperature.
- 3) Core and Blanket pressurizers are connected by an open line, making both volumes available for expansion.
- 4) Core and Blanket pressurizers are equal in volume.
- 5) No core solution is lost through the let-down system.
- 6) No condensation of vapor from the gas space occurs or vaporization of liquid from liquid phase; i.e. the stagnant liquid leg leading to the pressurizer acts as a piston compressing the gas with no mass transfer between phases.
- 7) Adiabatic compression.

The time required for the pressure to reach 2800 psia is plotted versus pressurizer gas volume on Figure 1 for the cases of infinite reactor operation at 5 Mw and 10 Mw, and of one day's operation at 5 Mw. The pressurizing gas assumed was oxygen. For comparison purposes the time versus volume curve for pure D_2O vapor is plotted on Figure 1 for the cases of infinite operation at 5 Mw. See appendix I for the derivation of equations leading to Figure 1.

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The temperature of the gas in the gas space after it has been compressed to 2800 psia can be found from the equation

$$T_p \frac{1-k}{k} = \text{constant} \quad (5)$$

where T = absolute temperature.

For the case under consideration the temperature of the gas after being compressed adiabatically to 2800 psia is 345°C (assuming the initial temperature is 300°C).

If the time required for the pressure to reach 2800 psia is small (≤ 5 minutes) the assumption of adiabatic compression is good. However in the case of large pressurizer gas volumes (> 200 liters total) in which the time required for the pressure to reach 2800 psia is greater than about 5 minutes, the mass transfer between liquid and gas phases may become quite significant. If mass transfer corresponding to equilibrium condition at the temperature of the core solution is assumed then an estimate of the time versus volume can be made by a trial and error method. These values are represented on Figure 1 by the dashed lines.

Estimation of Gas Phase Composition During Dumping Operation

Normal operation of the HRT involves the removal and let-down to atmospheric pressure of a stream of radiolytic gases from the main circulating lines of the core and blanket solutions. Before reaching the gas separators the radiolytic gas bubbles are in intimate contact with the reactor solutions. The solutions are therefore assumed saturated with the radiolytic gases (D_2 and O_2). The relationship between the concentration of gas in the liquid phase and its partial pressure in the bubble or gas phase is given by Henry's Law:

$$K_A = \frac{p_A}{x_A} \quad (1)$$

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The average temperature of the reactor solution at operating conditions is 280°C while the total pressure is 2000 psia. The partial pressures in a bubble (for average conditions) in the main circulating system are:

$$D_2O - 931 \text{ psi}$$

$$D_2 - 713 \text{ psi}$$

$$O_2 - \frac{356}{2000} \text{ psi}$$

At 280°C the values of the Henry's Law constant for D_2 and O_2 are [3]
 $\left\{ \text{assuming } K_A(D_2O) = \frac{18}{20} K_A(H_2O) \right\}$

$$K_{D_2} = 2.30 \times 10^5 \frac{\text{psi}}{\text{mol. fract.}}$$

$$K_{O_2} = 2.07 \times 10^5 \frac{\text{psi}}{\text{mol. fract.}}$$

The mole fraction of D_2 and O_2 in the liquid phase can now be estimated from equation (1)

$$x_{D_2} = 0.00311$$

$$x_{O_2} = 0.00172$$

Materials involved in the high-pressure systems are:

	<u>Volume, liters</u>	<u>Weight, lbs.</u>	<u>Density, lbs/ft³</u>
Core solution	490	920	52.65
Blanket solution	<u>1750</u>	<u>3240</u>	52.65
Total	2240	4160	

If all the liquid in the high-pressure system is assumed to be D_2O (essentially true) then there are 4160/20 or 208 lb moles of D_2O in the

high-pressure system. The amounts of D_2 and O_2 which are dissolved in this D_2O are:

$$\eta_{D_2} = 0.003110 (208) = 0.647 \text{ lb moles } D_2$$

$$\eta_{O_2} = 0.00172 (208) = 0.358 \text{ lb moles } O_2$$

As can be seen from the Henry's Law equation the amount of gas dissolved in solution is directly proportional to its partial pressure in the associated gas phase. Change in K_A is relatively small as compared to change in p_A . As the over-pressure ($2000 \text{ psia} - p_{D_2O}$) in the system is reduced, so are the partial pressures of deuterium and oxygen. As the partial pressures of deuterium and oxygen are reduced in the gas phase, these gases are stripped from the liquid phase and into the gas phase. When all the over-pressure is lost, essentially no deuterium or oxygen will remain in solution.

In the case of gas pressurization the gas feed is assumed to be 95% helium and 5% oxygen and the normal operating temperature of the pressurizer is 300°C . The composition of the gas phase in the pressurizers is (assuming complete removal of radiolytic gases from this space):

	<u>Partial Pressure</u>	<u>N, lb moles/ft³</u>
D_2O - 70.2%	1246 psi	0.1596
He - 28.3%	716	0.0647
O_2 - <u>1.5%</u>	<u>38</u>	0.00343
100.0%	2000 psi	

If the volume of the core and blanket pressurizers are each 90 liters then the total gas pressurizer volume is 180 liters ($\approx 6.35 \text{ ft}^3$), and the total amounts of gas (or vapor) present in the gas space are:

$$D_2O - 1.013 \text{ lb moles}$$

$$\text{He} - 0.411 \text{ lb moles}$$

$$O_2 - 0.0218 \text{ lb moles}$$

The amount of dissolved D_2 is high enough to cause some concern if all or a large part of it should suddenly be stripped into the gas phase. This could happen if the core were operating normally and a dumping operation were initiated suddenly.

By making a number of assumptions it is possible to calculate approximately the D_2 concentration in the gas phase as a function of total pressure during a dumping operation. Some of the assumptions are:

- 1) The radiolytic gases (D_2 and O_2) are always in equilibrium (according to Henry's Law) between liquid and gas phases. This is felt to be a good assumption since the gases are being stripped from the liquid to the gas phase during a dumping operation.
- 2) Helium is assumed to be insoluble. Initially the gas phase contains little or no radiolytic gases, but is rich in helium. During the dumping operation the tendency would be for helium to dissolve from the gas phase into the liquid phase. This is a relatively slow process as compared to the times involved in a dumping operation.
- 3) No internal recombination by Cu^{++} catalyst. This would be the case in a sudden dumping operation from full reactor power.
- 4) The temperature of the mixture in the high-pressure system (both gas and liquid phases) is uniform during the "dump".
- 5) No gas is vented from the high pressure system during the "dump".
- 6) No heat is lost from the system except the sensible heat leaving with the liquid being "dumped" to the low pressure system.

The concentration of D_2 in the Gas Phase of the HRT high pressure system is plotted versus total pressure during a dumping operation in Figure 2 for both the gas pressurized system and the D_2O vapor pressurized system. The methods of calculating the gas phase composition is given in Appendix II.

As seen from Figure 2 the concentration of D_2 builds up to values well above the lower explosive limits in oxygen. Also, sufficient oxygen is present to support combustion. The D_2 concentration reaches a higher maximum for the D_2O vapor pressurized system than it does for the gas pressurized system. This may not be a significant difference since the explosive limit is lower when gas is a diluent than when D_2O vapor is a diluent. In both cases, however, the concentration is explosive and the condition must be considered hazardous.

If the gas should explode in the gas pressurized system when the total pressure has been reduced to 1922 psia ($p_{D_2O} = 928$ psi) the heat input to the gas phase will be

$$(0.329 \text{ lb mole } D_2) (105,000 \text{ Btu/lb mole}) = 34,500 \text{ Btu}$$

Composition of gas phase at this time is:

$$N_{D_2} = 0.329 \text{ lb. mol}$$

$$N_g = 0.922 \text{ lb moles}$$

$$D_2O \text{ vapor} = 22.62 \text{ lbs}$$

Let t_f = final temperature $^{\circ}F$.

$$C_{pm}(\text{gases}) = 6.16 \text{ Btu/lb mole } ^{\circ}F.$$

$$C_p(D_2O) \approx 0.8 \text{ Btu/lb } ^{\circ}F$$

Then:

$$(t_f - 535.6)(6.16 \text{ Btu/lb mole } ^{\circ}F)(0.922 \text{ lb mole}) + (t_f - 535.6)(0.8 \text{ Btu/lb } ^{\circ}F)(22.62 \text{ lbs}) = 34,500 \text{ Btu}$$

Solving for t_f

$$t_f = 1990^{\circ}F$$

The final pressure, p_f , due to the gas temperature rise, can be estimated from the perfect gas law as

$$p_f = \frac{N_{\text{total}} (\text{gas phase}) R T_g}{V_g} = 5500 \text{ psia}$$

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In the case of vapor pressurization

$$p_f \approx 5000 \text{ psia}$$

If detonation occurs on either core or blanket side, rupture of the core vessel is likely.

A comparison between the calculations made for the gas pressurized system and the vapor pressurized system indicates that the pressure drop (with amount of liquid dumped) is much more gradual in the case of the gas pressurized system. This is shown in Figure 3 in which pressure is plotted versus amount of reactor solution dumped for each case.

Delay Time Before Dumping of Reactor Solution

The concentration of D_2 in the gas phase is highest shortly after the dumping operation begins. The maximum D_2 concentration during a "dump" approaches the concentration of D_2 in the gas phase of the gas separator during normal operations. At 300°C and 2000 psia this value is 20% D_2 . The hazard during a "dump" is aggravated, however, because the volume of the gas phase is much larger. One method to reduce this hazard is to delay the dumping operation (after power shutdown) in order to allow the dissolved Cu^{++} catalyst to recombine some of the radiolytic gases which are dissolved in the reactor solutions. It is desirable to know the maximum mole % of D_2 in the gas phase which might be expected during a "dump" as a function of % D_2 (present at saturation) recombined in the liquid phase before the dumping operation begins. These values have been estimated by the procedure outlined in Appendix II and are plotted versus % D_2 recombined in Figure 4. Presented in addition to values for an operating pressure of 2000 psia, are values for total initial pressures of 2200 psia, 1800 psia and 1600 psia.

Copper catalyst concentrations in the core solution may range from $0.0018 \frac{\text{g-mols}}{\text{liter}}$ ($\approx 80\%$ of the radiolytic gas recombined internally) to $0.0025 \frac{\text{g-mols}}{\text{liter}}$ (essentially all radiolytic gas recombined internally).^[6] In order to estimate the time required to recombine some of the gas after a power shutdown it is necessary to consider the average temperature of the core solution and to consider the residual power. Normally the power will be reduced by cutting back on the cooling water to the main heat exchanger. This causes a rise in the average temperature of the core solution which in turn reduces the reactivity. For the present case it will be assumed that the average temperature is allowed to reach 300°C . At this temperature the residual power is estimated^[1] to be (assuming ∞ operation time at 5 Mw)

$$P_f = \text{Power from fission heat} = 240 \text{ kw}$$

$$P_{fp} = \text{Power from fission product heat} = 120 \text{ kw}$$

$$P_r = \text{total residual power} = 360 \text{ kw.}$$

Assuming a G-value for fission heat of $1.67 \frac{\text{molecules } D_2O}{100 \text{ ev}}$ and for the fission product heat of $0.45 \frac{\text{molecules } D_2O}{100 \text{ ev}}$, the average D_2 production rate after a power shutdown is

$$v_{D_2} = 2.06 \times 10^{-6} \frac{\text{mols } D_2}{\text{mole sol'n-sec.}}$$

From CF54-9-64^[1] the time required for the temperature to reach 300°C after a power shutdown is ~ 25 seconds. This corresponds to the case of a circulation stop, however, and the time may be somewhat longer in the case of a controlled shutdown.

To estimate the delay time needed to recombine some of the radiolytic gas the following assumptions will be made:

1) The delay time will start after the temperature of the core solution reaches 300°C and the residual power is reduced to 360 kw.

2) The solution is saturated with deuterium and oxygen at this time (x_{sat} for $\text{D}_2 = 0.0031$ mole fraction).

Values for the delay time required have been calculated from equation 16 (Appendix III) and are listed in Table II.

TABLE II
DELAY TIMES AFTER POWER SHUTDOWN FOR CONTROLLED SHUTDOWN

% D_2 Recombined in Liquid Phase	Time, minutes					$\frac{\text{g mols Cu}^{++}}{\text{liter}}$
	$y = 0.0010$	$y = 0.0019$	$y = 0.0022$	$y = 0.0025$	$y = 0.0050$	
50	0.93	0.47	0.41	0.36	0.17	
70	1.66	0.83	0.71	0.62	0.31	
80	2.30	1.13	0.96	0.84	0.41	
90	3.66	1.67	1.43	1.25	0.60	
95	∞	2.43	2.02	1.73	0.80	

The values presented in Table II are plotted on Figure 5.

In the case of a circulation stoppage the temperature of the fuel solution will continue to rise above 300°C . Since the recombination rate constant increases exponentially with temperature, the time required to recombine a given percentage of the dissolved radiolytic gas will be less than in the case of a controlled shutdown (where the temperature of the fuel solution was held constant at 300°C). The relationship between fraction D_2 recombined and time is given by equation (21)

of Appendix III. This relationship is plotted for several copper concentrations on Figure 6. In this case, for a copper concentration of $0.0019 \frac{\text{g mols}}{\text{liter}}$, only 1.4 minutes delay time is required to recombine 90% of the dissolved gases as compared to 1.7 minutes for the case of a controlled shutdown (See Figure 5).

From Figure 1, the time required for the pressure to reach 2800 psia is 7.4 minutes for a gas space equal to 180 liters (2-90 liter pressurizers). It appears feasible then to wait the 1.4 minutes before dumping the contents of the reactor when both blanket and core pressurizer gas spaces are available for the core solution expansion.

In the case of the presently designed steam pressurized system (73 liters free volume), however, failure of the rupture discs to blow could permit the pressure to rise to 2800 psia in about 40 seconds (worst conditions). In this case it will not be feasible to wait the 1.4 minutes for 90% of the radiolytic gas to recombine. Only about 60% of the dissolved D_2 will recombine in 40 seconds (assuming $0.0019 \frac{\text{g mols Cu}^{++}}{\text{liter}}$).

In the case of the blanket (assumed pure D_2O), there is some question as to whether radiolytic gases will be produced. Since there is a considerable amount of gamma energy absorbed in the blanket, the γ -induced recombination of the radiolytic gases may be sufficient to eliminate these gases from consideration. Impurities (including Cu^{++}) will, however, tend to destroy the process by which γ -induced recombination takes place. In this case it may be desirable to design the blanket for copper recombination until such time as sufficient data is obtained to place faith in the γ -induced process.

The radiolytic gas production rate in the D_2O blanket has been estimated as [5, 6]

$$v_{D_2} = 93 P_c \frac{\text{cc(STP)}D_2}{\text{sec}} \quad (6)$$

where v_{D_2} = production rate of D_2 gas.

P_c = Power of core, Mw.

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This corresponds to a gas production rate at 5Mw core power of (assuming 1560 liters of D_2O in blanket loop)

$$v_{D_2} = 3.16 \times 10^{-7} \frac{\text{mols } D_2}{\text{mol } D_2O \text{ -sec.}} \quad (7)$$

For a gas production rate this small the minimum copper concentration needed to recombine all the gas produced is $\sim 1.7 \times 10^{-5} \frac{\text{g-mols } Cu^{++}}{\text{liter}}$. Also the blanket temperature is an average of $280^\circ C$. and will not heat up in case of a core circulation stoppage as does the core solution. At $280^\circ C$. the copper recombination rate constant is less than half the value at $300^\circ C$. At the copper concentration given above the dissolved radiolytic gases (after long term operation) will be at or very near saturation. The waiting period (after power shutdown and before the dump is initiated) necessary to recombine 90% of these gases is about 6 hours. Since this would be unreasonably long to wait before initiating a dump, a sufficient amount of copper catalyst should be used to hold the dissolved radiolytic gas level low enough to prevent explosive mixtures in the gas phase in the event of a dump. A plot of dissolved D_2 concentration versus copper concentration is given in Figure 7.

Methods of Pressurization

Probably the safest gas to pressurize with is helium containing 5% oxygen. This gas can be pressurized by means of a standard gas compressor, the gas mixture being stored in a reservoir at ~ 3000 psia. (Since the pressure in the reactor may possibly rise to a maximum of 2800 psia the reservoir is maintained at 3000 psia to insure a positive pressure on the reactor system at all times.) From this reservoir the gas is sent to the pressurizers, which are kept at 2000 psia. The gas is fed to the compressor from a mix tank which in turn is fed from oxygen and helium cylinders or tanks (see Figure 8).

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If the process is such that the gas can be thrown away then the pressurizing equipment (compressor, reservoir, mix tank) may be assembled outside the shield. This case will be considered first. If a standard oil lubricated gas compressor is used it may be necessary to install a device to remove oil from the gas. This oil absorber should be placed before the pressure reservoir.

Operation of System

Helium and oxygen gas is fed from tanks and/or cylinders to mix tank (95% He + 5% O₂). The compressor (standard) takes feed from the mix tank and delivers it to the gas reservoir through the oil absorber. Gas is then fed to the common line between core and blanket pressurizers. The line to the connecting pipe between the pressurizers must contain check valves or other suitable valves to prevent the transfer of material and consequently radioactivity to the reservoir, from the pressurizers, in event of a reactor pressure surge.

In order to prevent the build-up of radiolytic D₂ in the pressurizers a bleed line is provided to let down a quantity of gas continuously. Assuming the maximum or upper limit to the radiolytic gas production [5] in the pressurizer, the flow rate through the bleed line is as follows:

$$\text{Upper limit on D}_2 \text{ production} = 0.03 \frac{\text{cc D}_2'(\text{STP})}{\text{sec.}}$$

To keep concentration $\leq 1\%$ D₂ in pressurizer gas space set $0.01 f = 0.03$.

The flow rate, $f = 3 \text{ cc/sec (STP)} \approx 0.05 \text{ cc/sec}$ or 3 cc/min at 300°C and 2000 psia .

This flow rate is very small and the loss of He is therefore small enough to be thrown away economically.

The charcoal adsorber system is designed for 500 cc/min operation, which is about twice what is expected from the release of O₂ from the letdown stream. The gas load from the pressurizers would be $\sim 200 \text{ cc/min (STP)}$. The charcoal adsorbers should be able to handle this quantity easily.

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The question of let-down from the pressurizers is an important one. If a valve is used the leakage around the valve when it is completely shut-off might be greater than 500 cc/min (STP)*. So if the gas is to be sent through the charcoal beds and then to the stack, a more efficient let-down system than the valve-in-line system must be designed. This design will probably take the form of long capillary tubes in parallel with incremental cutting in or out of tubes to get the desired flow. A hydrogen analyzer should be in the line to determine the flow rate needed and to provide knowledge of radiolytic gas build-up in the pressurizers.

This let-down stream should be fed into the low-pressure entrainment separator and recombiner and allowed to follow the regular gas stream from that point on to the stack.

Loop Separate from Off-Gas System

Helium was used to pressurize the blanket of the HRE. Pressure was 1000 psia so the helium could be fed directly from cylinders (at 2000 psia) to the system. Large quantities of helium were used due to leaks and frequent dumping operations. Pressure of the HRT is twice as great as the HRE and similar leaks would cause even greater quantities of He to be lost.

If a let-down system cannot be devised to limit the bleed line flow to the small quantities previously estimated, then it may be necessary to recirculate the helium. In this case a let down line with throttle valve may be used with the gas passing through an entrainment separator and a recombiner and then back to the compressor. See Figure 9. This loop may be a high-pressure loop when operating normally, in which case throttle valves will not be needed.

* Communication from I. Spiewak

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In this case the compressor, reservoir and loop will be inside the shield. This may provide an answer to the gas handling question during a dump. The gas which collects in the condenser is sent back to the compressor which pumps it into the reservoir for storage until it is needed again. This would relieve the charcoal adsorber beds of a great part of their excess load during a dump.

The major drawback here is the lack of a compressor for the job at the present time. It must operate in a radiation field and will most likely have to pump radioactive gases.

PRESSURIZERS

For simplicity of construction, the core and blanket pressurizers should be the same size. Actually the blanket pressurizer for the D₂O blanket need not be as large as the core pressurizer. The size of the pressurizer is a function of the power surge expected in the solution with which it is associated. If slurries are used (or uranyl sulfate) in the blanket, then sizing of the blanket pressurizer is also a factor. However, if the same size pressurizer is used for both blanket and core solutions, the power from the blanket can equal approximately half that of the core before the blanket pressurizer would be considered too small.

Interconnection Between the Two Pressurizers

Since both pressurizers will be fed from the same pressure reservoir, some consideration should be given to the interconnection between the pressurizers. The simplest connection between the core and blanket pressurizers is an open line (probably 1" to 2" pipe). The feed line from the pressure reservoir should join this common connecting line (See Figure 8). This type interconnection and feed system should be investigated experimentally before its adoption into

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the HRT. To minimize the transfer of entrained liquid between the core and blanket systems, entrainment separators (wire mesh) can be placed in the vertical sections of the common line leading from each pressurizer.

Radiolytic Gases

One means of handling the radiolytic gases (as discussed earlier) is to have continuous bleed lines from each pressurizer.

A second means of reducing the D_2 concentration to a safe level involves the use of a water purge stream to the pressurizer. A purge stream of ten gallons per hour should be sufficient. [7]

A third means of controlling the radiolytic gas involves the use of a natural circulation catalytic recombiner in the pressurizer. In this case, no bleed lines or purge lines are present to cause leaks in the system. Since the possibility exists of explosive mixtures in the gas phase during a dump, the presence of a recombiner in the pressurizer may be highly undesirable.

Arrangement of Pressurizer

It does not matter as far as the reactor solution is concerned whether the pressurizer is vertical or horizontal. All that matters to the process is that there be no excessive resistance in the line leading to the gaseous space of the pressurizer. Since most of the development work conducted up to the present time has been with horizontal pressurizers, it will probably be best to stay with this arrangement. Whether one or more legs, leading to the pressurizer from the lower header is needed, will depend on the heat transfer area needed to maintain the reactor solutions at 300°C .

There are about 6 feet of space between the lower header and the bottom of the top plugs of the shield. In the D_2O vapor pressurizer design, the pressurizer drum is about 3-1/2 ft. above the lower header with the legs between the lower header and pressurizer drum inclined at an angle to give

greater heat transfer surface. This large area of heat transfer is not needed for the gas pressurizer and the level of liquid in the drum need not be more than about 12" above the lower header. (This space is needed to control the liquid level in the pressurizer).

Sizing of Gas Reservoir

The size of the gas reservoir should be small enough so that the design pressure of the low-pressure system will not be exceeded in case of a dump without cooling in which all the gas in the reservoir and pressurizers is dumped with the reactor solutions. This design pressure is 600 psia.

Calculations have been made, and are presented in Appendix IV, which indicate that a pressurizer volume of $\sim 6 \text{ ft.}^3$ is permissible.

Actually the system is relatively insensitive to reasonable gas volumes, as compared to other factors such as total expansion space, and amount of liquid solution in the dump tanks before the dumping operation occurs.

Handling of Gas During Dumping Operation

The amount of gas which must be handled by the low pressure system at this time is estimated from the perfect gas law.

$$N_g = \frac{pV}{RT}$$

where $p = 750 \text{ psi}$ partial pressure of noncondensables at 300°C

$$T = 300^\circ\text{C} \approx 1032^\circ\text{R}$$

$V = 90 \text{ liters}$, volume of pressurizer.

Solving for N_g

$$N_g = 0.218 \text{ lb-mol} \approx 78 \text{ ft.}^3 \text{ (STP)} \approx 107 \text{ ft.}^3 \text{ at } 100^\circ\text{C and } 1 \text{ atmos.}$$

On a dump the gas along with fuel solution is dumped into the dump tanks. From there the gas passes through the entrainment separator, gas recombiner and condenser in that order. For the present consideration the noncondensables then go to the cold traps, charcoal beds, off-gas filter and stack in that

order. At the present design capacity of the carcoal beds, it will require several hours or even days to relieve the low pressure system of the noncondensable gases.

The volume of the condenser is approximately 4.6 ft.³. In the present case most of the gas would collect there. If it did not go there immediately on the dump, it would soon be stripped to the condenser by the vapor from the flashing liquid in the dump tank. Gas binding would therefore occur in the condenser, reducing its capacity.

The noncondensable gases include too much radioactive gases (fission products) to vent directly to the stack. So some additional means must be provided for handling the gas at this time. One means (suggested by C. B. Graham) is to provide a gas hold up tank in the line between the gas condenser and the cold traps. (See Figure 8) Operation of this hold up tank would be as follows:

1. The check valve is set at, say 70 psi.
2. As dump proceeds, the low pressure system pressure rises above 70 psi which opens the check valve.
3. Gas from condenser passes into the tank, relieving the condenser.
4. A thermostatic valve is also in the line to prevent vapor from entering the hold up tank.
5. Gas is stored in the tank and released to the cold traps and charcoal adsorbers at the design flow rate. It will probably take several days to release all the gas. (A second dump during this period would be undesirable).

The volume needed in this hold up tank can be estimated from the gas law. Assuming a gas temperature of 300°F. the tank volume for several pressures are:

<u>Maximum Pressure in Tank, psia</u>	<u>Volume of tank, ft.³</u>
70	33
200	10
400	5

Some of the advantages and disadvantages of such an arrangement may be listed as follows:

Advantages:

1. The gas is fed to the tank as the pressure rises in the low-pressure system due to a dump. This gas can then be held in the tank at a high pressure until it can be released through the off-gas system. During this time the rest of the off gas system can operate normally.

2. Gas is removed from system and stored where it can be controlled.

3. Provides more volume for expansion in case of cooling water failure.

Disadvantages:

1. Gas stored in tank is radioactive and therefore tank must be placed inside shield.

2. Several control and check valves will be needed

Gas Hold-up Tank in Line Between Condenser and Cold Traps

Valves are a source of trouble and expense, so it may be possible and desirable to design the hold-up tank without the valves and send all gases through the tank. In this case a cooling surface should be provided inside the tank to condense out vapors.

Some advantages here include:

1. Provides added hold-up time for radioactive gases during normal operation as well as during dump.

2. Valves are eliminated.

Gas Trapped in High Pressure System (partial dump)

A third means of handling gas during a dump is to trap it in the high pressure system, i. e. dump only the liquid solution.

Some advantages and disadvantages of this method of handling gas are listed below:

Advantages:

1. Noncondensable gas is probably the last material to leave the high-pressure system on dump and so it is probably easy to get most or all liquid out of the high-pressure system into the low-pressure system before any gas is released to gas bind the condenser (assuming no gas vents).
2. No gas hold-up tank is needed in the low-pressure system.

Disadvantages:

1. The pressure will still be fairly high in high-pressure system. In case of leak some loss would still occur.
2. If the dump valve fails to close properly the gas may go to the low-pressure system anyway and gas bind the condenser.
3. As seen from Figure 2 the composition of the gas phase during a dump may be explosive. This is perhaps the most serious disadvantage to this method of handling the gas.

Redesign of Off-gas System

A fourth solution to the gas handling problem during a dumping operation is to increase the capacity of the off-gas system (beyond the condenser) so as to handle the gas from the pressurizer in a reasonable length of time.

Remove Gas from System by Chemical Means

If oxygen is used as the pressurizing means rather than helium it may be possible to remove the noncondensables during a dumping operation by chemical reaction. One example is to add the oxygen along with ordinary hydrogen

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(from cylinders) to a catalytic recombiner. The water is then condensed out with only the fission gases and residual hydrogen or oxygen passing on through the charcoal beds and eventually out the stack.

APPENDIX I

DERIVATION OF EQUATIONS RELATING TIME FOR PRESSURE TO RISE TO 2800 PSIA AFTER
CIRCULATION STOP WITH GAS VOLUME IN PRESSURIZERS

The derivations of the equations represented in Figure 1 are as follows:

Let ΔV = decrease in gas volume of pressurizers due to fuel solution expansion

Δp = pressure increase = 800 psi for final pressure of 2800 psia

p_o = 2000 psia

V_o = total gas space in both pressurizers

From equation (2)

$$p_o V_o^k = (p_o + \Delta p) (V_o - \Delta V)^k$$

Solving for ΔV

$$\Delta V = V_o \left\{ 1 - \left(\frac{p_o}{p_o + \Delta p} \right)^{1/k} \right\} \quad (8)$$

For $\Delta p = 800$ psi and $k = 1.29$ (mixture of O_2 and D_2O)

$$\Delta V = 0.230 V_o \quad (8a)$$

The change in density with temperature is estimated as [2]

$$\frac{d\rho}{dt} = -0.0925 \frac{\text{lbs}}{\text{ft}^3 \text{ } ^\circ\text{F}} \approx -0.1665 \frac{\text{lbs}}{\text{ft}^3 \text{ } ^\circ\text{C}}$$

where ρ = density

t = temperature

Since there is no net gain or loss of mass in the fuel solution

$$\rho_o V_c = (\rho_o + \Delta\rho) (V_c + \Delta V)$$

where ρ_o = fuel density at operating conditions = 50.6 lbs/ft³

V_c = initial fuel solution volume = 300 liters $\approx$ 10.6 ft³.

Solving for ΔV

$$\Delta V = \frac{\rho_o V_c}{\rho_o + \Delta\rho} - V_c = \frac{-V_c \Delta\rho}{\rho_o + \Delta\rho} \approx \frac{-V_c \Delta\rho}{\rho_o}$$

But

$$\Delta\rho \approx \Delta t \frac{d\rho}{dt}$$

Therefore

$$\Delta V \approx \frac{-V_c \Delta t \left(\frac{d\rho}{dt} \right)}{\rho_o} \quad (9)$$

where Δt = temperature rise in fuel solution °C.

For the present assumptions

$$\Delta V = 0.0349 \Delta t, \text{ ft}^3 \approx 0.988 \Delta t \text{ liters} \quad (9a)$$

From equation (8a) the expansion of core solution, ΔV , can be found as a function of total gas volume, V_o . The corresponding temperature rise in the core solution, Δt , is computed from equation (9a). From Figure 3 of CF 54-9-64, [1] the time can be found as a function of temperature rise for several operating power levels. Thus it is possible to estimate the time required after a circulation stop for the pressure to increase to 2800 psia. This time is plotted versus pressurizer gas volume on Figure 1 for the cases of infinite reactor operation at 5 Mw, and 10 Mw and of one day's operation at 5Mw.

APPENDIX II

DETERMINATION OF HRT GAS PHASE COMPOSITION DURING DUMPING OPERATION

The concentration of D_2 in the gas phase during a dumping operation can be approximated by a trial and error procedure based on heat and mass balances and Henry's Law. The total heat content of the contents of the high pressure system is given by

$$H = w_l h_f = w_g h_g + N_g C_{pm} (t - 32) \quad (10)$$

where H = total heat content of high pressure system, Btu.

w_l = weight of liquid in high pressure system (assumed D_2O), lbs.

w_g = weight of D_2O vapor, lbs.

h_f = enthalpy of liquid, Btu/lb.

h_g = enthalpy of vapor, Btu/lb.

N_g = total number of lb-mols of gas present (whether dissolved on in gas phase)

C_{pm} = mean heat capacity of gases, $\frac{\text{Btu}}{\text{lb mol}^\circ\text{F}}$

t = temperature, $^\circ\text{F}$

The calculation is accomplished by first coosing a vapor pressure of D_2O . This is done in incremental steps, the smaller the increment the more accurate the calculation. At operating conditions (280°C and 2000 psia) the partial pressure of D_2O is 930 psi. The first value chosen for the preparation of Figure 2 was $p_{D_2O} = 928$ psi. Let

subscript n = refer to n^{th} incremental step

$n + 1$ = refer to $(n + 1)^{\text{th}}$ incremental step.

Then the weight of D_2O liquid which flashes to vapor in this interval

$\left[(p_{D_2O})_n \text{ to } (p_{D_2O})_{n+1} \right]$ is found from

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Then the weight of D_2O liquid which flashes to vapor in this interval

$\left[(p_{D_2O})_n \text{ to } (p_{D_2O})_{n+1} \right]$ is found from

$$X_n = \frac{H_n - (w_l)_n (h_f)_{n+1} - (w_g)_n (h_g)_{n+1} - (N_g)_n C_{pm} [t_{n+1} - 32]}{(h_{fg})_{n+1}} \quad (11)$$

where X_n = weight of liquid D_2O flashing to vapor in the n^{th} incremental step., lbs.

h_{fg} = enthalpy change from liquid to vapor.

The volume of the gas phase can be estimated from the amount of D_2O vapor present.

$$(V_g)_{n+1} = \frac{(N_{D_2O})_{n+1} Z_{D_2O} RT}{(p_{D_2O})_{n+1}} \quad (12)$$

where V_g = volume of gas space, ft^3

$$(N_{D_2O})_{n+1} = (N_{D_2O})_n + \frac{X_n}{20} = \text{lb. mols of } D_2O \text{ vapor present.}$$

R = gas constant

Z = compressibility factor

The partial pressure due to the noncondensable gases present in the gas phase is

$$(p_g)_n = \frac{(N_g)_n RT}{(V_g)_n} \quad (13)$$

The total pressure on the system at the n^{th} incremental step is given by

$$(p_{D_2O})_n + (p_g)_n = p_{total} \quad (14)$$

Several conditions must be considered during the dumping operation in order to estimate the D_2 concentration in the gas phase. The solution is leaving the system through the dump lines and the gas is expanding due to the decreasing

pressure, D_2O liquid is flashing to vapor, and dissolved gases are being stripped out of solution. Temperature is also changing. To get an estimate of the gas phase composition versus pressure the following procedure was used:

1. Determine the overall heat content of the contents of the high pressure system using equation (10).
2. Choose a vapor pressure p_{D_2O} .
3. From the steam tables determine t , h_f , h_{fg} , h_g , z_{D_2O} (these values are for saturated conditions at p_{D_2O}).
4. Determine values for the Henry's Law constant for O_2 and D_2 [3] at t , $^{\circ}F$.
5. Determine the weight of D_2O liquid which has flashed to vapor in this interval (partial pressure of D_2O interval). This is found from equation (11).
6. The volume of the gas phase can now be determined from (equation 12).
7. The volume increase in the gas space multiplied by the density of the liquid solution is the weight of liquid dumped from the high-pressure system during this interval.
8. Assume values for N_{D_2} and N_{O_2} , the number of lb. mols of D_2 and O_2 in the gas phase.
9. From $N_{D_2} + N_{O_2} + N_{He} (=0.411) = N_g$ (total) determine the partial pressure of the gas. This is determined by equation (13).
10. Determine from the assumed values, the mol fraction, μ , of D_2 and O_2 in the gas phase (considering only the noncondensables).
11. From the mole fraction determine the partial pressures, p_{D_2} and p_{O_2} , exerted by the D_2 and O_2 in the gas phase. [i.e. $p_{D_2} = \mu_{D_2} p_g$].
12. From p_{D_2} and K_{D_2} , and p_{O_2} and K_{O_2} determine x_{D_2} and x_{O_2} , the mole fraction of gases dissolved in the liquid phase.
13. The mole fraction times the number of lb mols of liquid remaining in the system plus the mole fraction times the number of lb moles of liquid dumped in this pressure interval equals the number of lb moles, η , still

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dissolved in the liquid phase.

14. Subtract η_{D_2} from the total amount of D_2 present from the preceding pressure interval to get N_{D_2} . In a similar manner N_{O_2} is found. These values should equal the values assumed in step 8. If not, new values are assumed and steps 8 - 14 repeated until a check is obtained. When check is obtained p_g is fixed and the total pressure is given by equation (14). Also the D_2 composition is known for this pressure.
15. This procedure is then repeated for another chosen value for p_{D_2O} , making allowances for the ejected liquid solution and its dissolved gases.

APPENDIX III

DERIVATION OF EQUATIONS FOR DELAY TIME AFTER POWER SHUTDOWN AND
BEFORE DUMP IS INITIATED

Case A. Controlled Shutdown where Temperature = 300°C and Residual Power = 360 kw.

Let θ = time, seconds

y = concentration of copper catalyst, $\frac{\text{g. mols}}{\text{liter}}$

k_{Cu} = recombination rate constant for copper catalyst, $\frac{\text{liters}}{\text{g.mol Cu}^{++}\text{Sec.}}$

x_{D_2} = D_2 concentration in liquid core solution, mol. fraction.

The rate change of x_{D_2} with time can be represented by the differential equation

$$\frac{dx_{\text{D}_2}}{d\theta} = v_{\text{D}_2} - k_{\text{Cu}} y x \quad (15)$$

Equation (15) can be solved for θ , the required delay time (assuming $\theta = 0$ at time when temperature of core solution reaches 300°C and power is reduced to 360 kw after power shutdown).

$$\theta = \frac{1}{k_{\text{Cu}} y} \ln \left\{ \frac{\left(x_{\text{D}_2} \right)_{\text{sat}} - \frac{v_{\text{D}_2}}{k_{\text{Cu}} y}}{x_{\theta} - \frac{v_{\text{D}_2}}{k_{\text{Cu}} y}} \right\} \quad (16)$$

where $\left(x_{\text{D}_2} \right)_{\text{sat}} = 0.0031$ mol. fraction

x_{θ} = D_2 conc. at time θ $\left(\frac{x_{\theta}}{x_{\text{sat}}} = \text{fraction } \text{D}_2 \text{ unrecombined} \right)$

$k_{\text{Cu}} = 13.4 \frac{\text{liters}}{\text{g.mol Cu}^{++}\text{sec.}}$ at 300°C.

Case B. Uncontrolled Shutdown (Circulation Stoppage Assumed as Worst Case).

In this case the recombination rate constant, k_{Cu} , is not constant at all but varies exponentially with temperature. For the HRT fuel solution the expression for k_{Cu} is [4]

$$k_{Cu} = a e^{-\frac{b}{T}}$$

where $a = 2.37 \times 10^{10}$

$b = 12,200$

$T = \text{temperature, } ^\circ\text{K}$

To get an estimate of the delay time involved here, again assume that the delay time starts when the core solution reaches a temperature of 300°C . and that the production rate is still $2.06 \times 10^{-6} \frac{\text{moles } D_2}{\text{mole soln sec.}}$. The temperature versus time curve of CF-54-9-64 [1] (Figure 3 for 5 mw after ∞ operation) is approximated by the expression

$$\frac{T}{T} = \phi_1 - \phi_2 \theta \quad (17)$$

where $\phi_1 = 0.001742$

$$\phi_2 = 1.32 \times 10^{-7}$$

Equation (15) can now be written for this case .

$$\frac{dx}{d\theta} = v_{D_2} - ayxe - b(\phi_1 - \phi_2 \theta) \quad (18)$$

The solution of equation (18) is

$$\left[x_{\theta} e^{\beta e^{b\phi_2 \theta}} - (x_{D_2})_{\text{sat}} e^{\beta} \right] = \frac{v_{D_2}}{b\phi_2} \left\{ \text{Ei}(\beta e^{b\phi_2 \theta}) - \text{Ei}(\beta) \right\} \quad (19)$$

$$\text{where } \beta = \frac{a y e^{-\phi_1 b}}{b\phi_2}$$

Solving for x_{θ}

$$x_{\theta} = e^{-\beta e^{b\phi_2 \theta}} \left\{ (x_{D_2})_{\text{sat}} e^{\beta} + \frac{v_{D_2}}{b\phi_2} \left[\text{Ei}(\beta e^{b\phi_2 \theta}) - \text{Ei}(\beta) \right] \right\} \quad (20)$$

or in terms of y and θ only

$$x_{\theta} = e^{-8650 y e^{0.001610 \theta}} \left\{ (x_{D_2})_{\text{sat}} e^{0.00310 e^{8650 y} + 1.280 \times 10^{-3}} \left[\text{Ei}(8650 y e^{0.001610 \theta}) - \text{Ei}(8650 y) \right] \right\} \quad (20a)$$

For the present consideration the quantity $\frac{v_{D_2}}{b\phi_2} \left[\text{Ei}(\beta e^{b\phi_2 \theta}) - \text{Ei}(\beta) \right]$ is negligible compared to $(x_{D_2})_{\text{sat}} e^{\beta}$.

Equation (20a) then becomes

$$\text{fraction } D_2 \text{ unrecombined} = \frac{x_{\theta}}{(x_{D_2})_{\text{sat}}} = e^{-8650 y (1 - e^{0.001610 \theta})} \quad (21)$$

APPENDIX IV

CALCULATIONS FOR THE SIZING OF THE GAS RESERVOIR

The gas reservoir for the system is designed so that the design pressure of 600 psi for the low pressure system is not exceeded in the event.

- a) That all reactor materials and gases (pressurizers and reservoir) are dumped to the low pressure system and,
- b) That the cooling water supply to the low pressure system fails at this time.

The volumes involved in a dumping operation are assumed to be:

	<u>Core</u>	<u>Blanket</u>
High Pressure Circulation Loop	490	1750
Pressurizer	90	90
Dump System	980	2780
Condenser	130	130
Entrainment Separator	70	70
Condensate Tank	200	200
Recombiner	30	30
Cold Traps	30	30
Lines	<u>40</u>	<u>40</u>
	2060	5120

The estimated solution volumes, weights and enthalpies at operating conditions are:

<u>Solution Volumes</u>	<u>Volume, liters</u>	<u>Wt., lbs</u>	<u>Enthalpy Btu/lb</u>
Core (high press. sol'n)	490	920	531.4
Blanket (high press. sol'n)	1750	3240	531.4
Core (low press.)			
Dump tank	100	234	180
Condensate tank	183	428	180
Blanket (low press.)			
Dump tank	100	234	180
Condensate tank	183	428	180

When the reactor solutions are dumped, part of the liquid will flash to vapor. The reactor solutions will mix intimately with the solution already in the dump tanks, but will not mix with the liquid of the condensate tanks. The total volume into which the reactor solutions can expand is the difference between the total volume of both core and blanket systems and the volume of liquid normally held in the condensate tanks. This volume is 6800 liters (≈ 240 ft³).

The average enthalpy, h_m of the solution is

$$h_m = \frac{w_1 h_{f1} + w_2 h_{f2}}{w_1 + w_2} \quad (22)$$

where w_1 = total weight of solution in high pressure system = 4160 lbs.

w_2 = total weight of solution in dump tanks (normally) = 470 lbs.

h_{f1} = enthalpy of solution at operating temperature and pressure = 531.4 $\frac{\text{Btu}}{\text{lb.}}$

h_{f2} = enthalpy of solution at 100° C and atmospheric pressure = 180.0 $\frac{\text{Btu}}{\text{lb.}}$

Solving for h_m

$$h_m = 495.9 \frac{\text{Btu}}{\text{lb.}}$$

The equilibrium pressure which the system will reach on a dump with no cooling can now be found. Let

$$\gamma = \frac{h_m - h_f}{h_{fg}} \quad (23)$$

γ = wt fraction of vapor

The average specific volume, v_m , of the system is found from

$$v_m = v_f + \gamma v_{fg} \quad (24)$$

where v = sp. vol. (read from steam tables)

For this case (assuming no gas in the system)

$$v_m = \frac{240 \text{ ft}^3}{4630 \text{ lb}} = 0.0520 \text{ ft}^3/\text{lb.}$$

The equilibrium pressure cannot be solved for directly, but is found as follows:

1. Select a pressure, p .
2. From eq. 23 compute γ .
3. From p and γ and eq. 24 solve for v_m .
4. Continue by trial and error until $v_m = 0.0520 \text{ ft}^3/\text{lb.}$

The following results are obtained:

<u>p, psia</u>	<u>γ</u>	<u>$v_m, \text{ft}^3/\text{lb}$</u>
500	0.06159	0.0756
540	.05004	.0618
560	.04441	.0558
580	.03872	.0502
600	.03321	.0450
620	.02778	.0403
640	.02228	.0359

These values are plotted in Figure 10. From Figure 10 the equilibrium pressure (assuming no gas in system) is read as 573 psia.

Gas from the reservoir and pressurizers has the effect of decreasing v_m and thereby increasing the equilibrium pressure on the system. Adiabatic expansion of the gases is assumed. The final volume of gas at 600 psia (design pressure of low pressure system) is then given by

$$V_f = V_o \left(\frac{p_o}{p_f} \right)^{1/k} \quad (25)$$

where subscript f = refers to final conditions

o = refers to initial conditions

The final volume of the gas from the pressurizers is estimated from equation (25) assuming

- 1) Gas is helium at 300°C and 2000 psia
- 2) $k = 1.57$
- 3) $V_o = 2 * 90$ or 180 liters $\approx 6.4 \text{ ft}^3$.

Solving for $(V_f)_p$

$$(V_f)_p = 13.8 \text{ ft}^3.$$

The final volume of the gas from the reservoir is estimated assuming

1) Gas is helium at 25°C and 3000 psia

2) $k = 1.67$

3) $V_o = V_r$, volume of reservoir

Solving equation (25) for $(V_f)_r$

$$(V_f)_r = 2.63 V_r \quad (25a)$$

The average specific volume at equilibrium conditions is estimated by

$$v_m = \frac{V_T - (V_f)_{r+p}}{w_1 + w_2} \quad (26)$$

where V_T = total volume of reactor system = 240 ft³

$(V_f)_{r+p}$ = volume of gas at 600 psia

$w_1 + w_2$ = total weight of contents = 4630 lbs.

Results are shown for several assumed reservoir volumes.

Assumed Reservoir Volume, V_r , ft ³	$(V)_{fr}$, ft ³	$(V_f)_{r+p}$	Avg. sp. vol. v_m , ft ³ /lb	p_{eq} , psia	Excess press. due to gas psi
3	7.9	21.7	0.0473	591	18
6	15.8	29.6	.0456	598	25
10	26.3	40.1	.0433	608	35
20	52.5	66.3	.0376	633	60

From this it appears that a pressure reservoir volume of ~ 6 ft³ is permissible.

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TABLE OF NOMENCLATURE

c = Heat capacity

G = Radiolytic decomposition rates, molecules $D_2O/100$ e.v.

H = total heat content, Btu

h = enthalpy, Btu/lb.

K = Henry's Law Coefficient psi/mol.fract.

$k = c_p/c_v$

k_{Cu} = recombination rate constant for copper catalyst, $\frac{\text{liters}}{\text{g.mol } Cu^{++} \text{ sec.}}$

P = reactor power, Mw

p = pressure, psi

R = gas constant

T = absolute temperature, $^{\circ}R$, or $^{\circ}K$

t = temperature, $^{\circ}F$ or $^{\circ}C$

V = volume

v = gas production rate

w = weight, lbs.

X = weight of liquid which flashes to vapor, lbs.

x = mole fraction in liquid phase

y = copper ion concentration, $\frac{\text{g.moles}}{\text{liter}}$

Z = compressibility factor

η = amount of gas dissolved in liquid phase, lb. mols.

θ = time

ρ = density

ν = specific volume

$\mathcal{A}$ = mole fraction of gas in gas phase

Subscripts

A = refers to component A

f = refers to properties of the saturated liquid

f = refers to final conditions

f = refers to fission heat

fg = refers to change by evaporation

fp = refers to fission product heat

g = refers to properties of saturated vapor

l = refers to liquid phase

m = refers to average or mean value

n = refers to n^{th} incremental step

o = refers to initial conditions

p = refers to pressure, or pressurizer

r = refers to residual power

= refers to gas reservoir

v = refers to volume

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Fig. 1. Time Required After a Fuel Circulation Stop for the Pressure to Increase to 2800 psia as a Function of Pressurizer Volume. (Core and Blanket Pressurizer Volumes are Equal) (Pressurizing Gas is Oxygen.)

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Fig. 2. Concentration of D_2 in Gas Phase of HRT High Pressure System versus Pressure During Dumping Operation.

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Fig. 3. Pressure in High Pressure System vs. Volume of Liquid Solution Removed by Dumping Operation

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Fig. 4. Maximum Mole % D₂ Expected in Gas Phase During Dumping Operation vs. %D₂ Recombined in Liquid Phase Before Dumping Operation Begins

Fig. 5. Delay Time* Required After Power Shutdown Vs. % D₂ Recombined Internally for HRT Core Solution

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Fig. 6. Percent D_2 Recombined Vs. Delay Time After Power Shutdown for Circulation Stoppage.

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Fig. 7. D_2 Concentration in Liquid Phase of D_2O Blanket vs Cu^{++} Catalysis in Blanket

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Fig. 9. Schematic Diagram for Gas Recirculation Loop

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Fig. 10. Average Specific Volume of Vapor-Liquid Mixture vs. Pressure

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