EFFECTS OF THE MAXIMUM CREDIBLE ACCIDENT
RELEVANT TO THE DESIGN
OF THE
CONTAINMENT SHELL

EXPERIMENTAL LOW-TEMPERATURE
PROCESS HEAT REACTOR PROJECT

HD-15734

MASTER

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1. INTRODUCTION

To demonstrate that the containment shell of a nuclear reactor power plant is properly designed, it must be shown

- (1) that the internal pressure it can withstand does not exceed the pressure rise associated with the maximum credible accident,
- (2) that the fission products released by the maximum credible accident do not represent an unacceptably intense source of direct radiation at points outside the shell, and
- (3) that the gaseous and volatile fission products released by the maximum credible accident do not escape from the shell fast enough to cause unacceptable risks of exposure to radiation at points outside the shell even under adverse meteorological conditions.

This analysis deals with all three points just enumerated, but it is complete only with regard to the first, i.e., the adequacy of the internal pressure that the shell is designed to withstand. Regarding the second and third points, this analysis includes a thorough and detailed estimate of the extent to which fission products would escape from the reactor core into the containment shell, but does not go further. With the data presented herein, however, the usual methods for calculating the intensity of direct radiation from the shell and of the effects of fission-product leakage from the shell may be applied. It is expected that Sargent & Lundy will complete the work necessary to demonstrate that the radiation hazards resulting from the maximum credible accident are acceptably low.

This report, therefore, is a complete basis for judging the containment shell pressure rating, but only a partial basis for judging the necessity of shadow shielding and the acceptability of the allowable leakage rate.

The preliminary design of the containment shell is described in Sec. VI of the ELPHR Site Evaluation Report (SL-1760), pp. 20-23. The shell encloses a free-air volume of approximately 100,000 cu.ft., and is designed for a working pressure of 31 psig. It will be tested at a maximum pressure of 39 psig. The maximum allowable gaseous leakage from it in any 24-hr. period after pressurization to 31 psig is 0.10 per cent of its free-air volume.

Assessing the suitability of the containment shell involves seven specific tasks:

- (1) defining the maximum credible accident;
- (2) analyzing the thermal and hydraulic effects (other than meltdown) of the maximum credible accident on the reactor system;
- (3) estimating the extent to which the fuel-rod cladding will melt as a result of the maximum credible accident;
- (4) estimating the amount of energy released from the reactor system by the escaping steam and water and by a possible chemical reaction, and the corresponding pressure rise inside the containment shell;
- (5) estimating the kinds, amounts, and total radioactivity of fission products released to the atmosphere of the containment shell after the core melts;
- (6) estimating the direct gamma-ray dose from the shell after radioactivity is released to its interior; and
- (7) estimating the results of the escape of gaseous radionuclides and airborne radioactive particles from the containment shell at a rate determined by the maximum allowable leakage rate.

As implied by the earlier statements, this report presents conclusions regarding only the first five tasks; the remaining two will be completed by Sargent & Lundy. Appendixes I, II, III, and IV contain the detailed calculations carried out for Tasks 2, 3, 4, and 5.

In addition to the specific assumptions set forth in Sec. 3 of this report, it was assumed throughout that

- (1) the reactor core consists of 32 fuel assemblies,
- (2) each fuel assembly consists of a 10 x 10 square array of 100 rods of which all except the corner rods contain fuel and are clad with pure aluminum (the corner rods are assumed to be empty stainless-steel tubes),
- (3) the reactor power level is 40.1 MW, and
- (4) the full-power core lifetime is 1.45 years.

2. CONCLUSIONS

2.1 Definition of the Maximum Credible Accident

The most serious ELPHR accident whose occurrence is considered possible is an instantaneous gross rupture of the 18-in. coolant inlet pipe just outside the biological shield. The accident allows the unimpeded escape of water and steam from the broken pipe on both sides of the rupture, i.e., directly from the reactor vessel inlet pipe on the biological-shield side of the rupture and from the rest of the primary system on the other side.

2.2 Thermal and Hydraulic Effects (Other Than Meltdown) of the Maximum Credible Accident

Twelve seconds after the maximum credible accident all water will have been expelled from the reactor vessel. The average fuel-cladding temperature, the average coolant temperature inside the reactor vessel, and the fraction of the reactor-vessel volume occupied by water are plotted as functions of time during this 12-sec. interval in Fig. 1.

The average coolant temperature inside the steam generator and the fraction of the primary-side volume inside the steam generator occupied by water are plotted as functions of time after the accident in Fig. 2.

The average temperature inside the pressurizer and the fraction of the pressurizer volume occupied by water are plotted as functions of time after the accident in Fig. 3.

The mass flow rates from each side of the rupture are plotted as functions of time after the accident in Fig. 4.

These conclusions are supported by the calculations presented in Appendix I.

2.3 Extent of Cladding Meltdown

Four minutes after all water is expelled from the reactor vessel, or 4.2 min. after the maximum credible accident, the cladding of the hottest fuel rods will reach the melting point (1219 F). Subsequently the cladding on all fuel rods except those on the periphery

NO!

of each fuel assembly will melt. The cladding of the fuel rods on the periphery of each fuel assembly will not reach the melting point at all.

There is a 10 x 10 array of rods in each fuel assembly. All contain fuel except the corner ones. Accordingly, each fuel assembly has 32 fuel rods on the periphery. Therefore, the ratio of the number of fuel rods whose cladding will melt to the total number of fuel rods is $(96-32)/96$, or $2/3$.

These conclusions are supported by the calculations presented in Appendix II.

42.8%

THIS WAS
CHANGED
TO A 5X5
ARRAY

2.4 Energy Released From The Reactor System

The energy released from the reactor system as a result of the maximum credible accident was estimated for primary-system pressures of 900 psia and 300 psia. Even though the aluminum-clad core may not be operated at 900 psia, the higher pressure was assumed to insure that the most severe conditions possible were taken into account. In each case it was assumed that 10 per cent of the molten aluminum cladding (6.67 per cent of all aluminum in the core) reacts with water.

The energy released by the maximum credible accident followed by the aluminum-water reaction will raise the pressure in the containment shell to 31.9 psig if the primary-system pressure was initially 900 psia, and to 16.7 psig if the primary-system pressure was initially 300 psia. As mentioned in the introduction, the working pressure for which the containment shell is designed is 31 psig.

These conclusions are supported by the calculations presented in Appendix III.

2.5 Extent of Fission-Product Release To The Containment Shell

The radionuclides released by the melting of the cladding of two-thirds of all fuel rods have a gross activity of 365 kilocuries. This is two-thirds of all activity that would be released (552 kilocuries) if the cladding on all fuel rods melted. Table 1 lists the activity of each of the principal radionuclides that would be released if all cladding melted.

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TABLE 1

ACTIVITY OF PRINCIPAL RADIONUCLIDES THAT WOULD BE RELEASED FROM
THE ELPHR CORE IF ALL FUEL-ROD CLADDING MELTED

<u>Radionuclide</u>	<u>Activity (kilocuries)</u>
krypton-85 (metastable).....	1
krypton-85	8
krypton-87	1
krypton-88	2
strontium-89	7
strontium-90	1
technetium-99	6
rubidium-103	247
rubidium-106	52
rhodium-105	2
antimony-125	1
antimony-127	1
tellurium-129	1
tellurium-132	2
iodine-131	44
iodine-133	10
iodine-135	3
xenon-131	1
xenon-133	103
xenon-135	7
cesium-137	49
cesium-138	1
barium-140	2
TOTAL	<u>552</u>

These conclusions are supported by the calculations presented in Appendix IV.

Section VIII, pp 25-33 of The ELPHR Site Evaluation Report (SL-1670) presents estimates of effects of releasing 25 per cent of all fission products formed after 400 days of operation at full power. All source strengths calculated on this basis are considerably higher than those listed above; therefore, the direct-radiation, whole-body, inhalation, and ground-deposition doses to be calculated on the basis of Table 1 will be significantly lower than those appearing in the Site Evaluation Report.

3. ASSUMPTIONS

3.1 Thermal and Hydraulic Effects (Other Than Meltdown) of the Maximum Credible Accident

Analysis of the thermal and hydraulic effects (other than meltdown) of the maximum credible accident proceeded on the basis of nine assumptions:

- (1) The rupture occurs instantaneously in the cold leg, immediately outside the biological shield.
- (2) The inlet duct inside the reactor vessel collapses without plugging the inlet nozzle.
- (3) The coolant escapes from the pipe ends on each side of the rupture at sonic velocity.
- (4) The reactor coolant system is idealized into several volumes and fluid-flow resistances as follows: the reactor vessel, the pressurizer, and the steam generator are considered as volumes; both sides of the ruptured leg, the pipe between pressurizer and the hot leg, and the hot leg leading from the reactor vessel to the steam generator are considered as fluid-flow resistances (see sketch, Appendix I).
- (5) Water is considered as an incompressible fluid and its vapor as an ideal gas.
- (6) Saturation conditions prevail in the reactor coolant system after the accident.
- (7) Only adiabatic processes are considered, except in the reactor vessel and steam generator.
- (8) The temperature of the secondary coolant leaving the steam generator remains constant at 250° F.
- (9) Pressure variations due to different elevations are disregarded.

3.2 Extent of Cladding Meltdown

Analysis of the extent to which the fuel-rod cladding would melt as a consequence of the maximum credible accident proceeded on the basis of six assumptions:

- (1) The initial conditions for the meltdown analysis are the conditions existing 12 sec. after gross failure of the 18-in. inlet line, i.e., when there is no longer any water in the reactor vessel.
- (2) Water at 70° F. starts to be injected into the reactor vessel at a rate of 40 gpm 12 sec. after the pipe failure; the water leaves the reactor vessel through the ruptured inlet line at the boiling point (212° F.).

- (3) The radial distribution of the 40 gpm flow of cooling water leaving the spray nozzles is the same as the radial distribution of heat generation in the reactor core.
- (4) The water injected into the core removes heat only from the peripheral fuel rods in each fuel assembly.
- (5) The only process by which heat is removed from all other rods in each fuel assembly is radiation.
- (6) No metal-water reaction takes place; i.e., decay of radionuclides is the only source of heat considered.

3.3 Energy Released From The Reactor System

The energy released from the reactor system was estimated on the basis of three assumptions:

- (1) Two-thirds of the aluminum in the core melts; of this, approximately 10 per cent reacts exothermically with water.
- (2) The ambient temperature inside the containment shell is 100° F.
- (3) The water in the primary system is instantaneously released and flashes to steam adiabatically; i.e., heat is absorbed by the air inside the containment shell and none is transferred outside or stored by transfer to the structures inside.

The first assumption is conservative because it is unlikely that as much as 10 per cent of the molten aluminum will react; in fact, it is doubtful whether any aluminum will react. This statement is based on experiments by the Aerojet General Corporation reported in "A Study of the Reaction of Metal and Water" (AECD-3664) and "The Reaction of Molten Uranium and Zirconium Alloys with Water" (AGC-AE-17).

3.4 Extent of Fission-Product Release to the Containment Shell

The extent of fission-product release to the containment shell was estimated by applying the method set forth in the Experimental Gas-Cooled Reactor Preliminary Hazards Summary Report (ORO-196), Sec. 7.2.1, pp. 7.2-7.6.

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4. DISCUSSION

Because the design of the reactor and the analysis work reported herein proceeded concurrently, more accurate data concerning the reactor became available from time to time. The calculations reflect the later data wherever feasible, but some inconsistencies deserve comment.

Appendixes I and II were prepared first, on the basis of the most reliable estimate of primary-system volume (603 cu.ft.) then available. Operation of the aluminum-clad core at 900 psia and 415° F. was not envisioned; accordingly, the analysis presupposed operation at 300 psia and 285° F. only. At the lower pressure and temperature and assuming a primary-system volume of 603 cu.ft., the total mass of steam and water in the primary system is approximately 34,800 pounds.

When Appendix III was prepared, a more nearly accurate estimate of the primary system volume was available (686 cu.ft.), and operation of the aluminum-clad core at 900 psia and 415° F. was at least a possibility. With a volume of 686 cu.ft., the primary system contains approximately 38,300 pounds of steam and water at 300 psia and 285° F., and approximately 35,200 pounds of steam and water at 900 psia and 415° F.

The calculations presented in Appendixes I and II were not revised to account for the larger volume and higher pressure and temperature because it can be shown that although these changes in initial conditions affect the length of the interval between the accident and exposure of the core, they do not affect the extent to which the cladding melts. This is true because the temperature of the peripheral fuel rods continuously decreases after the accident; only that of the interior fuel rods rises. Variations in the length of time before the core is exposed represented by the changes discussed here are not significant.

However, the larger volume and higher pressure and temperature strongly affect the pressure rise in the containment shell; therefore, Appendix III was prepared on the basis of a primary-system volume of 686 cu. ft. and both sets of operating conditions.

APPENDIX I

ANALYSIS OF THERMAL AND HYDRAULIC EFFECTS (OTHER THAN MELTDOWN) OF THE ELPHR MAXIMUM CREDIBLE ACCIDENT ON THE REACTOR SYSTEM

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Arrows indicate positive direction for mass flows.

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REACTOR VESSEL CAPACITANCE: R

1. Mass Balance:

$$\dot{m}_R = -W_{N_i} + W_{H_i} \quad (I)$$

2. Constant Volume:

$$m_R (1 - x_R) v_W + m_R x_R v_{SR} = \text{volume of } R = \text{const.}$$

$$v_W \approx \text{const.}$$

Differentiating

$$\begin{aligned} \dot{m}_R (1 - x_R) v_W - m_R \dot{x}_R v_W + \dot{m}_R x_R v_{SR} \\ + m_R \dot{x}_R v_{SR} + m_R x_R \dot{v}_{SR} = 0 \end{aligned}$$

$$\dot{m}_R [(1 - x_R) v_W + x_R v_{SR}] + m_R \dot{x}_R (v_{SR} - v_W) + m_R x_R \dot{v}_{SR} = 0 \quad (II)$$

3. Saturation Conditions:

Clapeyron's law $p_R = p_0 e^{-\frac{L/R}{T_R + 460}} \quad (III')$

Assuming steam as ideal gas

$$v_{SR} = \left(\frac{R}{\mu}\right) \frac{T_R + 460}{p_0} e^{-\frac{L/R}{T_R + 460}} \quad (III)$$

and

$$\dot{v}_{SR} = v_{SR} \left(\frac{1}{T_R + 460} - \frac{L/R}{(T_R + 460)^2} \right) \dot{T}_R \quad (III')$$

4. Energy Balance:

Only heat balance is considered

Water enthalpy per unit weight

Steam enthalpy per unit weight

Weight in the system

$$i_{WR} = c_p T_R$$

$$i_{SR} = c_p T_R + L \quad (\text{saturated steam})$$

$$m_R = \underbrace{m_R x_R}_{\text{steam}} + \underbrace{m_R (1 - x_R)}_{\text{water}}$$

$$\text{Total enthalpy } I = \underbrace{m_R x_R (c_p T_R + L)}_{\text{steam}} + \underbrace{m_R (1 - x_R) c_p T_R}_{\text{water}}$$

$$I = m_R (c_p T_R + x_R L) = m_R i_R$$

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Differentiating

$$\dot{I} = \frac{\dot{}}{m_R i_R} = m_R \dot{i}_R + i_R \dot{m}_R$$

$$\frac{\dot{}}{m_R i_R} = \dot{m}_R (c_p T_R + x_R L) + m_R (c_p \dot{T}_R + \dot{x}_R L)$$

$$m_R \dot{i}_R = m_R \left(\frac{Q}{m_R} + \frac{1}{J} v_R \dot{p}_R \right) = Q + m_R v_R \dot{p}_R \frac{1}{J}$$

(If adiabatic process $Q=0$ and $m \dot{i}_R = \frac{1}{J} m_R v_R \dot{p}_R$)

Assuming

$$Q = U_R (1 - x_R) (\bar{T}_0 - T_R) \frac{v_W}{v_R}$$

Thus

$$m_R \dot{i}_R = \frac{1}{J} m_R v_R \dot{p}_R + U_R (1 - x_R) (\bar{T}_0 - T_R)$$

$$\text{If } W_{H_1} > 0 \quad \sum i_R \dot{m}_R = -W_{H_1} (c_p T_R + x_R L) + W_{H_1} (c_p T_J + x_J L)$$

$$\text{If } W_{H_1} < 0 \quad \sum i_R \dot{m}_R = - (W_{H_1} - W_{H_1}) (c_p T_R + x_R L)$$

Equating:

$$\text{If } W_{H_1} > 0; \quad m_R (c_p T_R + x_R L) + m_R (c_p \dot{T}_R + \dot{x}_R L) = \frac{1}{J} v_R m_R \dot{p}_R + \frac{U_W}{v_R} U_R (1 - x_R) (\bar{T}_0 - T_R) - W_{H_1} (c_p T_R + x_R L) + W_{H_1} (c_p T_J + x_J L)$$

(IV)

$$\text{If } W_{H_1} < 0; \quad m_R (c_p T_R + x_R L) + m_R (c_p \dot{T}_R + \dot{x}_R L) = \frac{1}{J} v_R m_R \dot{p}_R + U_R (1 - x_R) (\bar{T}_0 - T_R) \frac{v_W}{v_R} - (W_{H_1} - W_{H_1}) (c_p T_R + x_R L)$$

being $W_{H_1} > 0$ when $p_J > p_R$

$W_{H_1} < 0$ $p_J < p_R$

5. Specific Volume:

$$v_R = (1 - x_R) v_W + x_R v_{SR}$$

(V)

The set of equations (I) to (V) can be worked out in order to have all the parameters explicitly written

At the beginning of each time interval the initial value of the parameters can be determined.

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Initial value of the parameters:

Given values:

$$m_R (t=0) = m_{R0}$$

$$T_R (t=0) = T_{R0}$$

$$x_R (t=0) = x_{R0}$$

Calculated values:

$$p_{R0} = p_0 e^{-\frac{\ell/R}{T_R + 460}} \quad \text{by eq. (III')}$$

$$v_{SR0} = \left(\frac{R}{\mu}\right) \cdot \frac{T_R + 460}{p_0} e^{\frac{\ell/R}{T_R + 460}} \quad \text{by eq. (III)}$$

$$v_{R0} = (1 - x_{R0}) v_W + x_{R0} v_{SR0} \quad \text{by eq. (V)}$$

Derivative of the parameters:

From eq. (I)

$$\dot{m}_R = -W_{N1} + W_{H1} \quad (1)$$

Differentiating eq. (V): $\dot{v}_R = -\dot{x}_R v_W + \dot{x}_R v_{SR} + x_R \dot{v}_{SR}$

$$\dot{v}_R = \dot{x}_R (v_{SR} - v_W) + \dot{v}_{SR} x_R \quad (1')$$

Replacing in eq. (II)

$$\dot{m}_R v_R + m_R \dot{v}_R = 0 \quad (\text{as expected from the condition of constant volume}).$$

Thus

$$\dot{v}_R = -\frac{v_R}{m_R} \dot{m}_R \quad (2)$$

From eq. (1') and eq. (III') $\dot{v}_{SR} = \frac{\dot{v}_R}{x_R} - \frac{\dot{x}_R}{x_R} (v_{SR} - v_W) = v_{SR} \left(\frac{1}{T_R + 460} - \frac{\ell/R}{(T_R + 460)^2} \right) \dot{T}_R$

$$\frac{v_{SR}}{T_R + 460} \left(1 - \frac{\ell/R}{T_R + 460} \right) \dot{T}_R = \frac{\dot{v}_R}{x_R} - \frac{\dot{x}_R}{x_R} (v_{SR} - v_W) \quad (2')$$

Differentiating eq. (III'') $\dot{p}_R = p_0 e^{-\frac{\ell/R}{T_R + 460}} \cdot \frac{\ell/R}{(T_R + 460)^2} \dot{T}_R = p_R \frac{\ell/R}{(T_R + 460)^2} \dot{T}_R$

$$\dot{p}_R = p_R \frac{\ell/R}{(T_R + 460)^2} \dot{T}_R \quad (3)$$

Replacing in eq. (IV)

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$$\begin{aligned} \dot{m}_R (c_p T_R + x_R L) + m_R \dot{x}_R L + m_R \left(c_p - \frac{1}{J} v_R p_R \frac{L/R}{(T_R + 460)^2} \right) \dot{T}_R - U_R (1 - x_R) (\bar{T}_0 - T_R) \frac{v_W}{v_R} = \\ = -W_N (c_p T_R + x_R L) + W_N (c_p T_J + x_J L) \quad \text{if } W_N > 0 \\ + W_N (c_p T_R + x_R L) \quad \text{if } W_N < 0 \end{aligned} \quad (3')$$

Eq (2') and eq. (3') allow us to determine $\dot{x}_R$ and $\dot{T}_R$

From eq. (2')

$$\dot{x}_R = \frac{\dot{v}_R}{v_{SR} - v_W} - \frac{x_R v_{SR}}{T_R + 460} \left(1 - \frac{L/R}{T_R + 460} \right) \frac{\dot{T}_R}{v_{SR} - v_W} \quad (4)$$

Replacing in eq. (3')

$$\begin{aligned} \dot{m}_R (c_p T_R + x_R L) + m_R \frac{L \dot{v}_R}{v_{SR} - v_W} + \dot{T}_R m_R \left[c_p - \frac{1}{J} v_R p_R \frac{L/R}{(T_R + 460)^2} - \frac{L x_R v_{SR}}{T_R + 460} \left(1 - \frac{L/R}{T_R + 460} \right) \frac{1}{v_{SR} - v_W} \right] = \\ \frac{v_W v_R}{v_R} U_R (1 - x_R) (\bar{T}_0 - T_R) - W_N (c_p T_R + x_R L) + W_N (c_p T_J + x_J L) \quad \text{if } W_N < 0 \\ + W_N (c_p T_R + x_R L) \quad \text{if } W_N > 0 \end{aligned}$$

Finally

$$\dot{T}_R = \frac{-\dot{m}_R (c_p T_R + x_R L) - m_R \frac{L \dot{v}_R}{v_{SR} - v_W} + \frac{v_W v_R}{v_R} U_R (1 - x_R) (\bar{T}_0 - T_R) - W_N (c_p T_R + x_R L) + W_N (c_p T_J + x_J L) \quad \text{if } W_N < 0}{m_R \left[c_p - \frac{1}{J} v_R p_R \frac{L/R}{(T_R + 460)^2} - \frac{L x_R v_{SR}}{T_R + 460} \left(1 - \frac{L/R}{T_R + 460} \right) \frac{1}{v_{SR} - v_W} \right]} \quad (5)$$

In order to solve the derivatives, the procedure is the following:

Eq. (1) gives $\dot{m}_R$, where W_N , and W_H , should be previously determined from the equations for the fluid flow resistances.

Eq. (2) gives $\dot{v}_R$

Using $\dot{m}_R$ and $\dot{v}_R$, eq. (5) gives $\dot{T}_R$

Using $\dot{v}_R$ and $\dot{T}_R$, eq. (4) gives $\dot{x}_R$

Using $\dot{T}_R$, eq. (3) gives $\dot{p}_R$

Using $\dot{T}_R$, eq. (III') gives $\dot{v}_{SR}$

If it is desired to use the same routine for getting the initial parameters, only the following derivatives can be calculated

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$$\dot{m}_R = -W_{N1} + W_{H1}$$

$$\dot{T}_R = \frac{\dot{m}_R \left(\frac{v_R L}{v_{SR} - v_W} - c_p T_R - x_R L \right) + U_R (1 - x_R) (\bar{T}_0 - T_R) \frac{W_W}{v_R} - W_{N1} (c_p T_R + x_R L) + W_{H1} (c_p T_R + x_R L)}{m_R \left[c_p - \frac{1}{J} v_R p_R \frac{L/R}{(T_R + 460)^2} - \frac{L x_R v_{SR}}{T_R + 460} \left(1 - \frac{L/R}{T_R + 460} \right) \frac{1}{v_{SR} - v_W} \right]}$$

$$+ W_{H1} (c_p T_R + x_R L) \quad \text{if } W_{H1} > 0$$

$$+ W_{H1} (c_p T_R + x_R L) \quad \text{if } W_{H1} < 0$$

$$\dot{x}_R = \frac{-v_R \frac{\dot{m}_R}{m_R} - x_R v_{SR}}{v_{SR} - v_W} \left(1 - \frac{L/R}{T_R + 460} \right) \frac{\dot{T}_R}{T_R + 460}$$

The other parameters, at the end of the time interval Δt , can be calculated as before using the above mentioned parameters at the end of the time interval; i. e.

$$m_R(\Delta t) = m_{R0} + \dot{m}_R \Delta t$$

$$T_R(\Delta t) = T_{R0} + \dot{T}_R \Delta t$$

$$x_R(\Delta t) = x_{R0} + \dot{x}_R \Delta t$$

which replaced in eqs (III'), (III) and (V) give $p_R(\Delta t)$, $v_R(\Delta t)$ and $v_{SR}(\Delta t)$

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RUPTURED PIPE

STEAM GENERATOR SIDE: L

1. Pressure Balance:

$$p_0 - \frac{W_L^2}{A_L^2} \cdot \frac{v_0}{2g} - p_L = k_L W_L^2 \bar{v}_L \quad (I)$$

2. Specific volume at the exit:

$$v_L = (1 - x_L) v_w + x_L v_{sL} \quad (II)$$

3. Specific volume in the resistance:

$$\bar{v}_L \approx \frac{1}{2} (v_0 + v_L) \quad (III)$$

4. Specific volume of the saturated steam at the exit:

$$v_{sL} = \left(\frac{R}{A}\right) \frac{T_L + 460}{p_0} e^{\frac{L/R}{T_L + 460}} \quad (IV)$$

5. Pressure at the exit:

$$p_L = p_0 e^{-\frac{L/R}{T_L + 460}} \quad (V)$$

6. Continuity equation:

$$W_L = \frac{A_L}{v_L} u_{eL} \quad (VI)$$

7. Energy balance:

$$c_p T_0 + x_0 L = c_p T_L + x_L L + \frac{u_{eL}^2}{2gJ} \quad (VII)$$

8. Sonic velocity at the exit

The sonic velocity is given by

$$u_e = \sqrt{g \gamma \left(\frac{\partial p}{\partial \rho}\right)_s}$$
$$As \quad \frac{\partial p}{\partial \rho} = \frac{\partial p}{\partial v} \cdot \frac{dv}{d\rho}$$
$$and \quad \rho = \frac{1}{v} \quad ; \quad d\rho = -\frac{1}{v^2} dv \quad \frac{dv}{d\rho} = -v^2$$
$$\frac{\partial p}{\partial \rho} = -v^2 \frac{\partial p}{\partial v}$$

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As an adiabatic process

$$di = dQ + \frac{1}{J} v dp = \frac{1}{J} v dp$$

being $di = c_p dT + L dx$

Differentiating the Clapeyron's law

$$dp = p \frac{\ell/R}{(T+460)^2} dT$$

and
$$dT = \frac{(T+460)^2}{\ell/R} \frac{dp}{p}$$

Differentiating the expression for the specific volume:

$$v = (1-x) v_w + x v_s$$

$$dv = -v_w dx + v_s dx + x dv_s = (v_s - v_w) dx + x dv_s$$

and
$$dx = \frac{dv}{v_s - v_w} - \frac{x dv_s}{v_s - v_w}$$

From
$$v_s = \left(\frac{R}{p}\right) \frac{T+460}{p}$$

$$\frac{dv_s}{v_s} = \frac{dT}{T+460} - \frac{dp}{p}$$

and
$$dx = \frac{dv}{v_s - v_w} - \frac{x v_s}{v_s - v_w} \left(\frac{dT}{T+460} - \frac{dp}{p} \right)$$

Thus:
$$0 = c_p \frac{(T+460)^2}{\ell/R} \frac{dp}{p} + \frac{L}{v_s - v_w} dv - \frac{L x v_s}{v_s - v_w} \cdot \frac{T+460}{\ell/R} \cdot \frac{dp}{p} + \frac{L x v_s}{v_s - v_w} \cdot \frac{dp}{p} - \frac{v}{J} dp$$

$$0 = \frac{L}{v_s - v_w} dv + \left[\frac{c_p}{p} \frac{(T+460)^2}{\ell/R} - \frac{L x v_s}{v_s - v_w} \frac{T+460}{\ell/R} \frac{1}{p} + \frac{L x v_s}{v_s - v_w} \frac{1}{p} - \frac{v}{J} \right] dp$$

and
$$\frac{dp}{dv} = - \frac{\frac{L}{v_s - v_w}}{\frac{c_p}{p} \frac{(T+460)^2}{\ell/R} + \frac{L x v_s}{(v_s - v_w)p} \left(1 - \frac{T+460}{\ell/R} \right) - \frac{v}{J}}$$

$$\frac{\partial p}{\partial v} = v^2 \frac{p \frac{L}{v_s - v_w}}{c_p \frac{(T+460)^2}{\ell/R} + \frac{L x v_s}{v_s - v_w} \left(1 - \frac{T+460}{\ell/R} \right) - \frac{p v}{J}}$$

The sonic velocity is given by

$$u_{c_2}^2 = g v_c^2 \frac{L \frac{p_c}{v_{s_c} - v_w}}{c_p \frac{(T_c+460)^2}{\ell/R} + \frac{L x_c v_{s_c}}{v_{s_c} - v_w} \left(1 - \frac{T_c+460}{\ell/R} \right) - \frac{p_c v_c}{J}} \quad (VIII)$$

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HOT LEG PIPES : H_1 , H_2 , I and JOINT J

1. Pressure Balance : Pressurizer - Steam Generator

$$p_P - p_G = k_I W_I^2 v_P + k_{H_2} W_{H_2}^2 v_J \quad ; \quad p_J > p_G \quad \text{and} \quad W_{H_2} > 0 \quad (I)$$

$$- k_{H_2} W_{H_2}^2 v_G \quad ; \quad p_J < p_G \quad \text{and} \quad W_{H_2} < 0$$

Pressurizer - Reactor Vessel

$$p_P - p_R = k_I W_I^2 v_P + k_{H_1} W_{H_1}^2 v_J \quad ; \quad p_J > p_R \quad \text{and} \quad W_{H_1} > 0 \quad (II)$$

$$- k_{H_1} W_{H_1}^2 v_R \quad ; \quad p_J < p_R \quad \text{and} \quad W_{H_1} < 0$$

2. Continuity equation:

$$W_I = W_{H_1} + W_{H_2} \quad (III)$$

3. Energy balance:

$$W_{H_2} (c_p T_J + x_J L) + W_{H_1} (c_p T_J + x_J L) \quad ; \quad p_J > p_G \quad ; \quad p_J > p_R \quad (IV)$$

$$W_I (c_p T_P + x_P L) = W_{H_2} (c_p T_G + x_G L) + W_{H_1} (c_p T_R + x_R L) \quad ; \quad p_J < p_G \quad ; \quad p_J < p_R$$

4. Saturation conditions at the joint:

$$p_P - k_I W_I^2 v_P = p_J = p_o e^{-\frac{L/R}{T_J + 460}} \quad (V)$$

$$v_{sJ} = \left(\frac{R}{\mu} \right) \frac{T_J + 460}{p_o} e^{\frac{L/R}{T_J + 460}} \quad (VI)$$

5. Specific volume at the joint:

$$v_J = (1 - x_J) v_w + x_J v_{sJ} \quad (VII)$$

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REACTOR CORE

Heat Balance:

$$F \frac{dT_0}{dt} = C_1 t^{-0.2} + C_2 e^{-\lambda t} - U_R (1-x_R) (\bar{T}_0 - T_R) \frac{q_w}{U_R}$$

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REACTOR VESSEL CAPACITANCE: R

$$\dot{m}_R = -W_{H1} + W_{H1} \quad (1)$$

$$\dot{T}_R = \frac{\dot{m}_R \left(\frac{v_R L}{v_{SR} - v_W} - c_p T_R - x_R L \right) + U_R (1 - x_R) (\bar{T}_0 - T_R) \frac{v_R}{v_R} - W_{H1} (c_p T_R + x_R L) + W_{H1} (c_p T_J + x_J L)}{m_R \left[c_p - \frac{1}{J} v_R p_R \frac{c/R}{(T_R + 460)^2} - \frac{L x_R v_{SR}}{T_R + 460} \left(1 - \frac{c/R}{T_R + 460} \right) \frac{1}{v_{SR} - v_W} \right]} \quad \begin{matrix} \text{if } W_{H1} > 0 \\ \text{if } W_{H1} < 0 \end{matrix} \quad (2)$$

$$\dot{x}_R = \frac{-v_R \dot{m}_R}{v_{SR} - v_W} - \frac{x_R v_{SR}}{v_{SR} - v_W} \left(1 - \frac{c/R}{T_R + 460} \right) \frac{\dot{T}_R}{T_R + 460} \quad (3)$$

$$\dot{v}_R = -v_R \frac{\dot{m}_R}{m_R} \quad (4)$$

$$\dot{v}_{SR} = v_{SR} \left(1 - \frac{c/R}{T_R + 460} \right) \frac{\dot{T}_R}{T_R + 460} \quad (5)$$

$$\dot{p}_R = p_R \frac{c/R}{(T_R + 460)^2} \dot{T}_R \quad (6)$$

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PRESSURIZER: P

$$\dot{m}_P = -W_I \quad (1)$$

$$\dot{T}_P = \frac{\dot{m}_P \left(\frac{V_P L}{V_{SP} - V_W} - c_P T_P - x_P L \right) - W_I (c_P T_P + x_P L)}{m_P \left[c_P - \frac{1}{J} V_P \rho_P \frac{L/R}{(T_P + 460)^2} - \frac{L x_P V_{SP}}{T_P + 460} \left(1 - \frac{L/R}{T_P + 460} \right) \frac{1}{V_{SP} - V_W} \right]} \quad (2)$$

$$\dot{x}_P = \frac{-V_P \frac{\dot{m}_P}{m_P}}{V_{SP} - V_W} - \frac{x_P V_{SP}}{V_{SP} - V_W} \left(1 - \frac{L/R}{T_P + 460} \right) \frac{\dot{T}_P}{T_P + 460} \quad (3)$$

$$\dot{V}_P = -V_P \frac{\dot{m}_P}{m_P} \quad (4)$$

$$\dot{V}_{SP} = V_{SP} \left(1 - \frac{L/R}{T_P + 460} \right) \frac{\dot{T}_P}{T_P + 460} \quad (5)$$

$$\dot{P}_P = P_P \frac{L/R}{(T_P + 460)^2} \dot{T}_P \quad (6)$$

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STEAM GENERATOR: G

$$\dot{m}_G = W_{H_2} - W_L \quad (1)$$

$$\dot{T}_G = \frac{\dot{m}_G \left(\frac{v_G L}{v_{SG} - v_W} - c_p T_G - x_G L \right) + U_G (1 - x_G) (\bar{T}_B - T_G) \frac{v_W}{v_G} L (c_p T_G + x_G L) + W_{H_2} (c_p T_G + x_G L) \text{ if } W_{H_2} > 0}{\dot{m}_G \left[c_p - \frac{1}{J} v_G p_G \frac{L/R}{(T_G + 460)^2} - \frac{L x_G v_{SG}}{T_G + 460} \left(1 - \frac{L/R}{T_G + 460} \right) \frac{1}{v_{SG} - v_W} \right]} + W_{H_2} (c_p T_G + x_G L) \text{ if } W_{H_2} < 0 \quad (2)$$

$$\dot{x}_G = \frac{-v_G \frac{\dot{m}_G}{m_G}}{v_{SG} - v_W} - \frac{x_G v_{SG}}{v_{SG} - v_W} \left(1 - \frac{L/R}{T_G + 460} \right) \frac{\dot{T}_G}{T_G + 460} \quad (3)$$

$$\dot{v}_G = -v_G \frac{\dot{m}_G}{m_G} \quad (4)$$

$$\dot{v}_{SG} = v_{SG} \left(1 - \frac{L/R}{T_G + 460} \right) \frac{\dot{T}_G}{T_G + 460} \quad (5)$$

$$\dot{p}_G = p_G \frac{L/R}{(T_G + 460)^2} \dot{T}_G \quad (6)$$

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STEAM GENERATOR SIDE OF THE RUPTURED PIPE: L

$$p_6 - \frac{W_L^2}{A_L^2} \cdot \frac{v_6}{2g} - p_L = k_L W_L^2 \bar{v}_L \quad (I)$$

$$v_L = (1-x_L) v_w + x_L v_{SL} \quad (II)$$

$$\bar{v}_L = \frac{1}{2} (v_6 + v_L) \quad (III)$$

$$v_{SL} = \left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_0} e^{\frac{L/R}{T_L + 460}} \quad (IV)$$

$$p_L = p_0 e^{-\frac{L/R}{T_L + 460}} \quad (V)$$

$$W_L = \frac{A_L}{v_L} u_{CL} \quad (VI)$$

$$c_p T_6 + x_6 L = c_p T_L + x_L L + \frac{u_{CL}^2}{2gJ} \quad (VII)$$

$$u_{CL}^2 = v_L g L \frac{\frac{p_L}{v_{SL} - v_w}}{c_p \frac{(T_L + 460)^2}{L/R} + \frac{L x_L v_{SL}}{v_{SL} - v_w} \left(1 - \frac{T_L + 460}{L/R} \right) - \frac{p_L v_L}{J}} \quad (VIII)$$

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REACTOR VESSEL SIDE OF THE RUPTURED PIPE: N₁

$$p_R - \frac{W_{N_1}^2}{A_{N_1}^2} \cdot \frac{v_R}{2g} - p_{N_1} = k_{N_1} \frac{W_{N_1}^2}{v_{N_1}} \quad (I)$$

$$v_{N_1} = (1 - x_{N_1}) v_w + x_{N_1} v_{SN_1} \quad (II)$$

$$\bar{v}_{N_1} = \frac{1}{2} (v_R + v_{N_1}) \quad (III)$$

$$v_{SN_1} = \left(\frac{R}{\mu} \right) \cdot \frac{T_{N_1} + 460}{p_0} e^{-\frac{c/R}{T_{N_1} + 460}} \quad (IV)$$

$$p_{N_1} = p_0 e^{-\frac{c/R}{T_{N_1} + 460}} \quad (V)$$

$$W_{N_1} = \frac{A_{N_1}}{v_{N_1}} u_{CN_1} \quad (VI)$$

$$c_p T_R + x_{R,L} = c_p T_{N_1} + x_{N_1,L} + \frac{u_{CN_1}^2}{2gJ} \quad (VII)$$

$$u_{CN_1}^2 = v_{N_1} g L \frac{\frac{p_{N_1}}{v_{SN_1} - v_w}}{c_p \frac{(T_{N_1} + 460)^2}{c/R} + \frac{L x_{N_1} v_{SN_1}}{v_{SN_1} - v_w} \left(1 - \frac{T_{N_1} + 460}{c/R} \right) - \frac{p_{N_1} v_{N_1}}{J}} \quad (VIII)$$

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HOT LEG PIPES : H₁, H₂, I and JOINT J

$$p_p - p_g = k_I W_I^2 v_p + k_{H_2} W_{H_2}^2 v_J \quad ; \quad p_J > p_g \quad \text{and} \quad W_{H_2} > 0 \quad (I)$$

$$- k_{H_2} W_{H_2}^2 v_g \quad ; \quad p_J < p_g \quad \text{and} \quad W_{H_2} < 0$$

$$p_p - p_R = k_I W_I^2 v_p + k_{H_1} W_{H_1}^2 v_J \quad ; \quad p_J > p_R \quad \text{and} \quad W_{H_1} > 0 \quad (II)$$

$$- k_{H_1} W_{H_1}^2 v_R \quad ; \quad p_J < p_R \quad \text{and} \quad W_{H_1} < 0$$

$$W_I = W_{H_1} + W_{H_2} \quad (III)$$

$$W_{H_2} (c_p T_J + x_J L) + W_{H_1} (c_p T_J + x_J L) \quad ; \quad p_J > p_g \quad ; \quad p_J > p_R \quad (IV)$$

$$W_I (c_p T_p + x_p L) = W_{H_2} (c_p T_g + x_g L) + W_{H_1} (c_p T_R + x_R L) \quad ; \quad p_J < p_g \quad ; \quad p_J < p_R$$

$$p_p - k_I W_I^2 v_p = p_J = p_o e^{-\frac{L/R}{T+460}} \quad (V)$$

$$v_J = \left(\frac{R}{A}\right) \frac{T_J + 460}{p_o} e^{\frac{L/R}{T_J + 460}} \quad (VI)$$

$$v_J = (1 - x_J) v_w + x_J v_{SJ} \quad (VII)$$

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REACTOR CORE : 0

$$F \frac{\dot{T}_0}{T_0} = C_1 t^{-0.2} + C_2 e^{-\lambda t} - U_R (1 - x_R) (\bar{T}_0 - T_R) \frac{V_W}{V_R} \quad (1)$$

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CONSTANTS:

$$m_R(t=0) = 18,800 \text{ lb}$$

$$x_R(t=0) = 0$$

$$T_R(t=0) = 285^\circ\text{F}$$

$$V_R = 313 \text{ ft}^3$$

$$m_P(t=0) = 2,113 \text{ lb}$$

$$x_P(t=0) = 0.006,2$$

$$T_P(t=0) = 410.3^\circ\text{F}$$

$$V_P = 58 \text{ ft}^3$$

$$m_G(t=0) = 13,900 \text{ lb}$$

$$x_G(t=0) = 0$$

$$T_G(t=0) = 285^\circ\text{F}$$

$$V_G = 232 \text{ ft}^3$$

$$p_J(t=0) = p_P(t=0) = 4.24 \times 10^4 \frac{\text{lb}}{\text{ft}^2}$$

$$\bar{T}_O(t=0) = 423^\circ\text{F} \quad ; \quad \bar{T}_B = 250^\circ\text{F}$$

$$U_R = 268 \frac{\text{BTU}}{\text{sec}^\circ\text{F}}$$

$$U_G = 1,086 \frac{\text{BTU}}{\text{sec}^\circ\text{F}}$$

$$A_L = A_{N1} = 1.42 \text{ ft}^2$$

$$k_{N1} = 1.0 \times 10^{-3} \frac{\text{sec}^2}{\text{ft}^5}$$

$$k_L = 0.040 \frac{\text{sec}^2}{\text{ft}^5}$$

$$k_{N1} = k_{N2} = 0.030 \frac{\text{sec}^2}{\text{ft}^5}$$

$$k_I \approx \frac{1}{5} k_{N1}$$

$$c_P = 1 \frac{\text{BTU}}{\text{lb}^\circ\text{F}}$$

$$r_v \approx \frac{1}{60} \frac{\text{ft}^3}{\text{lb}}$$

$$L \approx 890 \frac{\text{BTU}}{\text{lb}}$$

$$C_1 = 2.28 \times 10^3 \text{ BTU sec}^{-0.8}$$

$$\frac{R}{\mu} = 85.9 \frac{\text{ft}}{^\circ\text{F}}$$

$$C_2 = 28.8 \times 10^3 \frac{\text{BTU}}{\text{sec}}$$

$$\frac{f}{R} = 8,833^\circ\text{F}$$

$$\lambda = 0.1 \text{ sec}^{-1}$$

$$J = 778 \frac{\text{lb ft}}{\text{BTU}}$$

$$F = 674 \frac{\text{BTU}}{^\circ\text{F}}$$

$$g = 32.2 \text{ ft/sec}^2$$

$$p_0 = 1.085 \times 10^9 \frac{\text{lb}}{\text{ft}^2}$$

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NOMENCLATURE

A	cross-sectional area, ft^2
c_p	specific heat at constant pressure, $\frac{BTU}{lb \cdot F}$
C_1	constant for fission power decay, $BTU \cdot sec^{-0.8}$
C_2	constant for heat diffusion, $\frac{BTU}{sec}$
F	heat capacitance of the core, $\frac{BTU}{F}$
g	gravitational acceleration, $\frac{ft}{sec^2}$
I	total enthalpy, BTU
i	enthalpy per unit weight, $\frac{BTU}{lb}$
J	mechanical equivalent of heat, $\frac{lb \cdot ft}{BTU}$
k	constant, characteristic for pressure drop ($\Delta p = k W^2 r$), $\frac{sec^2}{ft^5}$
l	latent heat of vaporization, $\frac{ft \cdot lb}{mole}$
L	, $\frac{BTU}{lb}$
m	weight, lb
p_0	constant for the Clapeyron law, $\frac{lb}{ft^2}$
p	absolute pressure, lb/ft^2
Q	heat added from surroundings, BTU
R	universal gas constant, $\frac{lb \cdot ft}{mole \cdot F}$
T	temperature, F
t	time, sec
u	velocity, $\frac{ft}{sec}$
U	over-all heat transfer coefficient times the transferring area, $\frac{BTU}{sec \cdot F}$
v	specific volume, $\frac{ft^3}{lb}$
W	mass flow, $\frac{lb}{sec}$
x	fraction of steam by weight, dimensionless
λ	heat diffusion decay constant, sec^{-1}
μ	molecular weight of steam, $\frac{lb}{mole}$
ρ	specific weight, $\frac{lb}{ft^3}$

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63-0030

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DR'N J. A. LANDONI CH'D APP'D SCALE = 12 SHEET 19 OF 20 ISSUE

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Subscripts

Capacitances	{	G	refers to steam generator
		P	pressurizer
		R	reactor vessel
Fluid-flow	{	H ₁	hot pipe reactor vessel-joint
		H ₂	steam generator-joint
		I	pressurizer-joint
Resistances	{	L	steam generator side of the cold leg
		N ₁	reactor vessel side of the cold leg
		J	joint
Joint		B	secondary coolant in the steam generator
		C	critical conditions at the exit nozzles
		S	saturated steam
		W	water
		O	clad

BLOW-DOWN ACCIDENT

680 0031

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ADDENDUM

REDUCTION IN THE NUMBER OF VARIABLES

REACTOR VESSEL CAPACITANCE V_R

1. Elimination of the specific volume by using the relationship

$$v_R = \frac{V_R}{m_R}$$

being V_R the capacitance volume, which is constant.

Replacing v_R in equations (2) and (3), the remaining set of 5 equations is as follows

$$\dot{m}_R = -W_{H_1} + W_{H_2} \quad (1)$$

$$\dot{T}_R = \frac{\dot{m}_R \left(\frac{T_R L}{m_R (v_{SR} - v_W)} - c_p T_R - x_R L \right) + v_W m_R (1 - x_R) (\bar{T}_0 - T_R) - W_{H_1} (c_p T_R + x_R L) + W_{H_2} (c_p T_R + x_R L) \text{ if } W_{H_1} > 0}{m_R \left[c_p - \frac{1}{J} \frac{V_R}{m_R} p_R \frac{q/R}{(T_R + 460)^2} - \frac{L x_R v_{SR}}{T_R + 460} \left(1 - \frac{L/R}{T_R + 460} \right) \frac{1}{v_{SR} - v_W} \right]} \quad (2)$$

$$\dot{x}_R = \frac{-\frac{V_R}{m_R^2} \dot{m}_R}{v_{SR} - v_W} - \frac{x_R v_{SR}}{v_{SR} - v_W} \left(1 - \frac{L/R}{T_R + 460} \right) \frac{\dot{T}_R}{T_R + 460} \quad (3)$$

$$\dot{v}_{SR} = v_{SR} \left(1 - \frac{L/R}{T_R + 460} \right) \frac{\dot{T}_R}{T_R + 460} \quad (4)$$

$$\dot{p}_R = p_R \frac{L/R}{(T_R + 460)^2} \dot{T}_R \quad (5)$$

2. Elimination of the variable v_{SR} , by using the relationship

$$v_R = (1 - x_R) v_W + x_R v_{SR}$$

and

$$V_R = m_R v_R$$

Thus

$$m_R (v_{SR} - v_W) = \frac{V_R - m_R v_W}{x_R}$$

$$\frac{m_R x_R v_{SR}}{v_{SR} - v_W} = \frac{V_R - (1 - x_R) v_W m_R}{V_R - m_R v_W} m_R x_R = m_R x_R \left(1 + \frac{x_R m_R v_W}{V_R - m_R v_W} \right)$$

The set of 4 equations is as follows

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$$\dot{m}_R = -W_{N1} + W_{H1} \quad (1)$$

$$\dot{T}_R = \frac{\left(\frac{x_R L V_R}{V_R - m_R V_W} - c_p T_R - x_R L \right) \dot{m}_R + U_R \frac{V_W}{V_R} m_R (1 - x_R) (\bar{T}_0 - T_R) - W_{N1} (c_p T_R + x_R L) + W_{H1} (c_p T_R + x_R L)}{m_R c_p - \frac{V_R P_R}{J} \left(\frac{L/R}{(T_R + 460)^2} - \frac{L m_R x_R}{T_R + 460} \left(1 - \frac{L/R}{T_R + 460} \right) \right) \left(1 + \frac{x_R m_R V_W}{V_R - m_R V_W} \right)} \quad (2)$$

$$\dot{x}_R = - \frac{\frac{V_R}{m_R} x_R \dot{m}_R}{V_R - m_R V_W} - x_R \left(1 + \frac{x_R m_R V_W}{V_R - m_R V_W} \right) \left(1 - \frac{L/R}{T_R + 460} \right) \frac{\dot{T}_R}{T_R + 460} \quad (3)$$

$$\dot{P}_R = P_R \frac{L/R}{(T_R + 460)^2} \dot{T}_R \quad (4)$$

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RUPTURED PIPE

STEAM GENERATOR SIDE - L

1. Elimination of $\bar{v}_L$, replacing (III) in (I)

$$p_0 - \frac{W_L^2}{A_L^2} \frac{V_0}{m_0} \frac{1}{2g} - p_L = \frac{k_L}{2} W_L^2 \left(\frac{V_0}{m_0} + v_L \right) \quad (1)$$

2. Elimination of v_L , replacing (IV) in (II) and (VII)

$$v_L = (1-x_L) v_w + x_L \left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_L} \quad (2)$$

$$u_{CL}^2 = v_L^2 \frac{g L p_L \frac{1}{\left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_L} - v_w}}{c_p \frac{(T_L + 460)^2}{2/R} + \frac{L x_L}{1 - v_w \frac{p_L}{T_L + 460} \left(\frac{\mu}{R} \right)} \left(1 - \frac{T_L + 460}{2/R} \right) - \frac{p_L v_L}{J}} \quad (6)$$

3. Elimination of u_{CL} replacing (6) in (III)

$$W_L^2 = A_L^2 g L \frac{\frac{p_L}{\left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_L} - v_w}}{c_p \frac{(T_L + 460)^2}{2/R} + \frac{L x_L}{1 - v_w \frac{p_L}{T_L + 460} \left(\frac{\mu}{R} \right)} \left(1 - \frac{T_L + 460}{2/R} \right) - \frac{T_L + 460}{J} \left(\frac{R}{\mu} \right)} \quad (4)$$

4. Elimination of v_L , replacing (2) in (1)

$$p_0 - \frac{W_L^2}{A_L^2} \frac{V_0}{2g m_0} - p_L = \frac{k_L}{2} W_L^2 \left[\frac{V_0}{m_0} + (1-x_L) v_w + x_L \left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_L} \right] \quad (1)$$

The set of 4 equations remains as follows

$$p_0 - \frac{W_L^2}{A_L^2} \frac{V_0}{2g m_0} - p_L = \frac{k_L}{2} W_L^2 \left[\frac{V_0}{m_0} + (1-x_L) v_w + x_L \left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_L} \right] \quad (1)$$

$$p_L = p_0 e^{-\frac{2/R}{T_L + 460}} \quad (2)$$

$$W_L^2 = A_L^2 g L \frac{\frac{p_L}{\left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_L} - v_w}}{c_p \frac{(T_L + 460)^2}{2/R} + \frac{L x_L}{1 - v_w \frac{p_L}{T_L + 460} \left(\frac{\mu}{R} \right)} \left(1 - \frac{T_L + 460}{2/R} \right) - \frac{T_L + 460}{J} \left(\frac{R}{\mu} \right)} \quad (3)$$

$$c_p T_0 + x_0 L = c_p T_L + x_L L + \frac{W_L^2}{2g J A_L^2} \left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_L} \quad (4)$$

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DEPT.

HOT LEG PIPES: H_1, H_2, I & JOINT T.J

1. Elimination of v_J , replacing (VI) in (VII).

$$v_J = (1-x_J) v_W + \frac{x_J}{p_J} \left(\frac{R}{\mu} \right) (T + 460)$$

2. Elimination of v_J , replacing v_J in (I) and (II)

$$p_P - p_G = k_I W_I^2 v_P + k_{H_2} W_{H_2}^2 \left[(1-x_J) v_W + \frac{x_J}{p_J} \left(\frac{R}{\mu} \right) (T + 460) \right] \text{ if } p_J > p_G$$

$$- k_{H_2} W_{H_2}^2 v_G \text{ if } p_G > p_J$$

$$p_P - p_R = k_I W_I^2 v_P + k_{H_1} W_{H_1}^2 \left[(1-x_J) v_W + \frac{x_J}{p_J} \left(\frac{R}{\mu} \right) (T + 460) \right] \text{ if } p_J > p_R$$

$$- k_{H_1} W_{H_1}^2 v_R \text{ if } p_R > p_J$$

The set of 6 equations can be written as follows

$$p_P - p_J = k_I W_I^2 v_P / m_P \quad (1)$$

$$p_J - p_G = k_{H_2} W_{H_2}^2 \left[(1-x_J) v_W + \frac{x_J}{p_J} \left(\frac{R}{\mu} \right) (T + 460) \right] \text{ if } p_J > p_G$$

$$- k_{H_2} W_{H_2}^2 \frac{v_G}{m_G} \text{ if } p_J < p_G \quad (2)$$

$$p_J - p_R = k_{H_1} W_{H_1}^2 \left[(1-x_J) v_W + \frac{x_J}{p_J} \left(\frac{R}{\mu} \right) (T + 460) \right] \text{ if } p_J > p_R$$

$$- k_{H_1} W_{H_1}^2 \frac{v_R}{m_R} \text{ if } p_J < p_R \quad (3)$$

$$W_I = W_{H_1} + W_{H_2} \quad (4)$$

$$p_J = p_0 e^{-\frac{L/R}{T+460}} \quad (5)$$

$$W_I (c_P T_P + x_P L) = W_{H_2} (c_P T_J + x_J L) + W_{H_1} (c_P T_J + x_J L) \text{ if } p_J > p_G, p_J > p_R$$

$$W_{H_2} (c_P T_G + x_G L) + W_{H_1} (c_P T_G + x_G L) \text{ if } p_J < p_G, p_J < p_R \quad (6)$$

Replacing (4) in (2)

$$p_J - p_G = k_{H_2} (W_I - W_{H_1})^2 \left[(1-x_J) v_W + \frac{x_J}{p_J} \left(\frac{R}{\mu} \right) (T + 460) \right] \text{ if } p_J > p_G$$

$$- k_{H_2} (W_I - W_{H_1})^2 \frac{v_G}{m_G} \text{ if } p_J < p_G \quad (2)$$

If $p_J > p_G$ in (2) and $p_J > p_R$ in (3), then, dividing (2) by (3)

$$\frac{p_J - p_G}{p_J - p_R} = \frac{k_{H_2}}{k_{H_1}} \left(\frac{W_I - W_{H_1}}{W_{H_1}} \right)^2$$

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$$\frac{k_{N1}}{k_{N2}} \frac{p_3 - p_6}{p_3 - p_R} W_{H1}^2 = (W_I - W_{H1})^2$$

$$W_{H1} \sqrt{\frac{k_{N1}}{k_{N2}} \frac{p_3 - p_6}{p_3 - p_R}} = W_I - W_{H1}$$

$$W_{H1} = \frac{W_I}{1 + \sqrt{\frac{k_{N1}}{k_{N2}} \frac{p_3 - p_6}{p_3 - p_R}}} \quad (3')$$

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REACTOR VESSEL CAPACITANCE: R

$$\dot{m}_R = -W_{N1} + W_{N1} \quad (1)$$

$$\dot{T}_R = \frac{\left(\frac{x_R L V_R}{T_R - m_R v_w} - c_p T_R - x_R L \right) \dot{m}_R + U_R \frac{v_w}{V_R} m_R (1 - x_R) (T_o - T_R) - W_{N1} (c_p T_R + x_R L) + W_{N1} (c_p T_R + x_R L) + W_{N1} (c_p T_R + x_R L) + W_{N1} (c_p T_R + x_R L)}{m_R c_p - \frac{V_R p_R}{J} \frac{L/R}{(T_R + 460)^2} - \frac{L m_R x_R}{T_R + 460} \left(1 - \frac{L/R}{T_R + 460} \right) \left(1 + \frac{x_R m_R v_w}{T_R - m_R v_w} \right)} \quad (2)$$

$$\dot{x}_R = - \frac{T_R x_R}{m_R (T_R - m_R v_w)} \dot{m}_R - \left(1 + \frac{x_R m_R v_w}{T_R - m_R v_w} \right) \left(1 - \frac{L/R}{T_R + 460} \right) \frac{x_R}{T_R + 460} \dot{T}_R \quad (3)$$

$$\dot{p}_R = p_R \frac{L/R}{(T_R + 460)^2} \dot{T}_R \quad (4)$$

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DEPT

PRESSURIZER : P

$$\dot{m}_p = -W_I \quad (1)$$

$$\dot{T}_p = \frac{\left(\frac{x_p L V_p}{V_p - m_p v_w} - c_p T_p - x_p L \right) \dot{m}_p - W_I (c_p T_p + x_p L)}{m_p c_p - \frac{T_p \beta_p}{J} \frac{R/R}{(T_p + 460)^2} - \frac{L m_p x_p}{T_p + 460} \left(1 - \frac{R/R}{T_p + 460} \right) \left(1 + \frac{m_p x_p v_w}{V_p - m_p v_w} \right)} \quad (2)$$

$$\dot{x}_p = - \frac{V_p x_p}{m_p (V_p - m_p v_w)} \dot{m}_p - \left(1 + \frac{x_p m_p v_w}{V_p - m_p v_w} \right) \left(1 - \frac{R/R}{T_p + 460} \right) \frac{x_p}{T_p + 460} \dot{T}_p \quad (3)$$

$$\dot{\beta}_p = \beta_p \frac{R/R}{(T_p + 460)^2} \dot{T}_p \quad (4)$$

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DEPT.

STEAM GENERATOR G

$$\dot{m}_G = W_{H_2} - W_L \quad (1)$$

$$\dot{T}_G = \frac{\left(\frac{x_G L V_G}{V_G - m_G v_w} - c_p T_G - x_G L \right) \dot{m}_G + U_G \frac{v_w}{V_G} m_G (\bar{T}_B - T_G) (1 - x_G) - W_L (c_p T_G + x_G L) + W_{H_2} (c_p T_G + x_G L)}{m_G c_p - \frac{V_G p_G}{J} \frac{L/R}{(T_G + 460)^2} - \frac{L m_G x_G}{T_G + 460} \left(1 - \frac{L/R}{T_G + 460} \right) \left(1 + \frac{x_G m_G v_w}{V_G - m_G v_w} \right)} \quad (2)$$

$$\dot{x}_G = - \frac{x_G \dot{T}_G}{m_G (V_G - m_G v_w)} - \left(1 + \frac{m_G x_G v_w}{V_G - m_G v_w} \right) \left(1 - \frac{L/R}{T_G + 460} \right) \frac{x_G}{T_G + 460} \dot{T}_G \quad (3)$$

$$\dot{p}_G = p_G \frac{L/R}{(T_G + 460)^2} \dot{T}_G$$

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DEPT.

STEAM GENERATOR SIDE OF THE RUPTURED PIPE: L

$$p_0 - \frac{W_L^2}{A_L^2} \frac{V_G}{2g m_0} - p_L = \frac{k_L}{2} W_L^2 \left[\frac{V_G}{m_0} + (1-x_L) v_w + x_L \left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_L} \right] \quad (1)$$

$$p_L = p_0 e^{-\frac{C/R}{T_L + 460}} \quad (2)$$

$$W_L^2 = A_L^2 g L \frac{\frac{p_L}{\left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_L} - v_w}}{c_p \frac{(T_L + 460)^2}{C/R} + \frac{L x_L}{1 - v_w \frac{p_L}{T_L + 460} \left(\frac{R}{\mu} \right)} \left(1 - \frac{T_L + 460}{C/R} \right) - \frac{T_L + 460}{J} \left(\frac{R}{\mu} \right)} \quad (3)$$

$$c_p T_G + x_G L = c_p T_L + x_L L + \left(\frac{R}{\mu} \right) \frac{T_L + 460}{2J} \frac{\frac{L}{\left(\frac{R}{\mu} \right) \frac{T_L + 460}{p_L} - v_w}}{c_p \frac{(T_L + 460)^2}{C/R} + \frac{L x_L}{1 - v_w \frac{p_L}{T_L + 460} \left(\frac{R}{\mu} \right)} \left(1 - \frac{T_L + 460}{C/R} \right) - \frac{T_L + 460}{J} \left(\frac{R}{\mu} \right)} \quad (4)$$

In order to solve this set of equations by trial-and-error the following procedure is suggested

1. Assume p_L in (2) and get T_L
2. Insert p_L and T_L in (4) and get x_L
3. Insert p_L , x_L and T_L in (3) and get W_L
4. Insert T_L , x_L and W_L in (1) and get p_L' in the other side
5. As $p_L' \neq p_L$ the same process is initiated with $\frac{1}{2} (p_L + p_L')$
6. If Δp_L is the tolerable error in p_L , when $|p_L - p_L'| < \Delta p_L$, the value of p_L is accepted together with the other parameters.

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REACTOR VESSEL SIDE OF THE RUPTURED PIPE : N_1

$$p_e = \frac{W_{N_1}^2}{A_{N_1}^2} \cdot \frac{V_R}{2g m R_1} - p_{N_1} = \frac{k N_1}{2} W_{N_1}^2 \left[\frac{V_R}{m R_1} + (1 - X_{N_1}) v_w + X_{N_1} \left(\frac{R}{A} \right) \frac{T_{N_1} + 460}{p_{N_1}} \right] \quad (1)$$

$$p_{N_1} = p_o e^{-\frac{L/R}{T_{N_1} + 460}} \quad (2)$$

$$W_{N_1} = A_{N_1}^2 g L \frac{\frac{p_{N_1}}{\left(\frac{R}{A} \right) \frac{T_{N_1} + 460}{p_{N_1}} - v_w}{c_p \frac{(T_{N_1} + 460)^2}{L/R} + \frac{L X_{N_1}}{1 - v_w \frac{p_{N_1}}{T_{N_1} + 460} \left(\frac{A}{R} \right)} \left(1 - \frac{T_{N_1} + 460}{L/R} \right) - \frac{T_{N_1} + 460}{J} \left(\frac{R}{A} \right)} \quad (3)$$

$$c_p T_a + X_R L = c_p T_{N_1} + X_{N_1} L + \left(\frac{R}{A} \right) \frac{T_{N_1} + 460}{2J} \frac{\frac{L}{\left(\frac{R}{A} \right) \frac{T_{N_1} + 460}{p_{N_1}} - v_w}}{c_p \frac{(T_{N_1} + 460)^2}{L/R} + \frac{L X_{N_1}}{1 - v_w \frac{p_{N_1}}{T_{N_1} + 460} \left(\frac{A}{R} \right)} \left(1 - \frac{T_{N_1} + 460}{L/R} \right) - \frac{T_{N_1} + 460}{J} \left(\frac{R}{A} \right)} \quad (4)$$

The procedure for solving this system of equations by trial-and-error is similar to that indicated on the previous page

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DEPT.

HOT LEG PIPES: H_1, H_2, I AND JOINT J

$$p_P - p_J = k_J W_J^2 \frac{T_P}{m_P} \quad (1)$$

$$p_J - p_G = \begin{cases} k_{H_2} W_{H_2}^2 \left[(1-x_J) v_w + \frac{x_J}{p_J} \left(\frac{R}{M} \right) (T_J + 460) \right] & \text{if } p_J > p_G \\ -k_{H_2} W_{H_2}^2 \frac{T_G}{m_G} & \text{if } p_J < p_G \end{cases} \quad (2)$$

$$p_J - p_R = \begin{cases} k_{H_1} W_{H_1}^2 \left[(1-x_J) v_w + \frac{x_J}{p_J} \left(\frac{R}{M} \right) (T_J + 460) \right] & \text{if } p_J > p_R \\ -k_{H_1} W_{H_1}^2 \frac{T_R}{m_R} & \text{if } p_J < p_R \end{cases} \quad (3)$$

$$W_J = W_{H_1} + W_{H_2} \quad (4)$$

$$p_J = p_0 e^{-\frac{L/R}{T+460}} \quad (5)$$

$$\begin{aligned} \text{if } p_J > p_G & \quad -W_{H_2} (c_P T_J + x_J L) & \quad W_{H_1} (c_P T_J + x_J L) & \quad \text{if } p_J > p_R \\ \text{if } p_J < p_G & \quad -W_{H_2} (c_P T_G + x_G L) & \quad + W_J (c_P T_P + x_P L) = & \quad W_{H_1} (c_P T_R + x_R L) & \quad \text{if } p_J < p_R \end{aligned} \quad (6)$$

If $p_J > p_R$ and $p_J > p_G$, equation (3) is replaced by

$$W_{H_1} = \frac{W_J}{1 + \sqrt{\frac{k_{H_1} p_J - p_G}{k_{H_2} p_J - p_R}}} \quad (3')$$

The following procedure is suggested for solving the system of equations by trial-and-error:

1. Assume W_J in (1) and get p_J
2. Insert p_J in (5) and get T_J
3. If $p_J < p_R$, insert p_J in (3) and get W_{H_1}
4. Insert W_{H_1} in (4) and get W_{H_2}
5. Insert W_{H_2} , p_J and T_J in (2) and get x_J
6. Insert x_J , T_J , W_{H_1} , and W_{H_2} in (6) and get W_J'
7. As $W_J' \neq W_J$ the same process is initiated with $\frac{1}{2} (W_J + W_J')$
8. If ΔW_J is the tolerable error in W_J ; when $|W_J - W_J'| < \Delta W_J$, the value of W_J is accepted together with the other parameters.
3. If $p_J > p_R$, but $p_J < p_G$, insert p_J in (2) and get W_{H_2}

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4. Insert W_{H_2} in (4) and get W_H .

5. Insert W_H , p_j and T_j in (3) and get x_j .

6. Follow as in 6.

3'. If $p_j > p_R$ and $p_j > p_G$, then insert p_j in (3') and get W_H .

4'. Follow as in 4.

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REACTOR CORE: O

$$F \bar{T}_0 = C_1 t^{-0.2} + C_2 e^{-\lambda t} - U_R \frac{V_W}{V_R} m_R (1 - X_R) (\bar{T}_0 - T_R) \quad (1)$$

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FIGURE 3. TEMPERATURE IN AND WATER LOSS FROM THE PRESSURIZER

FIGURE 4. EXHAUST MASS FLOW RATES

FIGURE 1. TEMPERATURES IN AND WATER LOSS FROM THE REACTOR VESSEL

FIGURE 2. TEMPERATURES AND WATER CONTENT VARIATION IN THE STEAM GENERATOR

APPENDIX II

ANALYSIS OF THE EXTENT OF CLADDING MELTDOWN AFTER THE ELPHR MAXIMUM CREDIBLE ACCIDENT

CONTENTS

Estimate of radial power distribution	1
Constants and initial values	4
Equations for meltdown	8
Nomenclature	9
Results	10

635 0047

ESTIMATE FOR RADIAL POWER DISTRIBUTION

Assuming a J_0 function as representative for the radial neutron flux and power, and relative distances from designs in the proposal for the ELPHR, calculation are as follows:

$$\text{Average: } \frac{1}{\pi R^2} \int_0^R J_0(r) 2\pi r dr = \frac{2}{R^2} \int_0^R J_0(r) r dr$$

$$\int_0^R J_0(r) r dr = r J_1(r)$$

$$\text{Total average: } \frac{2}{R^2} \int_0^R J_0(r) r dr = \frac{2}{R^2} r J_1(r) \Big|_0^R = \frac{2}{R} J_1(R)$$

$$R = 2.405$$

$$J_1(2.405) = 0.5191$$

$$\frac{2}{R^2} \int_0^R J_0(r) r dr = \frac{2}{2.405^2} 0.5191 = 0.432$$

1. Subassemblies A

$$\text{Average: } \frac{2.0 + 2.8}{2} = 2.4$$

$$R_1 = 2.4 \frac{2.405}{7.2} = 0.801 \quad ; \quad J_1(R_1) = 0.369$$

$$\frac{2}{R_1^2} \int_0^{R_1} J_0(r) r dr = \frac{2}{0.801^2} 0.369 = 0.920$$

2. Subassemblies B

$$\text{Average: } R_1 = 2 \frac{2.405}{7.2} = 0.668 \quad ; \quad J_1(R_1) = 0.316$$

$$R_2 = 4.5 \frac{2.405}{7.2} = 1.50 \quad ; \quad J_1(R_2) = 0.558$$

$$\frac{2}{R_2^2 - R_1^2} [J_1(R_2) R_2 - J_1(R_1) R_1] = \frac{2(1.50 \times 0.558 - 0.668 \times 0.316)}{1.50^2 - 0.668^2}$$

$$= 2 \frac{(0.834 - 0.211)}{(0.832) (2.168)} = 0.690$$

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3. Subassemblies C

Average: $R_1 = 2.8 \frac{2.405}{7.2} = 0.936$; $J_1(R_1) = 0.419$

$R_2 = 5.6 \frac{2.405}{7.2} = 1.87$; $J_1(R_2) = 0.5817$

$$\frac{2}{R_2^2 - R_1^2} [J_1(R_2) \cdot R_2 - J_1(R_1) \cdot R_1] = \frac{2 (1.87 \times 0.5817 - 0.936 \times 0.419)}{1.87^2 - 0.936^2}$$

$$= 2 \frac{(1.09 - 0.392)}{(0.936)(2.81)} = 0.531$$

4. Subassemblies D

Average: $R_1 = 4 \frac{2.405}{7.2} = 1.34$

$R_2 = 6.3 \frac{2.405}{7.2} = 2.11$

$J_1(R_1) = 0.53$

$J_1(R_2) = 0.567$

$$\frac{2}{R_2^2 - R_1^2} [J_1(R_2) \cdot R_2 - J_1(R_1) \cdot R_1] =$$

$$= 2 \frac{2.11 \times 0.567 - 1.34 \times 0.53}{2.11^2 - 1.34^2} =$$

$$= 2 \frac{1.20 - 0.71}{(3.45)(0.77)} = 0.390$$

5. Subassemblies E

Average: $R_1 = 4.5 \frac{2.405}{7.2} = 1.50$

$J_1(R_1) = 0.558$

$R_2 = 7.2 \frac{2.405}{7.2} = 2.405$

$J_1(R_2) = 0.519$

$$\frac{2}{R_2^2 - R_1^2} [J_1(R_2) \cdot R_2 - J_1(R_1) \cdot R_1] = 2 \frac{2.405 \times 0.519 - 1.5 \times 0.558}{2.4^2 - 1.5^2} = 2 \frac{1.25 - 0.839}{3.9 \times 0.9} =$$

$$= 0.234$$

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6. RATIOS OF POWER

<u>SUBASSEMBLIES</u>	<u>NUMBER</u>	<u>AVERAGE J_0</u>	
A	4	0.92	$4 \times 0.92 = 3.68$
B	8	0.69	$8 \times 0.69 = 5.52$
C	4	0.531	$4 \times 0.531 = 2.12$
D	8	0.39	$8 \times 0.39 = 3.12$
E	8	0.234	$8 \times 0.234 = 1.87$
	32		16.31

Average J_0 in reactor core: $\frac{16.31}{32} = 0.51$

Subassembly

A	$0.92 / 0.51 = 1.80$
B	$0.69 / 0.51 = 1.35$
C	$0.531 / 0.51 = 1.04$
D	$0.39 / 0.51 = 0.765$
E	$0.234 / 0.51 = 0.46$

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CONSTANTS AND INITIAL VALUES

1. EMISSIVITY OF HEAVILY OXIDIZED ALUMINUM

Data from Mc Adams, Heat Transmission

Temperature Emissivity

$$200^{\circ}\text{F} = 660^{\circ}\text{R} \quad 0.20$$

$$940^{\circ}\text{F} = 1,400^{\circ}\text{R} \quad 0.31$$

Assuming $\epsilon = a + bT$

$$0.20 = a + b(660)$$

$$0.31 = a + b(1400)$$

$$0.11 = 740b$$

$$b = 0.000,149$$

$$a = 0.20 - (0.000,149)(660) = 0.20 - 0.0981$$

$$a = 0.102$$

$$\epsilon = 0.102 + 0.149 \times 10^{-3} T$$

2. CONVEX SURFACE FOR RADIATION

The perimeters, which correspond to the different convex surface for radiation, can be determined as follows

$$P_1 = (4)(7p) + \pi D = 1.622 \text{ ft}$$

$$P_2 = (4)(5p) + \pi D = 1.205 \text{ ft}$$

$$P_3 = (4)(3p) + \pi D = 0.7887 \text{ ft}$$

$$P_4 = (4)(p) + \pi D = 0.372 \text{ ft}$$

$$\text{Active length } L = 42" = 3.5 \text{ ft}$$

$$A_1 = P_1 L = (1.622)(3.5) = 5.68 \text{ ft}^2$$

$$A_2 = P_2 L = (1.205)(3.5) = 4.22 \text{ ft}^2$$

$$A_3 = P_3 L = (0.7887)(3.5) = 2.76 \text{ ft}^2$$

$$A_4 = P_4 L = (0.372)(3.5) = 1.30 \text{ ft}^2$$

$$D = 0.4167 \text{ ft}$$

$$p = 0.052 \text{ ft}$$

refers to Row # 1

Row # 2

Row # 3

Row # 4

3. NUMBER OF FUEL RODS IN EACH ROW

According with the fuel subassembly design:

$$\left. \begin{array}{l} \text{Row \# 0} : 8 \times 4 = 32 \\ \text{Row \# 1} : 7 \times 4 = 28 \\ \text{Row \# 2} : 5 \times 4 = 20 \\ \text{Row \# 3} : 3 \times 4 = 12 \\ \text{Row \# 4} : 1 \times 4 = 4 \end{array} \right\}$$

Total number of fuel rods per subassembly: 96

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4. FUEL RODS ROW HEAT CAPACITANCE

Volume of UO_2 per rod at room temperature

$$V_{UO_2} = \frac{\pi}{4} (0.417)^2 (42) = 5.736 \text{ in}^3/\text{rod}$$

Actual density of UO_2 : $10.42 \frac{\text{gm}}{\text{cm}^3} = (10.42) (0.0361) = 0.376 \frac{\text{lb}}{\text{in}^3}$

Weight of UO_2 per rod

$$W_{UO_2} = (5.736) (0.376) = 2.16 \text{ lb/rod}$$

Specific heat of UO_2 : $0.077 \frac{\text{BTU}}{\text{lb} \cdot \text{R}}$

Volume of Al per rod only in the tubing along the active length at room temperature

$$V_{Al} = \frac{\pi}{4} (0.5^2 - 0.420^2) (42) = 2.43 \text{ in}^3/\text{rod}$$

Density of Al cladding : $2.70 \frac{\text{gm}}{\text{cm}^3} = 0.0976 \text{ lb/in}^3$

Weight of Al tubing per rod

$$W_{Al} = (0.0976) (2.43) = 0.237 \text{ lb/rod}$$

Specific heat of Al : $0.24 \frac{\text{BTU}}{\text{lb} \cdot \text{R}}$

Fuel Rod Heat Capacitance : $(2.16) (0.077) + (0.237) (0.24) = 0.223 \frac{\text{BTU}}{\text{R rod}}$

<u>Row #</u>	<u>Fuel Rods</u>	<u>Heat Capacitance</u>
0	32	$F_0 = (0.223) (32) = 7.14 \frac{\text{BTU}}{\text{R}}$
1	28	$F_1 = (0.223) (28) = 6.25 \frac{\text{BTU}}{\text{R}}$
2	20	$F_2 = (0.223) (20) = 4.46 \frac{\text{BTU}}{\text{R}}$
3	12	$F_3 = (0.223) (12) = 2.68 \frac{\text{BTU}}{\text{R}}$
4	4	$F_4 = (0.223) (4) = 0.892 \frac{\text{BTU}}{\text{R}}$

5. WATER INJECTION CHARACTERISTICS

Total mass flow $W = 40 \text{ gpm} = 20 \times 10^3 \text{ lb/hr}$

Inlet Temperature: 70°F

Exit Temperature: 212°F } $\Delta T_w = 212 - 70 = 142^\circ\text{F}$

Specific Heat of water: $c_p = 1 \frac{\text{BTU}}{\text{lb} \cdot \text{F}}$

$$W c_p \Delta T_w = (20 \times 10^3) (1) (142) = 2.84 \times 10^6 \frac{\text{BTU}}{\text{hr}}$$

$$= 789 \frac{\text{BTU}}{\text{sec}}$$

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6. AFTERHEAT

6.A. TEMPERATURE PROFILE IN FUEL

Using same data for Blow-down Accident Analysis, p. 18 Constants

$$\lambda = 0.1 \text{ sec}^{-1}$$

$$C_2 = 28.8 \times 10^3 \frac{\text{BTU}}{\text{sec}} \quad (\text{total core})$$

$$\bar{C}_2 = \frac{28.8 \times 10^3}{96 \times 32} = 9.38 \frac{\text{BTU}}{\text{sec}} \quad (\text{average per fuel rod})$$

6.B. FISSION PRODUCTS DECAY

Same reference:

$$C_1 = 3.28 \times 10^3 \text{ BTU sec}^{-0.8} \quad (\text{total core})$$

$$\frac{C_1}{0.8} = 2.85 \times 10^3 \text{ BTU sec}^{-0.8} \quad (\text{total core})$$

$$\frac{\bar{C}_1}{0.8} = \frac{2.85 \times 10^3}{96 \times 32} = 0.928 \text{ BTU sec}^{-0.8} \quad (\text{average per fuel rod})$$

7. END OF BLOW-DOWN CONDITIONS

Time: $t_b = 12 \text{ sec.}$

Average cladding temperature: $T = 440^\circ\text{F} = 800^\circ\text{R}$

8. CLAD MELTING POINT

Melting Point of pure Al: $659.7^\circ\text{C} = 933^\circ\text{K} = 1679^\circ\text{R} = 1219^\circ\text{F}$
(p. 305 of the Handbook of Chemistry and Physics, 31st Edition).

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SUBASSEMBLIES A

From p. 3 the factor for ratio of fluxes (or power) radially is: 1.80

$$\frac{C_1^0}{0.8} = (0.928) (1.80) (32) = 53.4 \text{ BTU sec}^{-0.8}$$

$$\frac{C_1^1}{0.8} = (0.928) (1.80) (28) = 46.8 \text{ BTU sec}^{-0.8}$$

$$\frac{C_1^2}{0.8} = (0.928) (1.80) (20) = 33.4 \text{ BTU sec}^{-0.8}$$

$$\frac{C_1^3}{0.8} = (0.928) (1.80) (12) = 20.0 \text{ BTU sec}^{-0.8}$$

$$\frac{C_1^4}{0.8} = (0.928) (1.80) (4) = 6.68 \text{ BTU sec}^{-0.8}$$

$$C_2^0 = (9.38) (1.80) (32) = 540 \text{ BTU sec}^{-1}$$

$$C_2^1 = (9.38) (1.80) (28) = 473 \text{ BTU sec}^{-1}$$

$$C_2^2 = (9.38) (1.80) (20) = 338 \text{ BTU sec}^{-1}$$

$$C_2^3 = (9.38) (1.80) (12) = 203 \text{ BTU sec}^{-1}$$

$$C_2^4 = (9.38) (1.80) (4) = 67.6 \text{ BTU sec}^{-1}$$

$$W_A c_p \Delta T_w = (789) \frac{1.80}{96+32} (96) = 44.4 \frac{\text{BTU}}{\text{sec}}$$

SUBASSEMBLIES E

From p. 3 the factor for ratio of fluxes (or power) radially is: 0.46

Similarly as before:

$$\frac{C_1^0}{0.8} = 13.7 \text{ BTU sec}^{-0.8}$$

$$\frac{C_1^1}{0.8} = 12.0 \text{ BTU sec}^{-0.8}$$

$$\frac{C_1^2}{0.8} = 8.53 \text{ BTU sec}^{-0.8}$$

$$\frac{C_1^3}{0.8} = 5.12 \text{ BTU sec}^{-0.8}$$

$$\frac{C_1^4}{0.8} = 1.71 \text{ BTU sec}^{-0.8}$$

$$C_2^0 = 138 \text{ BTU sec}^{-1}$$

$$C_2^1 = 121 \text{ BTU sec}^{-1}$$

$$C_2^2 = 86.4 \text{ BTU sec}^{-1}$$

$$C_2^3 = 54.8 \text{ BTU sec}^{-1}$$

$$C_2^4 = 17.3 \text{ BTU sec}^{-1}$$

$$W_E c_p \Delta T_w = 11.4 \frac{\text{BTU}}{\text{sec}}$$

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EQUATIONS FOR MELT-DOWN ACCIDENT

SUBASSEMBLY i

Row # 0 (32 fuel rods)

$$F_0 \dot{\bar{T}}_0 = C_1^0 t^{-0.2} + C_2^0 e^{-\lambda t} + \frac{\sigma A_1}{\epsilon_0^{-1} + \epsilon_1^{-1} - 1} (T_1^4 - T_0^4) - W/c_p \Delta T_w$$

$$\bar{T}_0 \geq 672^\circ R$$

Row # 1 (28 fuel rods)

$$F_1 \dot{\bar{T}}_1 = C_1^1 t^{-0.2} + C_2^1 e^{-\lambda t} + \frac{\sigma A_2}{\epsilon_1^{-1} + \epsilon_2^{-1} - 1} (T_2^4 - T_1^4) - \frac{\sigma A_1}{\epsilon_0^{-1} + \epsilon_1^{-1} - 1} (T_1^4 - T_0^4)$$

Row # 2 (20 fuel rods)

$$F_2 \dot{\bar{T}}_2 = C_1^2 t^{-0.2} + C_2^2 e^{-\lambda t} + \frac{\sigma A_3}{\epsilon_2^{-1} + \epsilon_3^{-1} - 1} (T_3^4 - T_2^4) - \frac{\sigma A_2}{\epsilon_1^{-1} + \epsilon_2^{-1} - 1} (T_2^4 - T_1^4)$$

Row # 3 (12 fuel rods)

$$F_3 \dot{\bar{T}}_3 = C_1^3 t^{-0.2} + C_2^3 e^{-\lambda t} + \frac{\sigma A_4}{\epsilon_3^{-1} + \epsilon_4^{-1} - 1} (T_4^4 - T_3^4) - \frac{\sigma A_3}{\epsilon_2^{-1} + \epsilon_3^{-1} - 1} (T_3^4 - T_2^4)$$

Row # 4 (4 fuel rods)

$$F_4 \dot{\bar{T}}_4 = C_1^4 t^{-0.2} + C_2^4 e^{-\lambda t} - \frac{\sigma A_4}{\epsilon_3^{-1} + \epsilon_4^{-1} - 1} (T_4^4 - T_3^4)$$

CORE MELT-DOWN

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NOMENCLATURE

A	area for radiation, ft^2
C	constant for fission decay power, $BTU \sec^{-0.2}$
C_2	heat diffusion, BTU/sec
C_p	specific heat of water, $\frac{BTU}{lb \cdot R}$
F	fuel rods row heat capacitance, $\frac{BTU}{R}$
$\bar{T}$	absolute temperature, $^{\circ}R$
t	time after blow-down accident, sec.
W	mass flow of water, $\frac{lb}{sec}$
ΔT_w	temperature rise in the water, $^{\circ}R$
ϵ	emissivity, dimensionless
λ	heat diffusion decay constant, sec^{-1}
σ	Stefan-Boltzmann constant, $\frac{BTU/sec}{ft^2 \cdot R^4}$

Subscripts

$\begin{matrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \end{matrix}$	refers to different rows in their areas, capacitances, emissivities or temperatures
i	different subassemblies in their water mass flow; $i = A, B, C, D, E$

Superscripts

$\begin{matrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \end{matrix}$	refers to different rows in their fission decay power constants or heat diffusion constants
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CORE MELT-DOWN

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TIME REQUIRED TO REACH THE ALUMINUM MELTING POINT : 1,219 °F

AFTER BLOW-DOWN ACCIDENT : $t_0 = 12 \text{ sec.}$

<u>SUB ASSEMBLY</u>	<u>Row No.</u>	<u>TIME (min.)</u>
A	1	4 1/2
	4	4
E	1	54
	4	29

All the fuel rods reach the cladding melting point, except those located on the periphery of each subassembly (Row # 0). Consequently the percent of the core melt-down can be estimated

$$\frac{4 + 12 + 20 + 28}{4 + 12 + 20 + 28 + 32} = \frac{64}{96} = \frac{2}{3}$$

CORE MELT-DOWN

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APPENDIX III

ANALYSIS OF THE ENERGY RELEASED FROM THE REACTOR SYSTEM AFTER THE ELPHR MAXIMUM CREDIBLE ACCIDENT

CONTENTS

Determination of maximum pressures and temperatures in the containment shell	1
Summary of results.....	10
Correction for changed primary-system volume.....	11
Revised summary of results.....	15

DESIGN CRITERIA FOR CONTAINMENT VESSEL

The maximum pressures and temperatures are produced in the containment vessel following a rupture of the reactor coolant system.

For this calculation, the chemical reaction of the aluminum, and flashing of the water and steam is assumed to occur instantaneously.

1. Air in the container

Free Volume of Air : $V = 100,000 \text{ ft}^3$

Ambient Temperature : $T = 100^\circ \text{F}$

Pressure : $p = 14.7 \text{ psia} = 1 \text{ atm.}$

By the ideal gases law:

$$pV = nRT = M \frac{R}{\mu} T$$

$$\mu = 28.8 \text{ lb/mole}$$

$$R = 1,545 \frac{\text{lb ft}}{\text{mole}^\circ \text{R}}$$

$$M = \frac{pV}{\frac{R}{\mu} T} = \frac{(14.7)(144)(10^5)}{\frac{1,545}{28.8}(460+100)} = 7.05 \times 10^3 \text{ lb}$$

2. Water in the reactor system

Considering a volume of water which corresponds to 31,000 lb for 900 psia in the system, then at 300 psia, multiplying by the ratio of the specific volumes:

$$31,000 \frac{0.0212}{0.0189} \approx 34,800 \text{ lb}$$

Water at 285°F : 34,800 lb

Water at 415°F : 31,000 lb

3. Steam in the reactor system

In the pressurizer, there are 23 ft³ of steam at saturation pressure.

At 300 psia

$$v = 1.543 \text{ ft}^3/\text{lb}$$

$$M_s = \frac{23}{1.543} = 14.9 \text{ lb}$$

At 900 psia

$$v = 0.5006 \text{ ft}^3/\text{lb}$$

$$M_s = \frac{23}{0.5006} = 46.0 \text{ lb}$$

4. Chemical reaction Al-water

The standard heat of reaction can be calculated from the heat of formation tables.

CONTAINMENT VESSEL

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From Chemical Engineers' Handbook, p. 236 and following.

Reaction

Heat of Formation

68.3 Kcal/mole of H_2O (exothermic)

399 Kcal/mole of Al_2O_3 (exothermic)

Heat released by the Al-water reaction: $\Delta H = 399 - 3 \times 68.3 = 194$ Kcal/mole of Al_2O_3

or

$$\Delta H = 349 \times 10^3 \frac{BTU}{mole}$$

As two atoms of Al participate in the reaction per molecule of Al_2O_3 , then

$$\Delta H = \frac{349 \times 10^3}{2 (27)} = 6.5 \times 10^3 \frac{BTU}{lb \text{ of } Al} \quad (\text{exothermic})$$

Considering only 6.67% of Al involved in the chemical reaction.

Total weight of Al in the core: 768.6 lb

6.67% of the Al weight in the core: $6.67 \cdot \frac{768.6}{100} = 51.2$ lb of Al.

Heat release: $\Delta H = (51.2) (6.5 \times 10^3) = 0.333 \times 10^6$ BTU

4. Hydrogen release

As three moles of hydrogen are released per two moles of aluminum, thus

$$51.2 \frac{3}{27} = 5.7 \text{ lb of } H_2$$

5. Heat Balance

5. A. Air

Specific heat at constant pressure:

$$c_p = 0.25 \frac{BTU}{lb \cdot F}$$

Enthalpy change:

$$\Delta H_A = (7.05 \times 10^3) (0.25) (T - 100) = 1.76 \times 10^3 T - 0.176 \times 10^6 \text{ BTU}$$

5. B. Water

The amount of water which participates in the Al-water reaction is

$$(51.2) \frac{3 \times 18}{2 \times 27} = 51.2 \text{ lb of water}$$

This amount of water is negligible compared with the total amount of water in the reactor system.

Case 300 psia

35 ft³ of the pressurizer are occupied by water at saturation pressure, that is

$$\frac{35}{0.0189} = 1.85 \times 10^3 \text{ lb at } 417^\circ F$$

and $34,800 - 1,850 = 32,950$ lb at $285^\circ F$

CONTAINMENT VESSEL

683.0060

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DEPT.

Specific heat of water $c_p = 1 \frac{\text{BTU}}{\text{lb} \cdot ^\circ\text{F}}$

Initial enthalpy: $[(32.95 \times 10^3)(285) + (1.85 \times 10^3)(417)](1) = (9.40 + 0.77) \times 10^6$
 $= 10.17 \times 10^6 \text{ BTU}$

Enthalpy change: $\Delta H_w = 34.8 \times 10^3 (1-x) h_f - 10.17 \times 10^6 \text{ BTU}$

Case 900 psia

Similarly as before: $\frac{35}{0.0212} = 1.65 \times 10^3 \text{ lb at } 532^\circ\text{F}$

and $31,000 - 1,650 = 29,350 \text{ lb at } 415^\circ\text{F}$

Initial enthalpy: $[(29.35)(415) + (1.65)(532)] 10^3 = (12.18 + 0.88) 10^6$
 $= 13.06 \times 10^6 \text{ BTU}$

Enthalpy change: $\Delta H_w = 31 \times 10^3 (1-x) h_f - 13.06 \times 10^6 \text{ BTU}$

5. C. Steam

Case 300 psia

Initial enthalpy: $(14.9)(1,203) = 17.9 \times 10^3 \text{ BTU}$

Enthalpy change: $\Delta H_s = 34.8 \times 10^3 \times h_v - 17.9 \times 10^3 \text{ BTU}$

Case 900 psia

Initial enthalpy: $(46.0)(1,195) = 55.0 \times 10^3 \text{ BTU}$

Enthalpy change: $\Delta H_s = 31 \times 10^3 \times h_v - 55 \times 10^3 \text{ BTU}$

5. D. Hydrogen

Specific heat at constant pressure: $c_p = 3.5 \frac{\text{BTU}}{\text{lb} \cdot ^\circ\text{F}}$

Enthalpy change: $\Delta H_H = (5.7)(3.5)(T - 285) = 20T - 5.68 \times 10^3 \text{ BTU}$

5. E Chemical heat

As previously indicated: $\Delta H = 0.333 \times 10^6 \text{ BTU}$

The heat balance can be written as follows: $\Delta H_A + \Delta H_w + \Delta H_s + \Delta H_H = \Delta H$

Case 300 psia

$\underbrace{1.76 \times 10^3 T - 0.176 \times 10^6 \text{ BTU}}_{\Delta H_A} + \underbrace{34.8 \times 10^3 (1-x) h_f - 10.17 \times 10^6 \text{ BTU}}_{\Delta H_w} + \underbrace{34.8 \times 10^3 \times h_v - 0.018 \times 10^6 \text{ BTU}}_{\Delta H_s}$

$\underbrace{+ 20T - 0.006 \times 10^6 \text{ BTU}}_{\Delta H_H} = \underbrace{0.333 \times 10^6 \text{ BTU}}_{\Delta H}$

$1.76 \times 10^3 T + 20T + 34.8 \times 10^3 \times h_v + 34.8 \times 10^3 (1-x) h_f = 10.70 \times 10^6 \text{ BTU}$

$x = \frac{10.70 \times 10^6 - 1.78 \times 10^3 T - 34.8 \times 10^3 h_f}{34.8 \times 10^3 (h_v - h_f)}$

THE HEAT BALANCE
IS BASED ON
ENTHALPY, NOT
INTERNAL
ENERGY

CONTAINMENT VESSEL

600 0061

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$$x = \frac{308 - 0.0512 T - h_f}{h_v - h_f} \quad (1)$$

Case 300 psia

Similarly as before:

$$1.76 \times 10^3 T + 20T + 31 \times 10^3 \times h_v + 31 \times 10^3 (1-x) h_f = 12.63 \times 10^3 \text{ BTU}$$

$$x = \frac{440 - 0.0574 T - h_f}{h_v - h_f} \quad (1')$$

6. Pressure

The partial pressure of the steam p_s must be equal to the saturation pressure at the water temperature.

Case 300 psia

$$p_s = \frac{1,545}{144} \cdot \frac{34,800}{18} \cdot \frac{x}{105} (460 + T) = \frac{460 + T}{4.83} x$$

$$x = \frac{4.83 p_s}{T + 460} \quad (2)$$

Case 900 psia

$$p_s = \frac{1,545}{144} \cdot \frac{31,000}{18} \cdot \frac{x}{105} (460 + T) = \frac{460 + T}{5.41} x$$

$$x = \frac{5.41 p_s}{T + 460} \quad (2')$$

Case 300 psia

Solving simultaneously (1) and (2)

At $T = 200^\circ\text{F}$

$$p_s = 11.53 \text{ psia}$$

$$h_f = 200 \frac{\text{BTU}}{16}$$

$$h_v = 1178 \frac{\text{BTU}}{16}$$

$$\left. \begin{array}{l} h_f = 200 \frac{\text{BTU}}{16} \\ h_v = 1178 \frac{\text{BTU}}{16} \end{array} \right\} \Delta h = h_v - h_f = 978 \frac{\text{BTU}}{16}$$

$$\text{In (1)} \quad x = \frac{308 - (0.0512)(200) - 200}{978} = \frac{98}{978} = 0.100$$

$$\text{In (2)} \quad x = \frac{4.83 \times 11.53}{660} = 0.0844$$

At $T = 210^\circ\text{F}$

$$p_s = 14.12 \text{ psia}$$

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635 0062

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$$\left. \begin{array}{l} h_f = 210 \frac{\text{BTU}}{\text{lb}} \\ h_v = 1182 \frac{\text{BTU}}{\text{lb}} \end{array} \right\} \Delta h = h_v - h_f = 972 \frac{\text{BTU}}{\text{lb}}$$

$$\text{In (1)} \quad x = \frac{308 - (0.0512)(210) - 210}{972} = \frac{87}{972} = 0.0896$$

$$\text{In (2)} \quad x = \frac{4.83 + 14.12}{670} = 0.102$$

$$\left. \begin{array}{ll} \text{Thus, if } T = 200^\circ\text{F} & \Delta x = 0.100 - 0.84 = +0.16 \\ T = 210^\circ\text{F} & \Delta x = 0.090 - 0.102 = -0.12 \end{array} \right\} 10 \frac{0.16}{0.28} \approx 6$$

$$T = 206^\circ\text{F}$$

$$p_s = 13.0 \text{ psia}$$

$$x = 0.094$$

Partial pressure of air and hydrogen:

$$p' = \frac{1545}{144} \frac{7.05 \times 10^3}{10^5} + \frac{5.7}{2} (460 + 206) = \frac{248}{9.32 \times 10^3} (666)$$

$$p' = 17.8 \text{ psia}$$

$$\text{Total pressure: } p = p_s + p' = 13.0 + 17.8 = 30.8 \text{ psia}$$

$$\text{Relative pressure } p = 16.1 \text{ psig.}$$

Case 900 psia

Solving simultaneously (1') and (2')

$$\text{At } T = 250^\circ\text{F}$$

$$p_s = 29.83 \text{ psia}$$

$$\left. \begin{array}{l} h_f = 248 \frac{\text{BTU}}{\text{lb}} \\ h_v = 1196 \frac{\text{BTU}}{\text{lb}} \end{array} \right\} \Delta h = h_v - h_f = 948 \frac{\text{BTU}}{\text{lb}}$$

$$\text{In (1')} \quad x = \frac{440 - (0.0574)(250) - 248}{948} = \frac{178}{948} = 0.188$$

$$\text{In (2')} \quad x = \frac{5.41 + 29.83}{710} = 0.227$$

$$\text{At } T = 240^\circ\text{F}$$

$$p_s = 24.97 \text{ psia}$$

$$\left. \begin{array}{l} h_f = 240 \frac{\text{BTU}}{\text{lb}} \\ h_v = 1192 \frac{\text{BTU}}{\text{lb}} \end{array} \right\} \Delta h = h_v - h_f = 952 \frac{\text{BTU}}{\text{lb}}$$

$$\text{In (1')} \quad x = \frac{440 - (0.0574)(240) - 240}{952} = \frac{186}{952} = 0.195$$

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$$X = \frac{5.41 \times 24.97}{700} = 0.193$$

$$\left. \begin{array}{l} \text{Thus if } T = 250^\circ\text{F} \\ T = 240^\circ\text{F} \end{array} \right\} \begin{array}{l} \Delta x = 0.188 - 0.227 = -0.039 \\ \Delta x = 0.195 - 0.193 = \frac{0.002}{0.041} \end{array} \quad 10 \frac{0.002}{0.041} < 1^\circ\text{F}$$

$$T = 240^\circ\text{F}$$

$$p_s = 25.0 \text{ psia}$$

$$X = 0.194$$

$$\text{Partial pressure of air and hydrogen: } p' = \frac{248}{9.32 \times 10^3} (700) = 18.6 \text{ psia}$$

$$\text{Total pressure: } p = p_s + p' = 25.0 + 18.6 = 43.6 \text{ psia}$$

$$\text{Relative pressure } p = 28.9 \text{ psig}$$

SUMMARY OF RESULTS FOR PRESSURE BUILD-UP IN CONTAINMENT VESSEL CONSIDERING ALUMINUM-WATER REACTION.

Normal Operating

Partial Pressures

Total Pressures

<u>Pressure</u>	<u>Steam</u>	<u>Air and Hydrogen</u>	<u>Absolute</u>	<u>Relative</u>
psia	psia	psia	psia	psig
300	13.0	17.8	30.8	16.1
900	25.0	18.6	43.6	28.9

CONTAINMENT VESSEL

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7. Chemical reaction Al-O₂

For this assumption the heat of reaction is greater than that for Al-H₂O, but now oxygen is consumed.

The heat released is: $\Delta H = 399 \text{ Kcal/mole of Al}_2 \text{ O}_3$ (exothermic)

or $\Delta H = 718 \times 10^3 \frac{\text{BTU}}{\text{mole}}$

As two atoms of Al participate in the reaction per molecule of Al₂O₃, then:

$$\Delta H = \frac{718}{2 \times 27} 10^3 = 13 \times 10^3 \frac{\text{BTU}}{\text{lb of Al}} \quad (\text{exothermic})$$

Considering only 6.67% of Al involved in the chemical reaction

$$\Delta H = (51.2)(13 \times 10^3) = 0.667 \times 10^6 \text{ BTU}$$

8. Oxygen consumption

As 1 1/2 moles of O₂ are consumed per two moles of Al, then

$$51.2 \frac{3 \times 16}{2 \times 27} = 45.5 \text{ lb of O}_2$$

9. Heat Balance

9. A. Air

$$\begin{array}{ll} \text{Initial amount:} & 7.05 \times 10^3 \text{ lb} \quad (\text{Oxygen: } \frac{23.2}{100} 7.05 \times 10^3 = 1.64 \times 10^3) \\ \text{Oxygen depletion:} & 0.45 \times 10^3 \text{ lb} \\ \text{Final amount:} & 6.60 \times 10^3 \text{ lb} \end{array}$$

$$\text{Enthalpy change: } \Delta H_A = (6.60 \times 10^3)(0.25)(T-100) = 1.65 \times 10^3 T - 0.165 \times 10^6 \text{ BTU}$$

9. B. Water

Case 300 psia

$$\text{Enthalpy change } \Delta H_W = 34.8 \times 10^3 (1-x) h_f - 10.17 \times 10^6 \text{ BTU}$$

Case 900 psia

$$\text{Enthalpy change } \Delta H_W = 31 \times 10^3 (1-x) h_f - 13.06 \times 10^6 \text{ BTU}$$

9. C. Steam

Case 300 psia

$$\text{Enthalpy change: } \Delta H_S = 34.8 \times 10^3 \times h_v - 17.9 \times 10^3 \text{ BTU}$$

Case 900 psia

$$\text{Enthalpy change } \Delta H_S = 31 \times 10^3 \times h_v - 55 \times 10^3 \text{ BTU}$$

9. D. Chemical heat

As previously indicated $\Delta H = 0.667 \times 10^6 \text{ BTU}$

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Writing the heat balance as before:

Case 300 psia

$$1.65 \times 10^3 T + 34.8 \times 10^3 h_v + 34.8 \times 10^3 (1-x) h_f = 0.667 \times 10^6 + (0.165 + 0.012) \times 10^6 + 10.17 \times 10^6 = 11.02 \times 10^6 \text{ BTU}$$

$$x = \frac{11.02 \times 10^6 - 1.65 \times 10^3 T - 34.8 \times 10^3 h_f}{34.8 \times 10^3 (h_v - h_f)}$$

$$x = \frac{317 - 0.0474 T - h_f}{h_v - h_f} \quad (1)$$

Case 900 psia

$$1.65 \times 10^3 T + 31 \times 10^3 h_v + 31 \times 10^3 (1-x) h_f = 0.667 \times 10^6 + (0.165 + 0.055) \times 10^6 + 13.06 \times 10^6 = 13.95 \times 10^6 \text{ BTU}$$

$$x = \frac{13.95 \times 10^6 - 1.65 \times 10^3 T - 31 \times 10^3 h_f}{31 \times 10^3 (h_v - h_f)}$$

$$x = \frac{450 - 0.0532 T - h_f}{h_v - h_f} \quad (1')$$

10. Pressure

Case 300 psia

As before $x = \frac{4.83 \text{ ps}}{T + 460} \quad (2)$

Case 900 psia

$$x = \frac{5.41 \text{ ps}}{T + 460} \quad (2')$$

Case 300 psia

Solving simultaneously (1) and (2)

If $T = 210^\circ \text{F}$

$$p_s = 14.12 \text{ psia}$$

$$\left. \begin{array}{l} h_f = 210 \frac{\text{BTU}}{\text{lb}} \\ h_v = 1182 \frac{\text{BTU}}{\text{lb}} \end{array} \right\} \Delta h = 972 \frac{\text{BTU}}{\text{lb}}$$

In (1) $x = \frac{317 - (0.0474)(210) - 210}{972} = \frac{97}{972} = 0.100$

In (2) $x = \frac{4.83 \times 14.12}{670} = 0.102$

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If $T = 200^\circ\text{F}$

$$p_s = 11.53 \text{ psia}$$

$$\left. \begin{array}{l} h_f = 200 \frac{\text{BTU}}{\text{lb}} \\ h_v = 1178 \frac{\text{BTU}}{\text{lb}} \end{array} \right\} \Delta h = 978 \frac{\text{BTU}}{\text{lb}}$$

$$\text{In (1)} \quad x = \frac{317 - (0.0474)(200) - 200}{978} = \frac{117}{978} = 0.120$$

$$\text{In (2)} \quad x = \frac{4.83 \times 11.53}{660} = 0.0844$$

Thus

$$T = 210^\circ\text{F}$$

$$p_s = 14.1 \text{ psia}$$

$$x = 0.101$$

$$\text{Partial pressure of air: } p_s' = \frac{6.60 \times 10^3}{28.6} (460 + 210) = \frac{(231)(670)}{9.32 \times 10^3} = 16.6 \text{ psia}$$

$$\text{Total pressure: } p = p_s + p_s' = 14.1 + 16.6 = 30.7 \text{ psia}$$

$$\text{Relative pressure: } p = 16.0 \text{ psig.}$$

Case 900 psia

Solving simultaneously (1') and (2')

$$\text{At } T = 250^\circ\text{F}$$

$$p_s = 29.83 \text{ psia}$$

$$\left. \begin{array}{l} h_f = 248 \frac{\text{BTU}}{\text{lb}} \\ h_v = 1196 \frac{\text{BTU}}{\text{lb}} \end{array} \right\} \Delta h = 948 \frac{\text{BTU}}{\text{lb}}$$

$$\text{In (1')} \quad x = \frac{450 - (0.0532)(250) - 248}{948} = \frac{189}{948} = 0.199$$

$$\text{In (2')} \quad x = \frac{5.41 \times 29.83}{710} = 0.227$$

$$\text{At } T = 240^\circ\text{F}$$

$$p_s = 24.97 \text{ psia}$$

$$\left. \begin{array}{l} h_f = 240 \frac{\text{BTU}}{\text{lb}} \\ h_v = 1192 \frac{\text{BTU}}{\text{lb}} \end{array} \right\} \Delta h = 952 \frac{\text{BTU}}{\text{lb}}$$

$$\text{In (1')} \quad x = \frac{450 - (0.0532)(240) - 240}{952} = \frac{198}{952} = 0.208$$

$$\text{In (2')} \quad x = \frac{5.41 \times 24.97}{700} = 0.193$$

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Thus if $T = 240^\circ\text{F}$
 $T = 250^\circ\text{F}$

$$\Delta x = 0.208 - 0.193 = 0.015$$

$$\Delta x = 0.199 - 0.227 = -0.028$$

$$0.043$$

$$10 \cdot \frac{0.015}{0.043} \approx 3$$

$$T = 243^\circ\text{F}$$

$$p_s = 26.7 \text{ psia}$$

$$x = 0.204$$

Partial pressure of air

$$p' = \frac{231}{9.32} \frac{703}{10^3} = 17.4 \text{ psia}$$

Total pressure:

$$p = p_s + p' = 26.7 + 17.4 = 44.1 \text{ psia}$$

Relative pressure:

$$p = 29.4 \text{ psig.}$$

SUMMARY OF RESULTS FOR PRESSURE BUILD-UP IN CONTAINMENT VESSEL CONSIDERING ALUMINUM-OXYGEN REACTION

Normal Operating

Partial Pressures

Total Pressures

Pressure

Steam

Air

Absolute

Relative

psia

psia

psia

psia

psig

300

14.1

16.6

30.7

16.0

900

26.7

17.4

44.1

29.4

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CORRECTIONS BY NEW VOLUMES OF THE REACTOR COOLANT SYSTEM

1. Reactor Coolant System Volumes

<u>Item</u>	<u>Volume (ft³)</u>
Reactor Vessel	346
Steam Generator	129
Hot Leg	61
Cold Leg	105
Pressurizer	45
Total Internal Volume	686
Pressurizer { Water	22
{ Steam	23
	45

} CORRECT FOR 218 FT³

$$\begin{array}{r} 475 \\ 218 \\ \hline 693 \end{array}$$

$$\begin{array}{r} 641 \\ 166 \\ \hline 475 \end{array}$$

The volume of steam remains as previously stated. There are changes only in the water volume

2. Water in Reactor Coolant System

Total volume, except pressurizer: $686 - 45 = 641 \text{ ft}^3$

Volume of water in the pressurizer: 22 ft^3

Case 300 psia

Water at an average temperature of 285°F ; $v_f = 0.0173 \frac{\text{ft}^3}{\text{lb}}$

$$M_w = \frac{641}{0.0173} = 37.1 \times 10^3 \text{ lb}$$

Water in the pressurizer at 417°F ; $v_f = 0.0189 \frac{\text{ft}^3}{\text{lb}}$

$$M'_w = \frac{22}{0.0189} = 1.16 \times 10^3 \text{ lb}$$

Case 900 psia

Water at an average temperature of 415°F ; $v_f = 0.0188 \frac{\text{ft}^3}{\text{lb}}$

$$M_w = \frac{641}{0.0188} = 34.1 \times 10^3 \text{ lb}$$

Water in the pressurizer at 532°F ; $v_f = 0.0212 \frac{\text{ft}^3}{\text{lb}}$

$$M'_w = \frac{22}{0.0212} = 1.04 \times 10^3 \text{ lb}$$

3. Water Enthalpy

Case 300 psia

$$\text{Initial enthalpy} = (37.1 \times 10^3)(285) + (1.16 \times 10^3)(417) = (10.57 + 0.484) \times 10^6 = 11.06 \times 10^6 \text{ BTU}$$

$$\text{Enthalpy change: } \Delta H_w = 38.3 \times 10^3 (1-x) h_f - 11.06 \times 10^6 \text{ BTU}$$

CONTAINMENT VESSEL
VOLUME CORRECTION

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Case 900 psia

Initial enthalpy: $(34.1 \times 10^3) (415 - 11.04 \times 10^3) (532) = (14.15 + 0.554) \times 10^6$
 $= 14.71 \times 10^6 \text{ BTU}$

Enthalpy change $\Delta H_w = 35.1 \times 10^3 (1-x) h_f - 14.71 \times 10^6 \text{ BTU}$

4. Heat Balance

Writing the heat balance as before and considering only the change in the enthalpy of water:

Case 300 psia

$$1.78 \times 10^3 T + 38.3 \times 10^3 (1-x) h_f + 38.3 \times 10^3 x h_v = (0.333 + 11.06 + 0.176 + 0.006 + 0.018) \times 10^6$$
$$= 11.59 \times 10^6 \text{ BTU}$$

$$x = \frac{11.59 \times 10^6 - 1.78 \times 10^3 T - 38.3 \times 10^3 h_f}{38.3 \times 10^3 (h_v - h_f)}$$

$$x = \frac{303 - 0.0465 T - h_f}{h_v - h_f} \quad (1)$$

Case 900 psia

$$1.78 \times 10^3 T + 35.1 \times 10^3 (1-x) h_f + 35.1 \times 10^3 x h_v = (0.333 + 14.71 + 0.176 + 0.006 + 0.055) \times 10^6$$
$$= 15.28 \times 10^6 \text{ BTU}$$

$$x = \frac{15.28 \times 10^6 - 1.78 \times 10^3 T - 35.1 \times 10^3 h_f}{35.1 \times 10^3 (h_v - h_f)}$$

$$x = \frac{4.36 - 0.0507 T - h_f}{h_v - h_f} \quad (1')$$

4. Pressure

Case 300 psia

$$p_s = \frac{1,545}{144} - \frac{38.3 \times 10^3}{18 \times 10^5} x (T + 460) = \frac{460 + T}{4.38} x$$

$$x = \frac{4.38 p_s}{460 + T} \quad (2)$$

Case 900 psia

$$p_s = \frac{1,545}{144} - \frac{35.1 \times 10^3}{18 \times 10^5} x (T + 460) = \frac{460 + T}{4.78} x$$

$$x = \frac{4.78 p_s}{T + 460} \quad (2')$$

Case 300 psia

Solving simultaneously (1) and (2') by using Keenan and Keyes - Thermodynamic Properties

CONTAINMENT VESSEL

VOLUME CORRECTION

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of Steam.

At $T=210^{\circ}\text{F}$

$$p_s = 14.12 \text{ psia}$$

$$h_f = 210 \text{ BTU/lb}$$

$$h_v = 1182 \text{ BTU/lb}$$

$$\left. \begin{array}{l} h_f = 210 \text{ BTU/lb} \\ h_v = 1182 \text{ BTU/lb} \end{array} \right\} \Delta h = 972 \text{ BTU/lb}$$

$$\text{In (1)} \quad x = \frac{303 - (0.0465)(210) - 210}{972} = \frac{83}{972} = 0.0854$$

$$\text{In (2)} \quad x = \frac{4.38 \times 14.12}{670} = 0.0924$$

At $T=208^{\circ}\text{F}$

$$p_s = 13.57 \text{ psia}$$

$$h_f = 208 \text{ BTU/lb}$$

$$h_v = 1181 \text{ BTU/lb}$$

$$\left. \begin{array}{l} h_f = 208 \text{ BTU/lb} \\ h_v = 1181 \text{ BTU/lb} \end{array} \right\} \Delta h = 973 \text{ BTU/lb}$$

$$\text{In (1)} \quad x = \frac{303 - (0.0465)(208) - 208}{973} = \frac{85}{973} = 0.0873$$

$$\text{In (2)} \quad x = \frac{4.38 \times 13.57}{668} = 0.0891$$

At $T=206^{\circ}\text{F}$

$$p_s = 13.03 \text{ psia}$$

$$h_f = 206 \text{ BTU/lb}$$

$$h_v = 1180 \text{ BTU/lb}$$

$$\left. \begin{array}{l} h_f = 206 \text{ BTU/lb} \\ h_v = 1180 \text{ BTU/lb} \end{array} \right\} \Delta h = 974 \text{ BTU/lb}$$

$$\text{In (1)} \quad x = \frac{303 - (0.0465)(206) - 206}{974} = \frac{88}{974} = 0.0904$$

$$\text{In (2)} \quad x = \frac{4.38 \times 13.03}{666} = 0.857$$

$T = 208^{\circ}\text{F}$

$$p_s = 13.6 \text{ psia}$$

$$x = 0.088$$

$$\text{Partial pressure of air and hydrogen: } p' = \frac{248 \times 668}{9.32 \times 10^3} = 17.8 \text{ psia}$$

$$\text{Total pressure } p = p_s + p' = 13.6 + 17.8 = 31.4 \text{ psia}$$

$$\text{Relative pressure: } p = 16.7 \text{ psig.}$$

Case 900 psia.

Solving simultaneously (1') and (2') by using the same reference tables.

CONTAINMENT VESSEL
VOLUME CORRECTION

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At $T = 250^\circ\text{F}$

$$p_s = 29.83 \text{ psia}$$

$$h_f = 250 \text{ BTU/lb}$$

$$h_v = 1196 \text{ BTU/lb}$$

$$\left. \begin{array}{l} h_f = 250 \text{ BTU/lb} \\ h_v = 1196 \text{ BTU/lb} \end{array} \right\} \Delta h = 946 \text{ BTU/lb}$$

$$\text{In (1')} \quad x = \frac{436 - (0.0507)(250) - 250}{946} = \frac{173}{946} = 0.183$$

$$\text{In (2')} \quad x = \frac{4.78 \times 29.83}{710} = 0.201$$

At $T = 248^\circ\text{F}$

$$p_s = 28.80 \text{ psia}$$

$$h_f = 248 \text{ BTU/lb}$$

$$h_v = 1195 \text{ BTU/lb}$$

$$\left. \begin{array}{l} h_f = 248 \text{ BTU/lb} \\ h_v = 1195 \text{ BTU/lb} \end{array} \right\} \Delta h = 947 \text{ BTU/lb}$$

$$\text{In (1')} \quad x = \frac{436 - (0.0507)(248) - 248}{947} = \frac{175}{947} = 0.185$$

$$\text{In (2')} \quad x = \frac{4.78 \times 28.8}{708} = 0.195$$

At $T = 246^\circ\text{F}$

$$p_s = 27.80 \text{ psia}$$

$$h_f = 246 \text{ BTU/lb}$$

$$h_v = 1195 \text{ BTU/lb}$$

$$\left. \begin{array}{l} h_f = 246 \text{ BTU/lb} \\ h_v = 1195 \text{ BTU/lb} \end{array} \right\} \Delta h = 948 \text{ BTU/lb}$$

$$\text{In (1')} \quad x = \frac{436 - (0.0507)(246) - 246}{948} = \frac{178}{948} = 0.188$$

$$\text{In (2')} \quad x = \frac{4.78 \times 27.8}{706} = 0.188$$

$T = 246^\circ\text{F}$

$$p_s = 27.8 \text{ psia}$$

$$x = 0.188$$

$$\text{Partial pressure of air and hydrogen: } p' = \frac{248 \times 706}{9.32 \times 10^3} = 18.8 \text{ psia}$$

$$\text{Total pressure: } p = p_s + p' = 27.8 + 18.8 = 46.6 \text{ psia}$$

$$\text{Relative pressure: } p = 31.9 \text{ psig.}$$

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SUMMARY OF RESULTS FOR PRESSURE BUILD-UP IN CONTAINMENT VESSEL
CONSIDERING ALUMINUM-WATER REACTION

Normal Operating

Partial Pressures

Total Pressures

Pressure

Steam

Air and Hydrogen

Absolute

Relative

psia

psia

psia

psia

psig

300

13.6

17.8

31.4

16.7

900

27.8

18.8

46.6

31.9

CONTAINMENT VESSEL
VOLUME CORRECTION

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APPENDIX IV

ANALYSIS OF THE EXTENT OF FISSION-GAS RELEASE AFTER THE ELPHR MAXIMUM CREDIBLE ACCIDENT

NOTE: This Appendix contains results applicable to a core with stainless-steel cladding as well as to one with aluminum cladding, because the stainless-steel core was analyzed first and because much of the analysis applies to both cores.

CONTENTS

Fission-gas release per fuel rod of the stainless steel-clad core	1
Fission-gas release from a fuel-element rupture	4
Fission-gas release per fuel rod of the aluminum-clad core	25
Summary of activity release per fuel rod	30
Total release for reactor core	31
Summary of activity release per core	32

FISSION GAS RELEASE PER FUEL ROD OF THE STAINLESS STEEL CORE

From ORO-196 EGCR Preliminary Hazards Summary Report, p. 7.3, the activity release from the fuel is given by:

$$ACT_i = \frac{\nu_i}{3.7 \times 10^{10}} \left(\frac{y_i \Sigma_f \phi + 3.1 \times 10^{16}}{\lambda_i + \nu_i} \right) \lambda_i \left[\frac{1 - e^{-\lambda t}}{\lambda} - \frac{e^{-\lambda t}}{\nu} (1 - e^{-\nu t}) \right]$$

where

ACT_i : activity of isotope i , $\frac{\text{Curie}}{\text{MW}}$

ν_i : experimentally determined escape coefficient for isotope i , sec^{-1}

y_i : fission yield of isotope i , dimensionless

Σ_f : macroscopic fission cross-section, cm^{-1}

ϕ : neutron flux, $\frac{\text{neutrons}}{\text{cm}^2 \cdot \text{sec}}$

λ_i : radioactive decay constant for isotope i , sec^{-1}

t : irradiation time, sec

For those isotopes for which saturation is reached, the equations become:

$$ACT_{i, \text{SAT}} = \frac{\nu_i}{3.7 \times 10^{10}} \left(\frac{y_i \Sigma_f \phi + 3.1 \times 10^{16}}{\lambda_i + \nu_i} \right)$$

ELPHR Characteristics (from "A Proposal for an Experimental Low Temperature Process Heat Reactor")

Core Life: 3.1 years = (3.1) (365) (24) (3600) = $0.978 \times 10^8 \text{ sec}$

Reactor Power: 40.1 MW (thermal)

No. of subassemblies: 32

No. of rods per subassembly: 100

Power per rod: $\frac{40.1}{32 \times 100} = 12.5 \frac{\text{KW}}{\text{rod}}$

References: ANL-4807

WAPD-173

WAPD-183

ORNL-2505

ORO-196

FISSION GAS RELEASE

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ESCAPE COEFFICIENTS : λ

<u>ELEMENT</u>	<u>ATOMIC NUMBER</u>	<u>λ (sec⁻¹)</u>	<u>COMMENTS</u>
Zn	30	1×10^{-7}	ASSUMED SAME AS Cs.
Ga	31	1×10^{-7}	ASSUMED SAME AS Cs
Ge	32	1×10^{-7}	ASSUMED SAME AS Cs
As	33	1×10^{-7}	ASSUMED SAME AS Cs.
Se	34	1×10^{-7}	ASSUMED SAME AS Cs.
Br	35	6×10^{-9}	SAME AS ORNL 2505
Kr	36	1×10^{-7}	SAME AS ORNL 2505
Rb	37	1×10^{-7}	ASSUMED SAME AS Cs.
Sr	38	7×10^{-10}	SAME AS ORNL 2505
Y	39	2×10^{-12}	SAME AS ORNL 2505
Zr	40	1×10^{-11}	SAME AS ORNL 2505
Nb	41	1×10^{-11}	ASSUMED SAME AS Zr
Mo	42	4×10^{-10}	SAME AS ORNL 2505
Tc	43	1×10^{-7}	ASSUMED SAME AS Cs
Ru	44	4×10^{-8}	ASSUMED SAME AS I
Rh	45	4×10^{-8}	ASSUMED SAME AS I
Pd	46	4×10^{-8}	ASSUMED SAME AS I
Ag	47	4×10^{-8}	ASSUMED SAME AS I
Cd	48	4×10^{-8}	ASSUMED SAME AS I
In	49	4×10^{-8}	ASSUMED SAME AS I
Sn	50	4×10^{-8}	ASSUMED SAME AS I
Sb	51	4×10^{-8}	ASSUMED SAME AS I
Te	52	3×10^{-9}	SAME AS ORNL 2505
I	53	4×10^{-8}	SAME AS ORNL 2505
Xe	54	7×10^{-8}	SAME AS ORNL 2505
Cs	55	1×10^{-7}	SAME AS ORNL 2505
Ba	56	6×10^{-10}	SAME AS ORNL 2505
La	57	6×10^{-10}	ASSUMED SAME AS Ba
Ce	58	1×10^{-11}	SAME AS ORNL 2505
Pr	59	1×10^{-11}	ASSUMED SAME AS Ce
Nd	60	1×10^{-11}	ASSUMED SAME AS Ce

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<u>ELEMENT</u>	<u>ATOMIC NUMBER</u>	<u>λ (sec⁻¹)</u>	<u>COMMENTS</u>
Pm	61	1×10^{-11}	ASSUMED SAME AS Ce.
Sm	62	1×10^{-11}	ASSUMED SAME AS Ce
Eu	63	1×10^{-11}	ASSUMED SAME AS Ce.

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FISSION GAS RELEASE FROM A FUEL ELEMENT RUPTURE

When $\lambda > 0.10$, the term $\gamma \Sigma \phi = 3.1 \times 10^{16}$ will be evaluated from the tables in ANL-4807

ELEMENT	Mass No.	$\lambda + \nu$	λ (sec ⁻¹)	ν (sec ⁻¹)	No. ($\frac{\text{atoms}}{\text{MW}}$) SAT.
Zn	72		3.9×10^{-5}	1×10^{-7}	1.19×10^{15}
	73		5.8×10^{-3}	"	0.01×10^{15}
Ga	72		1.3×10^{-5}	1×10^{-7}	1.20×10^{15}
	73		3.8×10^{-5}	1×10^{-7}	8.08×10^{14}
Ge	75		1.4×10^{-4}	1×10^{-7}	3.45×10^{14}
	77		1.2×10^{-2}	"	11.53×10^{14}
	77		1.6×10^{-5}	"	0.22×10^{16}
	78		9.2×10^{-5}	"	0.014×10^{16}
As	77		4.8×10^{-6}	1×10^{-7}	7.175×10^{16}
	78		1.3×10^{-4}	"	6.790×10^{16}
	79		1.3×10^{-3}	"	14.20×10^{16}
	81		1.1×10^{-3}	"	5.88×10^{17}
Se	79		3.4×10^{13}	1×10^{-7}	0.48×10^{17}
	81		2.0×10^{-4}	"	0.09×10^{17}
	81		8.5×10^{-4}	"	0.34×10^{17}
	83		1.05×10^{-2}	"	6.79×10^{17}
	83		6.7×10^{-4}	"	"
	84		5.8×10^{-3}	"	0.12×10^{17}
Br	82		5.4×10^{-6}	6×10^{-9}	0.49×10^{17}
	83		8.0×10^{-5}	"	2.49×10^{17}
	84		3.5×10^{-4}	"	0.02×10^{17}
	85		3.9×10^{-3}	"	18.60×10^{17}
	87		1.2×10^{-2}	"	5.78×10^{17}
	88		4.5×10^{-2}	"	1.05×10^{17}
	89		1.5×10^{-1}	"	0.67×10^{17}
					0.26×10^{17}
					0.09×10^{17}
					26.47×10^{17}

* When $\lambda < 0.10$, the values for No are listed on pp. 11-12

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<u>ELEMENT</u>	<u>MASS No</u>	<u>$\lambda(\text{sec}^{-1})$</u>	<u>$\gamma(\text{sec}^{-1})$</u>	<u>$N_0(\frac{\text{atoms}}{\text{MW}}) \text{ SAT.}$</u>
Kr	85	4.4×10^{-5}	1×10^{-7}	7.05×10^{18}
	85	2.3×10^{-9}	"	*
	87	1.5×10^{-4}	"	5.67×10^{18}
	88	7.0×10^{-5}	"	17.0×10^{18}
	89	4.4×10^{-3}	"	0.32×10^{18}
	90	2.1×10^{-2}	"	0.07×10^{18}
	91	7.1×10^{-2}	"	0.02×10^{18}
	92	2.3×10^{-1}	"	0.01×10^{18}
	93	3.5×10^{-1}	"	—
	94	5.0×10^{-1}	"	—
Rb	86	4.1×10^{-7}	1×10^{-7}	30.14×10^{18}
	88	6.5×10^{-4}	"	*
	89	7.5×10^{-4}	"	1.82×10^{18}
	89			1.91×10^{18}
Sr	89	1.5×10^{-7}	7×10^{-10}	3.73×10^{18}
	90	1.1×10^{-9}	"	8.67×10^{21}
	91	2.0×10^{-5}	"	*
	92	7.1×10^{-5}	"	0.08×10^{21}
	93	1.65×10^{-3}	"	0.02×10^{21}
	94	5.8×10^{-3}	"	—
Y	90	3.0×10^{-6}	2×10^{-12}	8.77×10^{21}
	91	2.3×10^{-4}	"	8.2×10^{18}
	91	1.4×10^{-7}	"	2.8×10^{18}
	92	5.5×10^{-5}	"	1.16×10^{22}
	93		"	28.3×10^{18}
	94		"	96.9×10^{18}
	95		"	2.2×10^{18}
				1.7×10^{18}
				1.17×10^{22}

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<u>ELEMENT</u>	<u>MASS No</u>	<u>λ (sec⁻¹)</u>	<u>ν (sec⁻¹)</u>	<u>No ($\frac{\text{atoms}}{\text{MW}}$) SAT.</u>
Zr	95	1.2×10^{-7}	1×10^{-11}	1.30×10^{22}
	97	1.1×10^{-5}	"	0.02×10^{22}
				1.32×10^{22}
Nb	95	2.1×10^{-6}	1×10^{-11}	0.01×10^{21}
	95	2.3×10^{-7}	"	5.80×10^{21}
	96	1.2×10^{-2}	"	-
	97	1.5×10^{-4}	"	0.01×10^{21}
				5.82×10^{21}
Mo	99	2.9×10^{-6}	4×10^{-10}	6.7×10^{20}
	101	8.0×10^{-4}	"	0.02×10^{20}
	102	1.1×10^{-3}	"	0.61×10^{20}
	103	2.3×10^{-3}	"	-
				6.73×10^{20}
Tc	99	3.3×10^{-5}	1×10^{-7}	5.15×10^{19}
	100	7.0×10^{-4}	"	0.22×10^{19}
	101	2.8×10^{-2}	"	-
	102	7.7×10^{-3}	"	-
				5.37×10^{19}
Ru	103	1.9×10^{-7}	4×10^{-8}	5.7×10^{21}
	105	4.3×10^{-5}	"	0.01×10^{21}
	106	2.2×10^{-8}	"	*
	107	2.9×10^{-3}	"	-
				5.71×10^{21}
Rh	104	2.0×10^{-4}	4×10^{-8}	5.4×10^{18}
	104	1.5×10^{-2}	"	0.02×10^{18}
	105	5.3×10^{-6}	"	53.0×10^{18}
	106	2.3×10^{-2}	"	-
	107	4.4×10^{-4}	"	0.14×10^{18}
	110	2.1×10^{-5}	"	1.16×10^{18}
	111	5.4×10^{-4}	"	0.05×10^{18}
				59.8×10^{18}

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<u>ELEMENT</u>	<u>Mass No.</u>	<u>λ (sec⁻¹)</u>	<u>λ (sec⁻¹)</u>	<u>No. ($\frac{\text{atoms}}{\text{MW}}$) SAT</u>
Pd	109	1.5×10^{-5}	4×10^{-8}	5.88×10^{17}
	111	4.4×10^{-4}	"	0.01×10^{17}
	112	9.2×10^{-6}	"	2.82×10^{17}
				8.71×10^{17}
Ag	110	1.8×10^{-2}	4×10^{-8}	—
	111	1.0×10^{-6}	"	5.30×10^{18}
	112	6.0×10^{-5}	"	0.04×10^{18}
	113	3.6×10^{-5}	"	0.11×10^{18}
	114	6.1×10^{-3}	"	—
	115	5.5×10^{-4}	"	—
Cd				5.45×10^{18}
	115	3.6×10^{-6}	4×10^{-8}	0.84×10^{18}
	116	1.3×10^{-7}	"	1.12×10^{18}
	117	6.8×10^{-4}	"	0.05×10^{18}
				2.01×10^{18}
In	115	4.3×10^{-5}	4×10^{-8}	7.13×10^{16}
	117	9.9×10^{-5}	"	3.15×10^{16}
	118	2.6×10^{-3}	"	0.12×10^{16}
	119	6.6×10^{-4}	"	0.57×10^{16}
				11.0×10^{16}
Sn	119	5.5×10^{-7}	4×10^{-8}	5.6×10^{18}
	121	7.2×10^{-6}	"	0.60×10^{18}
	123	6.1×10^{-8}	"	3.70×10^{18}
	123	2.9×10^{-4}	"	0.02×10^{18}
	123	8.4×10^{-7}	"	4.65×10^{18}
	125	1.2×10^{-3}	"	—
	126	2.3×10^{-4}	"	0.14×10^{18}
	128	1.3×10^{-3}	"	0.23×10^{18}
				14.94×10^{18}

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ELEMENT	MASS No.	$\lambda(\text{sec}^{-1})$	$\nu(\text{sec}^{-1})$	$N_0 \left(\frac{\text{atoms}}{\text{MW}} \right) \text{SAT}$
Sb	125	8.1×10^{-9}	4×10^{-8}	*
	126	2.1×10^{-5}	"	1.45×10^{18}
	127	2.0×10^{-6}	"	14.0×10^{18}
	128	1.7×10^{-4}	"	0.18×10^{18}
	129	4.6×10^{-5}	"	5.50×10^{18}
	130	5.0×10^{-4}	"	0.93×10^{18}
	131	5.8×10^{-3}	"	0.24×10^{18}
	132	2.6×10^{-3}	"	0.45×10^{18}
	133	1.2×10^{-3}	"	1.50×10^{18}
				24.25×10^{18}
Te	125	1.4×10^{-7}	3×10^{-9}	0.03×10^{20}
	127	8.9×10^{-8}	"	0.85×10^{20}
	127	2.1×10^{-5}	"	0.03×10^{20}
	129	2.5×10^{-7}	"	2.36×10^{20}
	129	1.6×10^{-4}	"	0.02×10^{20}
	131	6.4×10^{-6}	"	0.21×10^{20}
	131	4.6×10^{-4}	"	0.02×10^{20}
	132	2.5×10^{-6}	"	5.47×10^{20}
	133	1.8×10^{-4}	"	0.08×10^{20}
	134	2.6×10^{-3}	"	0.07×10^{20}
I	135	5.8×10^{-3}	"	-
	136	5.8×10^{-3}	"	-
				9.14×10^{20}
	131	1×10^{-6}	4×10^{-8}	9.3×10^{20}
	132	8.0×10^{-5}	"	-
	133	8.6×10^{-6}	"	2.2×10^{20}
	134	2.2×10^{-4}	"	0.1×10^{20}
	135	2.9×10^{-5}	"	0.6×10^{20}
	136	8.1×10^{-3}	"	-
	137	3.1×10^{-2}	"	-
				12.2×10^{20}

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ELEMENT	MASS No.	$\lambda(\text{sec}^{-1})$	$V(\text{sec}^{-1})$	No. $\left(\frac{\text{atoms}}{\text{MW}}\right)$ SAT.
Xe	131	6.7×10^{-7}	7×10^{-8}	0.01×10^{21}
	133	1.5×10^{-6}	"	1.35×10^{21}
	135	7.5×10^{-4}	"	-
	135	2.1×10^{-5}	"	0.09×10^{21}
	137	3.0×10^{-3}	"	-
	138	6.8×10^{-4}	"	-
	139	1.7×10^{-2}	"	-
	140	4.4×10^{-2}	"	-
	141	2.3×10^{-1}	"	-
	142	0.7	"	-
	143	0.7	"	-
	144	0.9	"	-
				1.45×10^{21}
				*
Cs	136	5.9×10^{-7}	1×10^{-7}	*
	137	6.7×10^{-10}	"	*
	138	3.5×10^{-4}	"	5.67×10^{18}
	139	1.2×10^{-4}	"	1.61×10^{18}
	140	1.1×10^{-3}	"	0.18×10^{18}
	142	1.1×10^{-2}	"	0.16×10^{18}
Ba				7.61×10^{18}
	137	5.0×10^{-3}	6×10^{-10}	-
	139	1.3×10^{-4}	"	0.01×10^{21}
	140	6.3×10^{-7}	"	3.06×10^{21}
	141	6.5×10^{-4}	"	-
	142	1.9×10^{-3}	"	-
	143	2.3×10^{-2}	"	-
La				3.07×10^{21}
	140	4.8×10^{-6}	6×10^{-10}	3.99×10^{20}
	141	5.2×10^{-5}	"	0.28×10^{20}
	142	1.6×10^{-4}	"	0.11×10^{20}
	143	6.1×10^{-3}	"	-
				4.38×10^{20}

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ELEMENT	MASS No.	λ (sec ⁻¹)	λ (sec ⁻¹)	No. ($\frac{\text{atoms}}{\text{MW}}$) SAT.
Ce	141	2.7×10^{-7}	1×10^{-11}	0.66×10^{22}
	143	5.8×10^{-6}	"	0.03×10^{22}
	144	2.9×10^{-8}	"	2.06×10^{22}
	145	1.1×10^{-4}	"	-
	146	8.0×10^{-4}	"	-
Pr	143	5.9×10^{-7}	1×10^{-11}	2.75×10^{22}
	144	1.1×10^{-3}	"	-
	145	4.3×10^{-5}	"	0.03×10^{21}
	146	4.6×10^{-4}	"	-
Nd	147	7.3×10^{-7}	1×10^{-11}	2.90×10^{21}
	149	9.7×10^{-5}	"	1.11×10^{21}
Pm	147	5.5×10^{-9}	1×10^{-11}	1.11×10^{21}
	149	4.1×10^{-6}	"	1.10×10^{22}
	151	9.7×10^{-4}	"	0.01×10^{22}
	152	2.3×10^{-3}	"	-
	153	2.3×10^{-3}	"	-
	154	2.3×10^{-3}	"	-
Sm	153	4.1×10^{-6}	1×10^{-11}	1.11×10^{22}
	155	4.6×10^{-4}	"	1.14×10^{19}
	156	6.4×10^{-6}	"	0.02×10^{19}
Eu	156	1.1×10^{-8}	1×10^{-11}	1.16×10^{19}
	156	5.2×10^{-7}	"	1.33×10^{20}
	157	1.3×10^{-5}	"	0.08×10^{20}
	158	1.3×10^{-4}	"	-
				1.41×10^{20}

FISSION GAS RELEASE

635 0584

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Se-79

$$N_0 = \frac{(3.7 \times 10^{-4})(3.1 \times 10^{16})(3.4 \times 10^{-13})}{(1 \times 10^{-7} + 3.4 \times 10^{-13})} \int \frac{1 - e^{-(3.4 \times 10^{-13})(0.978 \times 10^8)}}{3.4 \times 10^{-13}} - \frac{e^{-(3.4 \times 10^{-13})(0.978 \times 10^8)}}{1 \times 10^{-7}} \left\{ 1 - e^{-(1 \times 10^{-7})(0.978 \times 10^8)} \right\}$$

$$N_0 = 3.42 \times 10^{15}$$

Kr-85

$$N_0 = \frac{(3.77 \times 10^{-3})(3.1 \times 10^{16})(2.3 \times 10^{-9})}{(1 \times 10^{-7} + 2.3 \times 10^{-9})} \int \frac{1 - e^{-(2.3 \times 10^{-9})(0.978 \times 10^8)}}{2.3 \times 10^{-9}} - \frac{e^{-(2.3 \times 10^{-9})(0.978 \times 10^8)}}{1 \times 10^{-7}} \left\{ 1 - e^{-(1 \times 10^{-7})(0.978 \times 10^8)} \right\}$$

$$N_0 = 1.81 \times 10^{20}$$

Rb-86

$$N_0 = \frac{(3.1 \times 10^{-7})(3.1 \times 10^{16})(4.1 \times 10^{-7})}{(1 \times 10^{-7} + 4.1 \times 10^{-7})} \int \frac{1 - e^{-(4.1 \times 10^{-7})(0.978 \times 10^8)}}{4.1 \times 10^{-7}} - \frac{e^{-(4.1 \times 10^{-7})(0.978 \times 10^8)}}{1 \times 10^{-7}} \left\{ 1 - e^{-(1 \times 10^{-7})(0.978 \times 10^8)} \right\}$$

$$N_0 = 1.88 \times 10^{16}$$

Sr-90

$$N_0 = \frac{(0.05)(3.1 \times 10^{16})(1.1 \times 10^{-9})}{(7 \times 10^{-10} + 1.1 \times 10^{-9})} \int \frac{1 - e^{-(1.1 \times 10^{-9})(0.978 \times 10^8)}}{1.1 \times 10^{-9}} - \frac{e^{-(1.1 \times 10^{-9})(0.978 \times 10^8)}}{7 \times 10^{-10}} \left\{ 1 - e^{-(7 \times 10^{-10})(0.978 \times 10^8)} \right\}$$

$$N_0 = 7.48 \times 10^{21}$$

Ru-106

$$N_0 = \frac{(0.0052)(3.1 \times 10^{16})(2.2 \times 10^{-8})}{(4 \times 10^{-8} + 2.2 \times 10^{-8})} \int \frac{1 - e^{-(2.2 \times 10^{-8})(0.978 \times 10^8)}}{2.2 \times 10^{-8}} - \frac{e^{-(2.2 \times 10^{-8})(0.978 \times 10^8)}}{4 \times 10^{-8}} \left\{ 1 - e^{-(4 \times 10^{-8})(0.978 \times 10^8)} \right\}$$

$$N_0 = 2.14 \times 10^{21}$$

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Sb-125

$$N_0 = \frac{(0.000,23)(3.1 \times 10^{16})(8.1 \times 10^{-9})}{4 \times 10^{-8} + 8.1 \times 10^{-9}} \left/ \frac{1 - e^{-\frac{(8.1 \times 10^{-9})(0.978 \times 10^8)}{8.1 \times 10^{-9}}}}{1 - e^{-\frac{(8.1 \times 10^{-9})(0.978 \times 10^8)}{4 \times 10^{-8}}}} \right\} \frac{1 - e^{-\frac{(4 \times 10^{-8})(0.978 \times 10^8)}{4 \times 10^{-8}}}}{1 - e^{-\frac{(4 \times 10^{-8})(0.978 \times 10^8)}{8.1 \times 10^{-9}}}}$$

$$N_0 = 6.76 \times 10^{13}$$

Cs-136

$$N_0 = \frac{(6.2 \times 10^{-5})(3.1 \times 10^{16})(5.9 \times 10^{-7})}{1 \times 10^{-7} + 5.9 \times 10^{-7}} \left/ \frac{1 - e^{-\frac{(5.9 \times 10^{-7})(0.978 \times 10^8)}{5.9 \times 10^{-7}}}}{1 - e^{-\frac{(5.9 \times 10^{-7})(0.978 \times 10^8)}{1 \times 10^{-7}}}} \right\} \frac{1 - e^{-\frac{(1 \times 10^{-7})(0.978 \times 10^8)}{1 \times 10^{-7}}}}{1 - e^{-\frac{(1 \times 10^{-7})(0.978 \times 10^8)}{5.9 \times 10^{-7}}}}$$

$$N_0 = 2.79 \times 10^{18}$$

Cs-137

$$N_0 = \frac{(6.2 \times 10^{-2})(3.1 \times 10^{16})(6.7 \times 10^{-10})}{1 \times 10^{-7} + 6.7 \times 10^{-10}} \left/ \frac{1 - e^{-\frac{(6.7 \times 10^{-10})(0.978 \times 10^8)}{6.7 \times 10^{-10}}}}{1 - e^{-\frac{(6.7 \times 10^{-10})(0.978 \times 10^8)}{1 \times 10^{-7}}}} \right\} \frac{1 - e^{-\frac{(1 \times 10^{-7})(0.978 \times 10^8)}{1 \times 10^{-7}}}}{1 - e^{-\frac{(1 \times 10^{-7})(0.978 \times 10^8)}{6.7 \times 10^{-10}}}}$$

$$N_0 = 1.26 \times 10^{21}$$

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65-0086

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<u>ELEMENT</u>	<u>MASS No.</u>	<u>ACTIVITY RELEASE</u> $\left(\frac{\text{Curie}}{\text{MW}} \right) = N_0 \frac{\lambda}{3.7 \times 10^{10}}$
Zn	72	$(1.19 \times 10^{15})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 3.22 \times 10^{-2}$
	73	$(0.01 \times 10^{15})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 2.7 \times 10^{-6}$
Ga	72	$(8.08 \times 10^{14})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 2.18 \times 10^{-3}$
	73	$(3.45 \times 10^{14})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.94 \times 10^{-3}$
Ge	75	$(0.221 \times 10^{16})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 5.97 \times 10^{-3}$
	77	$(0.014 \times 10^{16})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.38 \times 10^{-3}$
	77	$(7.175 \times 10^{14})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.194$
	78	$(6.79 \times 10^{16})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.184$
As	77	$(5.88 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 1.58$
	78	$(0.48 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.13$
	79	$(0.09 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.024$
	81	$(0.34 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.092$
Se	79	$(0.034 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 9.25 \times 10^{-3}$
	81	$(0.12 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.0324$
	81	$(0.49 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.132$
	83	$(0.08 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.0216$
	83	$(1.41 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.381$
	84	$(0.39 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.105$
Br	82	$(0.02 \times 10^{17})(6 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 0.324 \times 10^{-3}$
	83	$(18.6 \times 10^{17})(6 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 0.302$
	84	$(5.78 \times 10^{17})(6 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 0.0937$
	85	$(1.05 \times 10^{17})(6 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 0.0170$
	87	$(0.67 \times 10^{17})(6 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 0.0109$
	88	$(0.26 \times 10^{17})(6 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 4.2 \times 10^{-3}$
	89	$(0.09 \times 10^{17})(6 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 1.5 \times 10^{-3}$

FISSION GAS RELEASE

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ELEMENT

MASS No.

ACTIVITY RELEASE $\left(\frac{\text{Curie}}{\text{MW}} \right) = N_0 \frac{\lambda}{3.7 \times 10^{10}}$

Kr

85

$$(7.05 \times 10^{18}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 19.0$$

86

$$(181 \times 10^{18}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 489$$

87

$$(5.67 \times 10^{18}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 15.3$$

88

$$(17.0 \times 10^{18}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 45.9$$

89

$$(0.32 \times 10^{19}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 0.86$$

90

$$(0.07 \times 10^{19}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 0.189$$

91

$$(0.02 \times 10^{19}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 0.054$$

92

$$(0.01 \times 10^{19}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 0.027$$

93

94

97

Rb

86

$$(1.88 \times 10^{16}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 0.051$$

88

$$(1.82 \times 10^{18}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 4.92$$

89

$$(1.91 \times 10^{18}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 5.16$$

Sr

89

$$(8.67 \times 10^{21}) (7 \times 10^{-10}) (3.7 \times 10^{10})^{-1} = 164$$

90

$$(7.48 \times 10^{21}) (7 \times 10^{-10}) (3.7 \times 10^{10})^{-1} = 142$$

91

$$(0.08 \times 10^{21}) (7 \times 10^{-10}) (3.7 \times 10^{10})^{-1} = 1.51$$

92

$$(0.02 \times 10^{21}) (7 \times 10^{-10}) (3.7 \times 10^{10})^{-1} = 0.38$$

93

94

Y

90

$$(8.2 \times 10^{18}) (2 \times 10^{-12}) (3.7 \times 10^{10})^{-1} = 0.44 \times 10^{-3}$$

91

$$(2.8 \times 10^{18}) (2 \times 10^{-12}) (3.7 \times 10^{10})^{-1} = 0.15 \times 10^{-3}$$

91

$$(1.16 \times 10^{22}) (2 \times 10^{-12}) (3.7 \times 10^{10})^{-1} = 0.626$$

92

$$(28.3 \times 10^{18}) (2 \times 10^{-12}) (3.7 \times 10^{10})^{-1} = 1.53 \times 10^{-3}$$

93

$$(96.9 \times 10^{18}) (2 \times 10^{-12}) (3.7 \times 10^{10})^{-1} = 5.20 \times 10^{-3}$$

94

$$(2.2 \times 10^{22}) (2 \times 10^{-12}) (3.7 \times 10^{10})^{-1} = 0.12 \times 10^{-3}$$

95

$$(1.7 \times 10^{18}) (2 \times 10^{-12}) (2.7 \times 10^{10})^{-1} = 0.09 \times 10^{-3}$$

Zr

95

$$(1.30 \times 10^{22}) (1 \times 10^{-11}) (3.7 \times 10^{10})^{-1} = 3.51$$

97

$$(0.02 \times 10^{22}) (1 \times 10^{-11}) (3.7 \times 10^{10})^{-1} = 0.054$$

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ELEMENT

MASS No.

ACTIVITY RELEASE $\left(\frac{\text{Curie}}{\text{MW}}\right) = N_0 \frac{1}{3.7 \times 10^{10}}$

Nb

95

$$(0.01 \times 10^{21}) (1 \times 10^{-11}) (3.7 \times 10^{10})^{-1} = 2.7 \times 10^{-3}$$

95

$$(5.80 \times 10^{21}) (1 \times 10^{-11}) (3.7 \times 10^{10})^{-1} = 1.57$$

96

97

$$(0.01 \times 10^{21}) (1 \times 10^{-11}) (3.7 \times 10^{10})^{-1} = 2.7 \times 10^{-3}$$

Mo

99

$$(6.7 \times 10^{20}) (4 \times 10^{-10}) (3.7 \times 10^{10})^{-1} = 7.24$$

101

$$(0.02 \times 10^{20}) (4 \times 10^{-10}) (3.7 \times 10^{10})^{-1} = 0.022$$

102

$$(0.01 \times 10^{20}) (4 \times 10^{-10}) (3.7 \times 10^{10})^{-1} = 0.011$$

103

Tc

99

$$(5.15 \times 10^{19}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 139$$

100

$$(0.22 \times 10^{19}) (1 \times 10^{-7}) (3.7 \times 10^{10})^{-1} = 5.94$$

101

102

Ru

103

$$(5.7 \times 10^{21}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 6.16 \times 10^3$$

105

$$(0.01 \times 10^{21}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 10.8$$

106

$$(2.14 \times 10^{21}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 2.31 \times 10^3$$

107

Rh

104

$$(5.4 \times 10^{18}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 5.84$$

104

$$(0.02 \times 10^{18}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 0.02$$

105

$$(53.0 \times 10^{18}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 57.3$$

106

107

$$(0.14 \times 10^{18}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 0.15$$

110

$$(1.16 \times 10^{18}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 1.25$$

111

$$(0.05 \times 10^{18}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 0.05$$

Pd

109

$$(5.88 \times 10^{17}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 0.635$$

111

$$(0.01 \times 10^{17}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 0.001$$

112

$$(2.82 \times 10^{17}) (4 \times 10^{-8}) (3.7 \times 10^{10})^{-1} = 0.306$$

FISSION GAS RELEASE

635 0589

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ELEMENT

MASS No.

ACTIVITY RELEASE $\left(\frac{\text{Curie}}{\text{MW}}\right) = N_0 \frac{\lambda}{3.7 \times 10^{10}}$

Ag

110

111

112

113

114

115

$$(5.30 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 5.73$$

$$(0.04 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.043$$

$$(0.11 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.119$$

Cd

115

116

117

$$(0.84 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.908$$

$$(1.12 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 1.21$$

$$(0.05 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.054$$

In

115

117

118

119

$$(7.13 \times 10^6)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.077$$

$$(3.15 \times 10^6)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.034$$

$$(0.12 \times 10^6)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.001$$

$$(0.57 \times 10^6)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.006$$

Sn

119

121

123

123

123

125

126

128

$$(5.6 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 6.06$$

$$(0.60 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.65$$

$$(3.70 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 4.00$$

$$(0.02 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.02$$

$$(4.65 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 5.02$$

$$(0.14 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.15$$

$$(0.23 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.25$$

Sb

125

126

127

128

129

130

131

132

133

$$(67.6 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 73.1$$

$$(1.45 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 1.57$$

$$(14.0 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 15.1$$

$$(0.18 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.19$$

$$(5.50 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 5.94$$

$$(0.93 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 1.01$$

$$(0.24 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.26$$

$$(0.45 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 0.49$$

$$(1.50 \times 10^8)(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 1.62$$

FISSION GAS RELEASE

600 0090

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ELEMENT

MASS NO.

ACTIVITY RELEASE $\left(\frac{\text{Curie}}{\text{MW}}\right) = \text{No.} \frac{\gamma}{3.7 \times 10^{10}}$

Te

125

$$(0.63 \times 10^{20})(3 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 0.24$$

127

$$(0.85 \times 10^{20})(3 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 6.89$$

127

$$(0.03 \times 10^{20})(3 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 0.24$$

129

$$(2.36 \times 10^{20})(3 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 19.1$$

129

$$(0.02 \times 10^{20})(3 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 0.16$$

131

$$(0.21 \times 10^{20})(3 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 1.70$$

131

$$(0.02 \times 10^{20})(3 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 0.16$$

132

$$(5.47 \times 10^{20})(3 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 44.3$$

133

$$(0.08 \times 10^{20})(3 \times 10^{-9})(3.7 \times 10^{10})^{-1} = 0.65$$

134

$$(0.07 \times 10^{20})(3 \times 10^{-9})(2.7 \times 10^{10})^{-1} = 0.57$$

135

-

136

-

I

131

$$(9.3 \times 10^{20})(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 1.01 \times 10^3$$

132

-

133

$$(2.2 \times 10^{20})(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 238$$

134

$$(0.1 \times 10^{20})(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 10$$

135

$$(0.6 \times 10^{20})(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 65$$

136

-

137

-

Xe

131

$$(0.01 \times 10^{21})(7 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 19$$

133

$$(1.35 \times 10^{21})(7 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 2.56 \times 10^3$$

135

-

135

$$(0.09 \times 10^{21})(7 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 170$$

137

-

138

-

139

-

140

-

141

-

142

-

143

-

144

-

FISSION GAS RELEASE

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ELEMENT	MASS. NO.	ACTIVITY RELEASE $\left(\frac{\text{Curie}}{\text{MW}} \right) = \text{No.} \frac{D}{3.7 \times 10^{10}}$
Cs	136	$(2.79 \times 10^{12})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 7.54$
	137	$(1.26 \times 10^{21})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 3.40 \times 10^3$
	138	$(5.67 \times 10^{12})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 15.3$
	139	$(1.61 \times 10^{12})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 4.4$
	140	$(0.18 \times 10^{12})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.5$
	142	$(0.15 \times 10^{12})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.4$
Ba	137	-
	139	$(0.01 \times 10^{21})(6 \times 10^{-10})(3.7 \times 10^{10})^{-1} = 0.16$
	140	$(3.06 \times 10^{21})(6 \times 10^{-10})(3.7 \times 10^{10})^{-1} = 49.6$
	141	-
	142	-
La	143	-
	140	$(3.99 \times 10^{20})(6 \times 10^{-10})(3.7 \times 10^{10})^{-1} = 6.47$
	141	$(0.28 \times 10^{20})(6 \times 10^{-10})(3.7 \times 10^{10})^{-1} = 0.45$
	142	$(0.11 \times 10^{20})(6 \times 10^{-10})(3.7 \times 10^{10})^{-1} = 0.18$
	143	-
Ce	141	$(0.66 \times 10^{22})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 1.78$
	143	$(0.03 \times 10^{22})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 0.08$
	144	$(2.06 \times 10^{22})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 5.56$
	145	-
	146	-
Pr	143	$(2.87 \times 10^{21})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 0.78$
	144	-
	145	$(0.03 \times 10^{21})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 0.008$
	146	-
Nd	147	$(1.11 \times 10^{21})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 0.30$
	149	-

FISSION GAS RELEASE

656 0092

SIMILAR TO

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DEPT.

ELEMENT

MASS No

ACTIVITY RELEASE $\left(\frac{\text{Curie}}{\text{MW}}\right) = N_0 \frac{\lambda}{3.7 \times 10^{10}}$

Pm

147

$$(1.10 \times 10^{22})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 2.98$$

149

$$(0.01 \times 10^{22})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 0.03$$

151

152

153

154

Sm

153

$$(1.14 \times 10^{19})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 0.003$$

155

156

$$(0.02 \times 10^{19})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 5 \times 10^{-5}$$

Eu

155

$$(1.33 \times 10^{20})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 0.036$$

156

$$(0.08 \times 10^{20})(1 \times 10^{-11})(3.7 \times 10^{10})^{-1} = 2 \times 10^{-3}$$

157

158

FISSION GAS RELEASE

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Neglecting isotopes with an activity less than 1 Curie/MW and relisting isotopes with activities greater than 1 Curie/MW, only.

<u>ELEMENT</u>	<u>Mass No.</u>	<u>ACTIVITY RELEASE</u> ($\frac{\text{Curie}}{\text{MW}}$)
As	77	1.6
Kr	85	19.0
	85	489
	87	15.3
	88	45.9
Rb	88	4.9
	89	5.2
Sr	89	164
	90	142
	91	1.5
Zr	95	3.5
Nb	95	1.6
Mo	99	7.2
Tc	99	139
	100	5.9
Ru	103	6,160
	105	10.8
	106	2,310
Rh	104	5.8
	105	57.3
	110	1.3
Ag	111	5.7
Cd	115	1.2
Sn	119	6.1
	123	4.0
	123	5.0
Sb	125	73.1
	126	1.6
	127	15.1
	129	5.9
	130	1.0
	133	1.6

FISSION GAS RELEASE

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<u>ELEMENT</u>	<u>MASS No.</u>	<u>ACTIVITY RELEASE</u>	$\left(\frac{\text{Curie}}{\text{MW}}\right) = N_0 \frac{D}{3.7 \cdot 10^{10}}$
Te	127	6.9	
	129	19.1	
	131	1.7	
	132	44.3	
I	131	1,010	
	133	238	
	134	10	
	135	65	
Xe	131	19	
	133	2,560	
	135	170	
Cs	136	7.5	
	137	3,400	
	138	15.3	
	139	4.4	
Ba	140	49.6	
La	140	6.5	
Ce	141	1.8	
	144	3.6	
Pm	147	3.0	

FISSION GAS RELEASE

608 0095

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<u>ELEMENT</u>	<u>MASS No.</u>	<u>ACTIVITY RELEASE PER FUEL ROD (KCurie)</u>
As	77	$(1.6) (12.5 \times 10^{-6}) = 2 \times 10^{-5}$
Kr	85	$(19.0) (12.5 \times 10^{-6}) = 0.24 \times 10^{-3}$
	85	$(489) (12.5 \times 10^{-6}) = 6.11 \times 10^{-3}$
	87	$(15.3) (12.5 \times 10^{-6}) = 0.19 \times 10^{-3}$
	88	$(45.9) (12.5 \times 10^{-6}) = 0.57 \times 10^{-3}$
Rb	88	$(4.9) (12.5 \times 10^{-6}) = 6 \times 10^{-5}$
	89	$(5.2) (12.5 \times 10^{-6}) = 7 \times 10^{-5}$
Sr	89	$(164) (12.5 \times 10^{-6}) = 2.05 \times 10^{-3}$
	90	$(142) (12.5 \times 10^{-6}) = 1.77 \times 10^{-3}$
	91	$(1.5) (12.5 \times 10^{-6}) = 2 \times 10^{-5}$
Zr	95	$(3.5) (12.5 \times 10^{-6}) = 4 \times 10^{-5}$
Nb	95	$(1.6) (12.5 \times 10^{-6}) = 2 \times 10^{-5}$
Mo	99	$(7.2) (12.5 \times 10^{-6}) = 9 \times 10^{-5}$
Tc	99	$(139) (12.5 \times 10^{-6}) = 1.74 \times 10^{-3}$
	100	$(5.9) (12.5 \times 10^{-6}) = 7 \times 10^{-5}$
Ru	103	$(6,160) (12.5 \times 10^{-6}) = 77.0 \times 10^{-3}$
	105	$(10.8) (12.5 \times 10^{-6}) = 0.14 \times 10^{-3}$
	106	$(2,310) (12.5 \times 10^{-6}) = 28.9 \times 10^{-3}$
Rh	104	$(5.8) (12.5 \times 10^{-6}) = 7 \times 10^{-5}$
	105	$(57.3) (12.5 \times 10^{-6}) = 0.71 \times 10^{-3}$
	110	$(1.3) (12.5 \times 10^{-6}) = 2 \times 10^{-5}$
Ag	111	$(5.7) (12.5 \times 10^{-6}) = 7 \times 10^{-5}$
Cd	115	$(1.2) (12.5 \times 10^{-6}) = 1 \times 10^{-5}$
Sn	119	$(6.1) (12.5 \times 10^{-6}) = 8 \times 10^{-5}$
	123	$(4.0) (12.5 \times 10^{-6}) = 5 \times 10^{-5}$
	123	$(5.0) (12.5 \times 10^{-6}) = 6 \times 10^{-5}$
Sb	125	$(73.1) (12.5 \times 10^{-6}) = 0.91 \times 10^{-3}$
	126	$(1.6) (12.5 \times 10^{-6}) = 2 \times 10^{-5}$
	127	$(15.1) (12.5 \times 10^{-6}) = 0.19 \times 10^{-3}$
	129	$(5.9) (12.5 \times 10^{-6}) = 7 \times 10^{-5}$
	130	$(1.0) (12.5 \times 10^{-6}) = 1 \times 10^{-5}$
	133	$(1.6) (12.5 \times 10^{-6}) = 2 \times 10^{-5}$

FISSION GAS RELEASE

683 0598

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ELEMENT	MASS No	ACTIVITY RELEASE PER FUEL ROD (KCurie)
Te	127	$(6.9)(12.5 \times 10^{-6}) = 9 \times 10^{-5}$
	129	$(19.1)(12.5 \times 10^{-6}) = 0.24 \times 10^{-3}$
	131	$(1.7)(12.5 \times 10^{-6}) = 2 \times 10^{-5}$
	132	$(44.3)(12.5 \times 10^{-6}) = 0.55 \times 10^{-3}$
I	131	$(1,010)(12.5 \times 10^{-6}) = 12.6 \times 10^{-3}$
	133	$(238)(12.5 \times 10^{-6}) = 2.97 \times 10^{-3}$
	134	$(10)(12.5 \times 10^{-6}) = 0.12 \times 10^{-3}$
	135	$(65)(12.5 \times 10^{-6}) = 0.81 \times 10^{-3}$
Xe	131	$(19)(12.5 \times 10^{-6}) = 0.24 \times 10^{-3}$
	133	$(2,560)(12.5 \times 10^{-6}) = 32.0 \times 10^{-3}$
	135	$(170)(12.5 \times 10^{-6}) = 2.12 \times 10^{-3}$
Cs	136	$(7.5)(12.5 \times 10^{-6}) = 9 \times 10^{-5}$
	137	$(3,400)(12.5 \times 10^{-6}) = 42.5 \times 10^{-3}$
	138	$(15.3)(12.5 \times 10^{-6}) = 0.19 \times 10^{-3}$
	139	$(4.4)(12.5 \times 10^{-6}) = 6 \times 10^{-5}$
Ba	140	$(49.6)(12.5 \times 10^{-6}) = 0.62 \times 10^{-3}$
La	140	$(6.5)(12.5 \times 10^{-6}) = 8 \times 10^{-5}$
Ce	141	$(1.8)(12.5 \times 10^{-6}) = 2 \times 10^{-5}$
	144	$(5.6)(12.5 \times 10^{-6}) = 7 \times 10^{-5}$
Pm	147	$(3.0)(12.5 \times 10^{-6}) = 4 \times 10^{-5}$

FISSION GAS RELEASE

630 0097

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Neglecting isotopes with activities less than 0.1 Curie

<u>ISOTOPE</u>	<u>ACTIVITY RELEASE PER FUEL ROD (Curie)</u>
Kr-85 ^m	0.2
Kr-85	6.1
Kr-87	0.2
Kr-88	0.6
Sr-89	2.1
Sr-90	1.8
Tc-99	1.7
Ru-103	77.0
Ru-105	0.1
Ru-106	28.9
Rh-105	0.7
Sb-125	0.9
Sb-127	0.2
Te-129	0.2
Te-132	0.6
I-131	12.6
I-133	13.0
I-134	0.1
I-135	0.8
Xe-131	0.2
Xe-133	32.0
Xe-135	2.1
Cs-137	42.5
Cs-138	0.2
Ba-140	0.6

215.4 ≈ 215 Curie

These isotopes have long half-lives, therefore a decay period in the order of days is required to produce a significant amount of decay.

FISSION GAS RELEASE

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FISSION GAS RELEASE PER FUEL ROD OF ALUMINUM GLAD CORE

Core Life: 1.45 years = (1.45) (365) (24) (3,600) = 0.457 × 10⁸ sec.

The number of atoms of active isotope per MW is the same as before, except for those isotopes listed on pp. 11-12, which are as follows:

$$\text{Se-79} \quad N_0 = \frac{(3.7 \times 10^{-4})(3.1 \times 10^{16})(3.4 \times 10^{-13})}{(1 \times 10^{-7} + 3.4 \times 10^{-13})} \int \frac{1 - e^{-(3.4 \times 10^{-8})(0.457 \times 10^8)}}{3.4 \times 10^{-13}} - \frac{e^{-(3.4 \times 10^{-13})(0.457 \times 10^8)}}{1 \times 10^{-7}} \left\{ 1 - e^{-(1 \times 10^{-7})(0.457 \times 10^8)} \right\}$$

$$N_0 = 1.40 \times 10^{15}$$

$$\text{Kr-85} \quad N_0 = \frac{(3.17 \times 10^{-3})(3.1 \times 10^{16})(2.3 \times 10^{-9})}{(1 \times 10^{-7} + 2.3 \times 10^{-9})} \int \frac{1 - e^{-(2.3 \times 10^{-9})(0.457 \times 10^8)}}{2.3 \times 10^{-9}} - \frac{e^{-(2.3 \times 10^{-9})(0.457 \times 10^8)}}{1 \times 10^{-7}} \left\{ 1 - e^{-(1 \times 10^{-7})(0.457 \times 10^8)} \right\}$$

$$N_0 = 7.82 \times 10^{13}$$

$$\text{Rb-86} \quad N_0 = \frac{(3.1 \times 10^{-7})(3.1 \times 10^{16})(4.1 \times 10^{-7})}{(1 \times 10^{-7} + 4.1 \times 10^{-7})} \int \frac{1 - e^{-(4.1 \times 10^{-7})(0.457 \times 10^8)}}{4.1 \times 10^{-7}} - \frac{e^{-(4.1 \times 10^{-7})(0.457 \times 10^8)}}{1 \times 10^{-7}} \left\{ 1 - e^{-(1 \times 10^{-7})(0.457 \times 10^8)} \right\}$$

$$N_0 = 1.88 \times 10^{16}$$

$$\text{Sr-90} \quad N_0 = \frac{(0.05)(3.1 \times 10^{16})(1.1 \times 10^{-9})}{(7 \times 10^{-10} + 1.1 \times 10^{-9})} \int \frac{1 - e^{-(1.1 \times 10^{-9})(0.457 \times 10^8)}}{1.1 \times 10^{-9}} - \frac{e^{-(1.1 \times 10^{-9})(0.457 \times 10^8)}}{7 \times 10^{-10}} \left\{ 1 - e^{-(7 \times 10^{-10})(0.457 \times 10^8)} \right\}$$

$$N_0 = 1.76 \times 10^{21}$$

FISSION GAS RELEASE

63-0599

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Ru-106

$$N_0 = \frac{(0.0052)(3.1 \times 10^{16})(2.2 \times 10^{-8})}{(4 \times 10^{-8} + 2.2 \times 10^{-8})} \int \frac{1 - e^{-(2.2 \times 10^{-8})(0.457 \times 10^8)}}{2.2 \times 10^{-8}}$$

$$- \frac{e^{-(2.2 \times 10^{-8})(0.457 \times 10^8)}}{4 \times 10^{-8}} \left\{ 1 - e^{-(4 \times 10^{-8})(0.457 \times 10^8)} \right\}$$

$$N_0 = 1.20 \times 10^{21}$$

Sb-125

$$N_0 = \frac{(0.00023)(3.1 \times 10^{16})(8.1 \times 10^{-9})}{(4 \times 10^{-8} + 8.1 \times 10^{-9})} \int \frac{1 - e^{-(8.1 \times 10^{-9})(0.457 \times 10^8)}}{8.1 \times 10^{-9}}$$

$$- \frac{e^{-(8.1 \times 10^{-9})(0.457 \times 10^8)}}{4 \times 10^{-8}} \left\{ 1 - e^{-(4 \times 10^{-8})(0.457 \times 10^8)} \right\}$$

$$N_0 = 2.83 \times 10^{19}$$

Cs-136

$$N_0 = \frac{(6.2 \times 10^{-5})(3.1 \times 10^{16})(5.9 \times 10^{-7})}{(1 \times 10^{-7} + 5.9 \times 10^{-7})} \int \frac{1 - e^{-(5.9 \times 10^{-7})(0.457 \times 10^8)}}{5.9 \times 10^{-7}}$$

$$- \frac{e^{-(5.9 \times 10^{-7})(0.457 \times 10^8)}}{1 \times 10^{-7}} \left\{ 1 - e^{-(1 \times 10^{-7})(0.457 \times 10^8)} \right\}$$

$$N_0 = 2.78 \times 10^{18}$$

Cs-137

$$N_0 = \frac{(6.2 \times 10^{-5})(3.1 \times 10^{16})(6.7 \times 10^{-10})}{(1 \times 10^{-7} + 6.7 \times 10^{-10})} \int \frac{1 - e^{-(6.7 \times 10^{-10})(0.457 \times 10^8)}}{6.7 \times 10^{-10}}$$

$$- \frac{e^{-(6.7 \times 10^{-10})(0.457 \times 10^8)}}{1 \times 10^{-7}} \left\{ 1 - e^{-(1 \times 10^{-7})(0.457 \times 10^8)} \right\}$$

$$N_0 = 4.56 \times 10^{20}$$

FISSION GAS RELEASE

635-100

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ELEMENT	MASS No.	ACTIVITY RELEASE ($\frac{\text{Curie}}{\text{MW}} = N_0 \frac{\lambda}{3.7 \times 10^{10}}$)
Se	79	$(0.014 \times 10^{17})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 3.78 \times 10^{-3}$
Kr	85	$(78.2 \times 10^8)(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 2.12$
Rb	86	$(1.88 \times 10^{16})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 0.051$
Sr	90	$(1.76 \times 10^{21})(7 \times 10^{-10})(3.7 \times 10^{10})^{-1} = 33.3$
Ru	106	$(1.20 \times 10^{22})(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 1.29 \times 10^3$
Sb	125	$(28.3 \times 10^{18})(4 \times 10^{-8})(3.7 \times 10^{10})^{-1} = 30.6$
Cs	136	$(2.78 \times 10^8)(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 7.5$
	137	$(0.456 \times 10^{21})(1 \times 10^{-7})(3.7 \times 10^{10})^{-1} = 1.23 \times 10^3$

Neglecting isotopes with an activity less than 1 Curie per MW

ELEMENT	MASS No.	ACTIVITY RELEASE ($\frac{\text{Curie}}{\text{MW}}$)
Kr	85	2.12
Sr	90	33.3
Ru	106	1,230
Sb	125	30.6
Cs	136	7.5
	137	1,230

No. of rods per subassembly: 96

No. of subassemblies: 32

Reactor power: 40.1 MW (thermal)

Power per rod: $\frac{40.1}{32 \times 96} = 13.1 \frac{\text{KW}}{\text{rod}}$

Using the new release for the isotopes above mentioned, the value of 13.1 KW/rod instead of 12.5 KW/rod, and listing only the isotopes with activities greater than 0.1 Curie, then the list at pp. 12-13 is as follows:

FISSION GAS RELEASE

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<u>ELEMENT</u>	<u>MASS No.</u>	<u>ACTIVITY RELEASE PER FUEL ROD (K Curie)</u>	
Kr	85	(19.0) (1.31 x 10 ⁻⁶) =	0.25 x 10 ⁻³
	85	(212) (1.31 x 10 ⁻⁶) =	2.78 x 10 ⁻³
	87	(15.3) (1.31 x 10 ⁻⁶) =	0.20 x 10 ⁻³
	88	(45.9) (1.31 x 10 ⁻⁶) =	0.60 x 10 ⁻³
Sr	89	(164) (1.31 x 10 ⁻⁶) =	2.15 x 10 ⁻³
	90	(33.3) (1.31 x 10 ⁻⁶) =	0.44 x 10 ⁻³
Tc	99	(139) (1.31 x 10 ⁻⁶) =	1.82 x 10 ⁻³
Ru	103	(6,160) (1.31 x 10 ⁻⁶) =	80.7 x 10 ⁻³
	105	(10.8) (1.31 x 10 ⁻⁶) =	0.14 x 10 ⁻³
	106	(1,290) (1.31 x 10 ⁻⁶) =	16.9 x 10 ⁻³
Rh	105	(57.3) (1.31 x 10 ⁻⁶) =	0.75 x 10 ⁻³
Sb	125	(30.6) (1.31 x 10 ⁻⁶) =	0.40 x 10 ⁻³
	127	(15.1) (1.31 x 10 ⁻⁶) =	0.20 x 10 ⁻³
Te	129	(13.1) (1.31 x 10 ⁻⁶) =	0.25 x 10 ⁻³
	132	(44.3) (1.31 x 10 ⁻⁶) =	0.58 x 10 ⁻³
I	131	(1,010) (1.31 x 10 ⁻⁶) =	13.2 x 10 ⁻³
	133	(238) (1.31 x 10 ⁻⁶) =	3.12 x 10 ⁻³
	134	(10) (1.31 x 10 ⁻⁶) =	0.13 x 10 ⁻³
	135	(65) (1.31 x 10 ⁻⁶) =	0.85 x 10 ⁻³
	137	(19) (1.31 x 10 ⁻⁶) =	0.25 x 10 ⁻³
Xe	133	(2,560) (1.31 x 10 ⁻⁶) =	33.5 x 10 ⁻³
	135	(170) (1.31 x 10 ⁻⁶) =	2.23 x 10 ⁻³
	137	(1,230) (1.31 x 10 ⁻⁶) =	16.1 x 10 ⁻³
Cs	137	(15.3) (1.31 x 10 ⁻⁶) =	0.20 x 10 ⁻³
	138	(49.6) (1.31 x 10 ⁻⁶) =	0.65 x 10 ⁻³
Ba	140		

FISSION GAS RELEASE

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ISOTOPEACTIVITY RELEASE PBR FUEL ROD (Curie)

Kr-85m	0.2
Kr-85	2.8
Kr-87	0.2
Kr-88	0.6
Sr-89 } NOD	2.1
Sr-90	0.4
Tc-99 NOD	1.8
Ru-103 } NOD SL	80.7
Ru-105 } NOD	0.1
Ru-106 SL	16.9
Rh-105 SL	0.8
Sb-125	0.4
Sb-127	0.2
Te-129	0.3
Te-132	0.6
I-131	13.2
I-133	3.7
I-134	0.1
I-135	0.9
Xe-131	0.2
Xe-133	33.5
Xe-135	2.2
Cs-137	16.1
Cs-138	0.2
Ba-140	0.6
<hr/>	
178.2 $\approx$ 178 Curie	

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SUMMARY OF ACTIVITY RELEASE PER FUEL ROD IN CURIES

ISOTOPE	S.S. CORE	ALUMINUM CORE
Kr-85m	0.2	0.2
Kr-85	6.1	2.8
Kr-87	0.2	0.2
Kr-88	0.6	0.6
Sr-89	2.1	2.1
Sr-90	1.8	0.4
Tc-99	1.7	1.8
Ru-103	77.0	80.7
Ru-105	0.1	0.1
Ru-106	28.9	16.9
Rh-105	0.7	0.8
Sb-125	0.9	0.4
Sb-127	0.2	0.2
Te-129	0.2	0.3
Te-132	0.6	0.6
I-131	12.6	13.2
I-133	3.0	3.1
I-134	0.1	0.1
I-135	0.8	0.9
Xe-131	0.2	0.2
Xe-133	32.0	33.5
Xe-135	2.1	2.2
Cs-137	42.5	16.1
Cs-138	0.2	0.2
Ba-140	0.6	0.6
	215	178

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TOTAL RELEASE FOR REACTOR CORE

a. Isotopes which reach saturation

<u>ELEMENT</u>	<u>Mass No.</u>	<u>ACTIVITY RELEASE (Curie)</u>
Kr	85	(19.0) (40.1) = 761
	87	(15.3) (40.1) = 603
	88	(45.9) (40.1) = 1.84×10^3
Sr	89	(164) (40.1) = 6.58×10^3
Tc	99	(139) (40.1) = 5.58×10^3
Ru	103	(6,160) (40.1) = 247×10^3
	105	(10.8) (40.1) = 433
Rh	105	(57.3) (40.1) = 2.29×10^3
Sb	127	(15.1) (40.1) = 606
Te	129	(19.1) (40.1) = 766
	132	(44.3) (40.1) = 1.78×10^3
I	131	(1,010) (40.1) = 44.1×10^3
	133	(238) (40.1) = 9.54×10^3
	134	(10) (40.1) = 401
	135	(65) (40.1) = 2.61×10^3
Xe	131	(13) (40.1) = 761
	133	(2,560) (40.1) = 103×10^3
	135	(170) (40.1) = 6.82×10^3
Cs	138	(153) (40.1) = 613
Ba	140	(49.6) (40.1) = 1.99×10^3

b. Isotopes which do not reach saturation

<u>ELEMENT</u>	<u>Mass No.</u>	<u>ACTIVITY RELEASE (Curie)</u>
		<u>S.S. Core</u> <u>AI Core</u>
Kr	85	(489) (40.1) = 19.6×10^3 (212) (40.1) = 8.50×10^3
Sr	90	(142) (40.1) = 5.69×10^3 (33.3) (40.1) = 1.34×10^3
Ru	106	(2,310) (40.1) = 92.5×10^3 (1,290) (40.1) = 51.6×10^3
Sb	125	(73.1) (40.1) = 2.93×10^3 (30.6) (40.1) = 1.23×10^3
Cs	137	(3,400) (40.1) = 136×10^3 (1,230) (40.1) = 49.2×10^3

FISSION GAS RELEASE

635 105

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SUMMARY OF ACTIVITY RELEASE PER CORE, IN KCuries (10^3 Curies)

ISOTOPE	S.S. CORE	AI CORE
Kr-85 ^m	1	1
Kr-85	20	8
Kr-87	1	1
Kr-88	2	2
Sr-89	7	7
Sr-90	6	1
Te-99	6	6
Ru-103	247	247
Ru-106	93	52
Rh-105	2	2
Sb-125	3	1
Sb-127	1	1
Te-129	1	1
Te-132	2	2
I-131	44	44
I-133	10	10
I-135	3	3
Xe-131	1	1
Xe-133	103	103
Xe-135	7	7
Cs-137	136	49
Cs-138	1	1
Ba-140	2	2

699 ≈ 700 KCurie

552 ≈ 550 KCurie

24% OF THE SS CORE
MELTS DOWN THUS
20% OF EACH
OF THE FISSION
PRODUCTS IS RELEASED

FISSION GAS RELEASE

635 106

SIMILAR TO

DR. N. J. A. LANDONI	CH'D:	APP'D:	SCALE = 12	SHEET 32 OF 32	ISSUE
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