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SUBJECT: Determination of Maximum Permissible Leakage from the HRT Process Steam System

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FROM: E. H. Gift

SUMMARY

Calculations were made to determine the radiation hazard to HRT personnel as a result of leakage to the atmosphere from the process steam system in the event of a heat exchanger tube rupture. These calculations show that with the present four-minute delay before dumping approximately 1020 lb of fuel solution may be transferred to the steam system. The radiation hazard from fission products in the atmosphere will be negligible if the steam killer blower is operating. If this blower is not operating, a natural convection loop will be set up in the steam killer which will have a condensing capacity of 4 lb/min of steam at atmospheric pressure. In this latter case, the inhalation hazard will be negligible when the leak rate through the steam "stop" valves is less than 4 lb/min.

DISCLAIMER

Discussion of Results

At the start of HRT Run Number 18, the process steam system had leakage of about 0.5 liter liquid H_2O/min from each of the quick closing steam "stop" valves (No. 537 on the core system and No. 538 on the blanket system). In the event of a heat exchanger tube rupture, leakage from these valves could flow directly to the atmosphere through the possibly open steam vents on the steam killer. An estimate was required of the maximum permissible leakage rate from the system based on maximum permissible radiation exposure of the personnel.

Under the present dump system at the HRT, approximately four minutes are required between the initiation of a dump by the steam activity monitors and the actual opening of the dump valves. The first two minutes delay is for recombination of the radiolytic gases in the fuel solution. The delay was originally based on the time required to lower the radiolytic gas concentration in solution, after operation at 5 Mw, to nonexplosive limits. Based on single phase flow through the ruptured heat exchanger tube approximately 652 pounds of fuel solution could be transferred during the first two minutes.

The remaining two minutes delay is used to bleed off the overpressure. With the same flow assumptions, the total fuel transferred to the steam system at the end of four minutes is about 1020 pounds. The amount of fuel solution required to equalize the pressure between the two systems is about 2100 pounds when an adiabatic transfer is assumed.

Based on the above rate of flow for the four minutes available time for fuel transfer to the steam system, the allowable leakage was determined for the following conditions:

1. Reactor operating times of 40 and 400 days
2. 25 rem bone and external dose
3. 50 rem thyroid dose.

In addition, there are three cases which should be considered before the steam can escape to the atmosphere:

Case I. The blower to the steam killer continues operating at its design flow rate.

Case II. The blower ceases to operate, but a natural convection loop is set up.

Case III. The blower ceases to operate, and no natural convection loop is set up.

It is expected that the blower will continue to operate since it is unlikely that either a power failure or a blower failure will occur at the same time that the heat exchanger tube ruptures. The third case is not expected to occur at all, but is included simply to show the maximum accident.

If the conditions of Case I exist after the heat exchanger tube ruptures, there should be little or no escape of activity from the steam system to the atmosphere. The calculations show that the temperature inside the steam killer would become nearly equal to that of the air coolant. Thus the vapor pressure of the steam would be much less than atmospheric pressure.

For Case II, that of the natural convection cooling, the assumption was made that little or no activity could escape from the system as long as the temperature of the steam condensate leaving the steam killer was less than the boiling point of water. This is equivalent to assuming that no steam could escape from the steam system until the vapor pressure of steam in the steam killer equaled the atmospheric pressure. Under this assumption, for steam leak rates through the "stop" valves of less than 1.8 liters liquid H_2O/min (4.0 lb/min), essentially no activity would escape to the atmosphere. For leak rates greater than this, Figures (1) and (2) show the allowable leak rate versus the maximum allowable exposure time per Mw of total reactor power.

From the figures it can be seen that the hazard due to the bone seekers may be neglected in comparison with that from the iodine. This occurs because the heat exchanger was assumed to have a 90% entrainment separation efficiency; thus, most of the entrainable fission products would be left behind in the heat exchanger. These include the bone seekers. For the iodine it was assumed that the iodine bed had removed 88.12% of the equilibrium iodine buildup in the fuel solution, but that all of the iodine that was transferred to the steam system went directly to the vapor phase.

For Case III, in which it is assumed that no natural convection cooling occurs, the steam killer would be effective only in serving as a further dilution volume before the final release to the atmosphere. Figures (3) and (4) show the allowable leak rate versus maximum allowable escape time per Mw of total reactor power when it is assumed that there is no further accumulation of steam in the steam killer and that the steam vapor pressure in the steam killer is atmospheric.

To show that the whole body dose due to external radiation is negligible in comparison with the ingestion dose, three cases were considered. The first case assumed that the vent behaved as a steadily increasing point source with a man standing directly below the vent. The second case assumed that the man was standing in the cloud at the point of maximum ground concentration as given by Sutton's equation. The results of both of these cases are shown in Figure (5), from which it can be seen that they are negligible in comparison with the maximum ingestion dose for the same exposure time.

The third case considered was the exposure due to radiation from contaminated steam and condensate piping. Figure (6) shows the exposure time per Mw of reactor power required to give 25 rem external dose as a function of distance from long lengths of steam or condensate piping.

Estimate of Fuel Leakage into Steam System when a Heat Exchanger Tube Ruptures

The HRT steam system is designed with a radiation monitor between the heat exchangers and the steam drums which will initiate a dump when the steam activity shows the presence of fission products. The only immediate action toward dumping is the closing of the steam valves. Before the dump valves are actually opened, the system is provided with a two minute delay for internal recombination of radiolytic gases and a two minute delay to relieve the overpressure through the pressurizer bleed valves. Thus there are approximately four minutes available for fuel to flow into the steam system before the dump valves are actually opened.

At the time of the break the fuel system will probably be at a pressure of 1500 psia and the steam system pressure will be about 627 psia corresponding to a steam temperature of 491°F. Although the actual flow through the ruptured tube will probably be two-phase flow, single-phase flow is assumed for this calculation. The actual flow rate will thus be lower than the rates calculated here, but by not more than a factor of two.

Assuming that the ruptured tube looks like a flow nozzle, the flow through the tube is given by:

$$W = C \sqrt{\frac{2\, g_c\, \rho\, (-\Delta P)}{\left(\frac{1}{A_2}\right)^2 - \left(\frac{1}{A_1}\right)^2}} \qquad (1)$$

where,

C = Discharge coefficient ≈ 0.82

ρ = Density of discharging fuel, 53.04 lb/ft^3 at 270°C

ΔP = Pressure difference, lb_f/ft^2

g_c = Constant, 32.2 $lb_m/lb_f\text{-}ft/sec^2$

W = Mass flow rate, lb/sec

A_1 = Cross-sectional area of heat exchanger shell, ft^2

A_2 = Cross-sectional area of heat exchanger tube, = $3.272 \times 10^{-4} ft^2$

where $\frac{1}{A_1} <<< \frac{1}{A_2}$ and can be neglected.

The liquid and steam volumes of the fuel and steam systems are as follows:

1. The Fuel System

   a. D_2O liquid at $T = 270^{\circ}C$, 2283 liters

   b. D_2O liquid at $T = 312^{\circ}C$, 33 liters

   c. D_2O vapor at $T = 312^{\circ}C$, 75 liters

2. The Core Steam System

   a. H_2O liquid at $T = 491^{\circ}F$, 862.3 liters

   b. H_2O vapor at $T = 491^{\circ}F$, 2206.9 liters

3. The Blanket Steam System

   a. H_2O liquid at $T = 491^{\circ}F$, 866.9 liters

   b. H_2O vapor at $T = 491^{\circ}F$, 1599.2 liters

4. The liquid volume in the fuel system at a lower elevation than the heat exchangers

   a. The core vessel at $T = 270^{\circ}C$, 294 liters

   b. The blanket vessel at $T = 270^{\circ}C$, 1562 liters

   c. Piping volume at $T = 270^{\circ}C$, $\sim$ 161 liters

5. The nondrainable liquid in the blanket pressurizer at $270^{\circ}C$, $\sim$ 13 liters

There will be two conditions of flow from the fuel system, one in which the fuel system pressure is greater than saturation pressure and the other in which the pressure is saturation pressure. The first condition will exist until enough fuel has leaked into the heat exchanger so that the increased vapor volume in the fuel system has cooled the pressurizing liquid and vapor at 312°C to saturation at 270°C.

Assuming an adiabatic expansion the following equation applies to the liquid and vapor in the core pressurizer at the original temperature of $312^{\circ}C$:

$$h_T = h_L + \frac{(v_T - v_L)}{v_{fg}} h_{fg} \qquad (2)$$

where, h_T = Heat content of liquid and vapor in the pressurizer, Btu/lb

h_L, h_{fg} = Final heat content in pressurizer at T = 270°C, Btu/lb, (h_L, liquid; h_{fg}, liquid to vapor)

v_T, v_L, v_{fg} = Final specific volumes in pressurizer at T = 270°C, ft³/lb. (V_T, total; V_L, liquid) v_{fg}, liquid to vapor)

Original Conditions	V(ft³)	v(ft³/lb)	W(lb)	h(Btu/lb)	H(Btu)
Liquid D_2O at 312°C	1.17	0.02125	50.80	589.7	2.996×10^4
Vapor D_2O at 312°C	2.65 3.82	0.24942	10.63 61.43	1094.7	1.163×10^4 4.159×10^4

Solving for v_T of equation (2) and using the properties of D_2O at 270°C,

$$v_T = 0.15691 \ ft^3$$

from which the expanded vapor volume is:

$$V_T = W_T v_T = 9.64 \ ft^3 \ .$$

The mass of fuel solution removed from the fuel system during this expansion is:

$$W_f = (9.64 - 3.82) \ 53.04 = 308.7 \ lb \ .$$

The available mass of fuel solution at an elevation higher than the lowest heat exchanger tube is from the previously listed system volumes,

$$W = \frac{253}{28.32} \times 53.04 = 473.9 \ lb \ .$$

Thus, if the flow through the broken tube is fast enough 308.7 lb of fuel solution can flow into the heat exchanger before the saturation pressure at 270°C is reached in the fuel system.

In the core steam system the final pressure after the addition of 308.7 lb of fuel solution at 270°C can be calculated using equation 2, the core steam system volumes and the heat contents of the systems. Doing this the final pressure and temperature are 656.3 psia and 496°F, respectively. Similarly for the blanket steam system the pressure and temperature are 654.3 psia and 495.9°F, respectively.

The addition of the remaining 165.2 pounds of fuel above the level of the heat exchanger tubes to the steam systems will cause the final pressure and temperature to be 668.7 psia and 498°F, respectively, in the fuel steam system and 662.7 psia and 497°F in the blanket steam system.

Using equation (1), where ΔP is defined as the difference of the average pressures in the fuel system and the respective steam system, the flow rates can be calculated.

1. For a ruptured core heat exchanger tube

   a. Flow while fuel system pressure is greater than saturation pressure at 270°F

   $\therefore$ Average pressure in fuel system $= \dfrac{1500 + 805}{2} = 1153$ psia

   Average pressure in steam system $= \dfrac{654.3 + 627}{2} = 640.7$ psia

   $$\Delta P = 1153 - 641 = 512 \text{ psi} = 7.377 \times 10^4 \text{ lb/ft}^2.$$

   From equation (1), $W = 4.26$ lb/sec.

   The time required to flow 308.7 lb is then,

   $$t = \frac{308.7}{4.26 \times 2} = 36.2 \text{ sec.}$$

   b. Flow while fuel system pressure is at saturation pressure

   Average pressure in fuel system = 805 psia

   Average pressure in steam system $= \dfrac{654.3 + 666.8}{2} = 660.6$ psia

   $$\Delta P = 805 - 660.6 = 144.4 \text{ psi} = 2.079 \times 10^4 \text{ lb/ft}^2$$

   From equation (1), $W = 2.62$ lb/sec.

The time to flow the remaining available liquid is then,

$$t = \frac{473.9 - 308.7}{2.62 \times 2} = 31.5 \text{ sec.}$$

Thus the total time required to flow all the fuel above the level of the heat exchangers into the core steam system is 67.7 seconds. Similarly, for a ruptured blanket heat exchanger tube the time required for this fuel solution to be transferred is 72.7 sec. In both cases this is much less time than the total delay time of 4 minutes before the dump valves are opened, and at least this 473.9 lb of fuel solution should be expected to be transferred to the steam system when a heat exchanger tube ruptures.

It is probable that the fuel solution can continue to flow even after the fuel level in the two systems has reached the level of the ruptured heat exchanger tube. This situation is a result of the core and blanket systems being connected by the hole in the core vessel. The fuel can continue to flow through the ruptured tube until one of three things occurs:

1. The steam system pressure becomes equal to the fuel system pressure.
2. The fuel level in either the core or blanket system drops to the level of the hole in the core vessel.
3. The four minute delay is ended.

Thus, the maximum amount of fuel that can be transferred is that required to equalize the pressures in the two systems during an adiabatic expansion. This maximum amount of fuel solution is about 2100 lb.

Using equation (1) the amount of fuel solution which could be transferred was calculated for the flow times of 2 minutes and 4 minutes. At the end of 2 minutes approximately 652 lb of fuel solution may be transferred at which time the average temperature of the fuel system would be 516.7°F while that of the steam system would be 502.1°F. Similarly, at the end of four minutes 1020 lb of fuel solution may be transferred with the average fuel solution temperature being 512.7°F and the steam temperature being 508°F.

A plot of these predicted flows as a function of time after the heat exchanger tube rupture shows that the flow can be adequately represented by:

$$W = 432\ t^{0.62}$$

where, W = fuel solution transferred to the steam system, lb.

t = time after heat exchanger tube rupture, min.

A brief estimate of the criticality problem of both heat exchangers was made in the event that they become filled with 5 g/liter UO_2SO_4 solution. These calculations show that the heat exchangers and the blanket steam drum will be subcritical for all solution temperatures, both reflected with H_2O and unreflected. The core steam drum will be subcritical at 280°C for the H_2O reflected condition, but if filled at room temperature, it may be critical.

Estimate of Radiation Hazard Due to Steam Leakage

In the event of a heat exchanger tube leak or rupture, the steam system of the HRT may present a personnel radiation hazard. At the beginning of the December 1958 startup the steam valves, 537 and 538, each had leakage of 0.5 liters H_2O liquid/min at 1200 psig pressure difference. The steam system is vented to atmosphere at several points (all of which are outside the building) and is thus a likely escape path for fission products.

The radiation hazard from escaping fission products must be evaluated on the basis of the external whole body irradiation and also the long term ingestion hazard to specific organs. The effects of a particular group of isotopes have been evaluated and presented by T. H. J. Burnett.[1,2] Using this data, the ingestion effects can be estimated.

The accepted emergency dose to reactor personnel is assumed to be 25 rem for whole body dose and for the bone dose; and 50 rem for thyroid dose, in accordance with Burnett's recommendations. Some further assumptions which were made are:

1. Continuous reactor operating time of 40 and 400 days at a constant power level before the tube rupture.

2. All iodine which enters the steam system is concentrated in the vapor phase.

3. The iodine bed has been operating and has removed 88.12% of the equilibrium iodine.

4. The heat exchanger has an entrainment separation efficiency of at least 90%.

5. The path of the leaking steam is from the heat exchanger shell, to the steam drum, through the leaking steam valve, to the steam killer where it is either condensed or is released to the atmosphere through a possibly open vent valve.

The hazardous isotope activity in the fuel system is:

$$C_f = \frac{cp}{V\rho} \qquad (3)$$

where, c = Isotope concentration, curies/kw[2]

p = Total power of the system, 1000 kw

V = System liquid volume, 80.16 ft^3

ρ = Density of fuel solution at 270°C, 53.04 lb/ft^3

C_f = Isotope activity, curies/lb

$$C_f = \frac{c}{4.252} \quad (4)$$

Burnett has estimated the quantity, c, to be:

	Reactor Operating Time	
	40 days	400 days
For the bone seekers	460 curies/kw	680 curies/kw
For the iodines	247 curies/kw	248 curies/kw

During normal operation the total weight of water in the core or blanket heat exchangers and steam drums is about 1600 pounds. At 491°F this volume is about 30.45 ft^3 of H_2O liquid and 77.93 ft^3 H_2O vapor in the core steam system and 30.61 ft^3 of H_2O liquid and 56.47 ft^3 vapor in the blanket steam system.

It is expected that the bone seekers will be either insoluble or in solution and will thus be carried from the heat exchanger shell only as entrainment in the steam. Although the heat exchanger should have an entrainment separation efficiency of about 99% under these conditions, the value of 90% was used for these calculations since it is expected that some solid fission products will be carried by even dry steam. Thus, the bone seeker activity in the steam leaking through the steam "stop" valve will be:

$$A(t)_B = \frac{C_B(1 - E)\, W(t)}{(1600 + W(t) - Lt)} \quad (5)$$

where, $A(t)_B$ = Bone seeker activity of the leaking steam as a function of time, curies/lb.

E = Entrainment separation efficiency of the heat exchanger, $\approx$ 90%.

C_B = Bone seeker activity in fuel solution curies/lb.

$W(t)$ = Weight of fuel transferred to the steam system as a function of time, lb.

L = Leak rate through the steam valve, lb/min.

t = Time after heat exchanger tube rupture, min.

Since all the iodine, which is carried to the steam system, is assumed to concentrate in the vapor phase, this activity will be:

$$A(t)_I = \frac{0.1188\ C_I\ W(t)}{V(t)\ \rho_s(t)} \qquad (6)$$

where, $A(t)_I$ = Iodine activity of the leaking steam, curies/lb.

$V(t)$ = Vapor volume in the heat exchanger and steam drum as a function of time, ft^3.

$\rho_s(t)$ = Density of H_2O vapor in the heat exchanger and steam drum as a function of time, lb/ft^3.

When the flow rate of fuel solution being transferred into the steam system is calculated using equation (1) and the stated assumptions, the quantities, $W(t)$, $V(t)$, and $\rho_s(t)$ can be adequately represented by:

$$W(t) = 432\ t^{0.62} \qquad (7)$$

$$V(t) = 77.93\ e^{-0.07893\ t} \quad \text{(for a ruptured core heat exchanger tube)} \qquad (8)$$

$$V(t) = 56.50\ e^{-0.1296\ t} \quad \text{(for a ruptured blanket heat exchanger tube)} \qquad (9)$$

$$\rho_s(t) = 1.347\ e^{0.0511\ t} \quad \text{(for both a core or blanket heat exchanger tube rupture).} \qquad (10)$$

Thus:

$$A(t)_B = \frac{432(1 - E)\, C_B\, t^{0.62}}{(1600 + 432\, t^{0.62} - Lt)} \quad (11)$$

$$A(t)_I = \frac{0.4889\, C_I\, t^{0.62}}{e^{-0.02783\, t}} \quad \text{(for a core leak)} \quad (12)$$

$$A(t)_I = \frac{0.6743\, C_I\, t^{0.62}}{e^{-0.0785\, t}} \quad \text{(for a blanket leak)} \quad (13)$$

Considering only that steam which escapes to the atmosphere, the remaining portion of the steam system, primarily the steam killer, acts only as a dilution volume and a time delay before the atmosphere is reached. Thus, the activity of the steam which escapes to the atmosphere can be represented by:

$$\frac{dB}{dt} = \frac{A(t)\, L'}{V} - \frac{BL'}{\rho V} \quad (14)$$

where,
- B = Steam activity escaping to the atmosphere, curies/ft^3.
- L' = Leak rate to the atmosphere, lb/min.
- V = Volume of the steam killer, $\approx$ 15.6 ft^3.
- ρ = Density of steam in the steam killer, lb/ft^3.
- t = Time after heat exchanger tube rupture, min.

Solving equation (14) for B,

$$B = \frac{L'\, e^{-L't/\rho V}}{V} \int_0^t A(t)\, e^{L't/\rho V}\, dt \quad . \quad (15)$$

Dispersion of Fission Products in the Atmosphere

The concentration of these fission products in the atmosphere at any point can be readily estimated by Sutton's atmospheric dilution equation for a continuous point source.[4]

$$C(x,y) = \frac{2\,Q}{\pi\, C^2 \mu x^{2-n}} \; \exp\left[-\frac{y^2 + h^2}{C^2\, x^{2-n}}\right] \qquad (16)$$

where,

$C(x,y)$ = Concentration of activity, curies/meter^3

Q = Activity release rate = $\frac{BL'}{60\rho}$, curies/sec

ρ = density of steam released

B = curies/ft^3 of steam released

L' = leak rate from steam killer, lb/min

x = Distance downwind from source, meters

y = Distance crosswind from source, meters

h = Height of vent above ground, meters

μ = Wind velocity, meters/sec

n = Atmosphere stability parameter

C = Atmospheric diffusion coefficient, $(\text{meter})^{\frac{n}{2}}$

The worst case, as far as atmospheric dilution is concerned, at the HRT is that of the cold cloud conditions. Evaluating the constants, C and n, at a vent height of 18 ft above ground[4] the average cold cloud conditions at the HRT site are given below:

	Night	Day
μ, meters/sec	1.34 (3 mph)	3.13 (7 mph)
C^2	0.01	0.054
n	0.40	0.23
h, meters	5.49 (18 ft)	5.49 (18 ft)
y, meters	0	0

Solving Sutton's equation as a function of x shows that the maximum concentration for the day conditions occurs at 115 ft from the source and for the night conditions at 490 ft from the source.

Assuming a breathing rate of 30 liters/min, the maximum time of exposure in the cloud at the point of maximum concentration can be evaluated by:

$$I_m = \int_0^{t_m} \frac{C(x,y)_{max}}{3.333 \times 10^{-5}} \, dt \,, \ \mu c \,. \tag{17}$$

Burnett has estimated the allowable total inhalation of fission products, I_m, which yields 25 rem for the bone seekers and 50 rem for the iodines, to be:

	Reactor Operating Time	
	40 days	400 days
For the bone seekers	387 μc	134 μc
For the iodines	278 μc	278 μc

At the points of maximum cloud concentration, the quantity $C(x,y)$ can be represented by:

$$C(x,y) = K \frac{BL'}{60\rho} \tag{18}$$

where, K = Geometry factor from Sutton's equation, $K = 2.48 \times 10^{-3}$ for the day conditions and $K = 5.801 \times 10^{-3}$ for the night conditions, sec/meter^3.

The maximum allowable total inhalation of fission products becomes:

$$I_m = \frac{K \, L'^2 \, e^{-L't/\rho V}}{1.998 \times 10^{-3} \, \rho V} \int_0^{t_m} dt \int_0^{t} A(t) \, e^{L't'/\rho V} \, dt' \tag{19}$$

To solve equation (19) everything is known except the relationship between the leak rate, L, through the leaking steam "stop" valve 537 or 538 and the leak rate, L', to the atmosphere. Since it is assumed that the vent valve on the steam killer is open the leak rate to the atmosphere will depend entirely on the ability of the steam killer to condense the steam before it gets to the vent.

There are three possible histories for the steam leaking into the steam killer:

1. The blower to the steam killer continues operating at its design flow rate.
2. The blower ceases to operate, but a natural convection loop is set up.
3. The blower ceases to operate and no natural convection occurs.

Case 1:

If the blower continues to operate, the equilibrium conditions in the steam killer, following a heat exchanger tube rupture, can be estimated as follows:

$$\frac{Q_1}{Q_2} = \frac{U_1 A_1 \ (\Delta t_{LM})_1}{U_2 A_2 \ (\Delta t_{LM})_2} \ , \quad \frac{\text{normal operation}}{\text{operation after tube rupture}} \tag{20}$$

Since the major change in the overall heat transfer coefficient will be in the inside condensing and subcooling coefficient it should be reasonable to assume that the overall coefficient is not appreciably changed. Thus

$$\frac{Q_1}{Q_2} = \frac{(\Delta t_{LM})_1}{(\Delta t_{LM})_2} \ . \tag{21}$$

For normal operation of the condenser the following design conditions exist:

$Q_1 = 7.892 \times 10^6$ Btu/hr

$T_s = 334^\circ F$ (inlet steam temperature)

$T_c = 267^\circ F$ (condensate temperature)

$T_{air\ in} \cong 95^\circ F$

$G = 9000$ cfm of air maximum

$T_{air\ out} = 172^\circ F$

Using these values in equation (7) and assuming that the steam killer operates under countercurrent flow:

$$(\Delta t_{LM})_2 = \frac{Q_2}{5.059 \times 10^4} \quad .$$

From the previous section the condition of the steam in the steam drum and heat exchanger following a heat exchanger tube rupture are that of saturated steam at about 500°F. From the steam tables the steam leaking through the valve will have a heat content of 1201.7 Btu/lb and the temperature of the steam entering the steam killer will be about 320°F. The condensate leaving the steam killer will be at a temperature slightly greater than that of the 95°F air entering and have a corresponding heat content. Thus:

$$\frac{(320 - T_{air\ out}) - \Delta}{\ell n \dfrac{320 - T_{air\ out}}{\Delta}} = \frac{(1201.7 - 63)\ 60\ L}{5.059 \times 10^4} \qquad (22)$$

where, L = Leak rate through "stop" valves 537 or 538, lb/min

Δ = Temperature difference between the inlet air and the condensate leaving the condenser

$T_{air\ out}$ = Assumed approximately equal to the air inlet temperature of 95°F.

$$\frac{225 - \Delta}{\ell n \dfrac{225}{\Delta}} = 1.351\ L \quad . \qquad (23)$$

A possible range of leak rates, L, are from one to 20 lb/min. The log mean temperature difference can have values of:

$$1.351 \leq \frac{225 - \Delta}{\ln \frac{225}{\Delta}} \leq 27.02 \quad .$$

From this equation it can be seen that Δ cannot be greater than 0.1°F for leak rates up to 20 lb/min. Thus the temperature of the condenser will be approximately equal to the air temperature and the steam pressure inside the condenser will be much less than atmospheric pressure. For this case it is not expected that fission products can escape from the steam system when a heat exchanger tube is ruptured, and the blower continues to operate.

Case 2.

If for some reason the blower to the steam killer ceases to operate, it is expected that a natural convection loop will be set up. The steam killer consists of three rectangular sections 16'4-1/2" x 5'2-1/4" x 7" high. The sections are connected along the 5'2-1/4" side so that the overall dimensions of the condenser are 16'4-1/2" x 15'6-3/4" x 7". Directly above these sections lies a louvered section, approximately 8" high which leads directly to the atmosphere. There are 110, 5/8" OD, BWG 18 x 16' long tubes per section. Each tube has 10.25, 7/16" high fins per inch and there are three vertical staggered layers of tubes in each section. The tubes are arranged on a 1-5/8" horizontal pitch and a 1-7/16" vertical pitch.

The natural circulation equation for this system will be:

$$\int_0^h \rho \, d z = \frac{4f \, N \, G_{max}^2}{2g_c \, \rho_{avg}} \cong (\rho_{95} - \rho_T)\frac{h}{2} \qquad (24)$$

$$f = 0.23 + \frac{0.11}{(X_T - 1)^{1.08}} \left(\frac{D_o \, G_{max}}{\mu_{avg}} \right)^{-0.15} \qquad (25)$$

where, ρ = Density of air, lb/ft^3; ρ_{95}, density at inlet temperature; ρ_T, density at outlet temperature; ρ_{avg}, average density

N = Number of vertical tube banks

G_{max} = Mass velocity through minimum cross-section,

$$lb/sec\text{-}ft^2 = \frac{W_g}{3.6 \times 10^3 A_f} . \qquad (26)$$

W_g = Air flow rate, lb/hr

A_f = Minimum cross-section of condenser, $\approx 100\ ft^2$

g_c = Gravitational constant, $\frac{lb_m\ ft}{lb_f - sec^2}$

h = Height of condenser plus louvered section, ft

f = Friction coefficient for flow over staggered tubes[5]

X_T = Ratio of transverse pitch to tube diameter

D_o = Tube outside diameter, ft

μ_{avg} = Average viscosity, lb/sec-ft

For air the density and viscosity as functions of the temperature are,

$$\rho_T = \frac{39.66}{T} , \ lb/ft^3 \qquad (27)$$

$$\mu_T = 1.149 \times 10^{-5} \left(\frac{T}{492}\right)^{0.768} , \ lb/sec\text{-}ft \qquad (28)$$

$$\rho_{avg} = \frac{39.66 \ln \frac{T_2}{T_1}}{T_2 - T_1} , \ lb/ft^3 \qquad (29)$$

$$\mu_{avg} = \frac{1.127 \times 10^{-3}}{T_2 - T_1} \left[\left(\frac{T_2}{1000} \right)^{1.768} - \left(\frac{T_1}{1000} \right)^{1.768} \right], \text{ lb/sec-ft} \qquad (30)$$

T = Temperature of the air, $^{\circ}$R.

Substituting equations (25), (26), (27), (29), and (30) into equation (24), letting $T_1 = 95 + 460$ $^{\circ}$R, and solving for W_g gives,

$$W_g = \left[\frac{2.965 \times 10^{13} \left(0.07146 - \frac{39.66}{T_2} \right) \ln \frac{T_2}{555}}{(T_2 - 555)^{0.85} \left[\left(\frac{T_2}{1000} \right)^{1.768} - 0.3538 \right]^{0.15}} \right]^{0.5405} . \qquad (31)$$

Using the same steam side assumptions as were used in the previous forced convection case,

$$Q = \left(1201.7 - h_{T_c} \right) 60 \, L = 0.249 \, W_g \, (T_2 - 555) = UA \frac{(780 - T_2) - \Delta}{\ln \frac{780 - T_2}{\Delta}} . \qquad (32)$$

A = Heat transfer area $\approx$ 872 ft^2

U = Overall heat transfer coefficient, Btu/lb-$^{\circ}$F-ft^2

$\cong$ Natural convection coefficient = 1.8 Btu/lb-$^{\circ}$F-ft^2

Δ = Temperature difference between the outlet condensate temperature and the inlet air temperature, $^{\circ}$F

L = Leak rate from leaking valve, lb/min

h_{T_c} = Heat content of the condensate at the outlet temperature, T_c

$T_c = 555 + \Delta$, ^{o}R

T_2 = Outlet air temperature, ^{o}R.

Based on the assumption that the steam pressure in the condenser is that corresponding to saturated steam at the temperature of the condensate leaving the condenser, the following table shows the quantities, W_g, Δ, T_c, condenser steam pressure P_{T_c}, and L as functions of the outlet air temperature, T_2:

Tabe IV

T_2 (^{o}R)	W_g (lb/hr)	Δ ^{o}F	T_c (^{o}R)	P_{T_c} (psia)	L (lb/min)
555	0	0	0	--	0
560	2.086×10^4	<0.05	555	0.815	0.3801
565	2.958×10^4	2.3	557.3	0.875	1.08
570	3.65×10^4	25.0	580	1.69	2.04
575	4.224×10^4	82.0	637	7.02	3.32
580	4.729×10^4	175.0	730	43.3	5.11

Plotting the condenser steam pressure, P_{T_c}, versus the valve leak rate, L, shows that the condenser steam pressure is atmospheric when the leak rate is about 4.0 lb/min. Thus, it would be expected that even with an open vent on the steam killer, little or no steam would escape at leak rates below 4.0 lb/min. All leakage greater than 4.0 lb/min would be expected to escape from the system as steam. Thus, the quantity, L', in equation (19) is simply the leak rate through the steam valves minus four.

Case 3:

If the blower ceases to operate and no natural convection occurs, the steam killer and the steam piping between the leaking valve and the steam killer will be simply a large reservoir into which the leaking steam will be diluted before reaching the atmosphere. Since there would be no condensation of steam and assuming no accumulation of steam in the steam killer, the quantity, L', in equation (19) will equal the leak rate through the steam valve.

Figures (1), (2), (3), and (4) show the results of solving equation (19) as functions of the maximum allowable exposure time per unit total power for emergency radiation doses of bone seekers and iodines and the leak rate in liters of liquid H_2O per minute through the steam "stop" valves 537 or 538. Figures (1) and (2) represent the hazard when the condensing capacity of the steam killer is limited by natural convection cooling of the steam killer. For this case there will be essentially no ingestion hazard for leak rates less 1.8 liters liquid H_2O per minute (4.0 lb/min). The maximum possible hazard is represented by Figures (3) and (4), which represent the case for which there is no condensation of steam in the steam killer.

Both sets of figures show that for this situation the iodine ingestion hazard is greater than that due to bone seekers. This is primarily the result of the entrainment efficiency of the heat exchanger and the assumption that all the iodine which enters the heat exchanger shell appears in the vapor phase. A check of the iodine distribution coefficients shows that depending on the relative volumes of liquid and vapor in the heat exchanger and steam drum up to 85% of the iodine can be in the vapor phase. Since the distribution coefficients are based on equilibrium solubilities, it is felt that no credit should be taken for the iodine solubility in the uranyl sulfate solution in the heat exchanger.

The external whole body radiation dose although generally of less severity than the ingestion hazard from a fission product-bearing cloud can be calculated through use of the Wigner-Way equation. The gamma and beta source from a reactor operating at total power, P in watts, for a time, T_o in days, at the time after shutdown of $\tau - T_o$ can be expressed as:

$$S_\gamma = 2.546 \times 10^{10} P\left[(\tau - T_o)^{-0.2} - \tau^{-0.2}\right] \frac{\text{photons}}{\text{sec}}$$

$$S_\beta = 5.092 \times 10^{10} P\left[(\tau - T_o)^{-0.2} - \tau^{-0.2}\right] \frac{\text{betas}}{\text{sec}} .$$

The average photon energy is 0.7 Mev and the average beta energy is 0.4 Mev.

Evaluating the equations for one minute after shutdown for the reactor operating times of 40 days and 400 days gives:

	40 days	400 days
S_γ $\frac{\text{photons}}{\text{sec-Mw}}$	9.68×10^{16}	1.01×10^{17}
S_β $\frac{\text{betas}}{\text{sec-Mw}}$	1.926×10^{17}	2.02×10^{17}

Since the entrainment separation in the heat exchanger has been assumed to remove at least 90% of the solid fission products, but will not remove any of the gaseous fission products, the above sources as given by the Wigner-Way equation will be high. For shutdown times from zero to one hour the ratio of gaseous fission product energy release to total energy release ranges from about 5% to 10%. Thus, about 90% to 95% of the total energy release during this time is from the solid fission products. Since the heat exchanger will hold at least 90% of the total solid fission products, the actual energy release rate will be no more than 19% of that predicted by the Wigner-Way equation. If credit is taken for the removal of about 80% of the gaseous fission products during reactor operation, the energy release rate would be only 11% of that predicted by Wigner-Way. For the remaining calculations, the 11% value has been used. For ease of calculation it is also assumed the total amount of fuel solution that would be transferred in four minutes is suddenly dumped into the heat exchanger shell at the time of the tube rupture.

There are three cases to consider in estimating the external whole body radiation dose:

1. An individual standing directly below the vent who sees the radiation source but is not in the cloud.

2. An individual downwind from the source standing in the cloud where Sutton's equation gives a maximum ground concentration.

3. Radiation from lines containing steam or condensate.

The first case can be estimated by considering the source as a continuously increasing point source and calculating the time required to receive 25 rem of gamma dose. The point source is then, neglecting the additional dilution by the steam killer, at any time:

$$Q_\gamma = 1.104 \times 10^{-5} S_\gamma R t$$

where, Q_γ = Source in photons/sec

R = Steam leak rate, lb/sec

t = Time, sec.

The dose rate from this source at any time is then:

$$d = \frac{1.104 \times 10^{-5} \times 83.8 \times 1.1}{6.77 \times 10^{4} \times 100} \quad \frac{E_\gamma \mu_E S_\gamma R t}{4\pi r^2}$$

where, d = Dose rate, rem/sec

E_γ = Photon energy = 0.7 Mev

μ_E = Energy absorption coefficient of air = 3.5×10^{-5} cm^{-1}

r = Distance from source to the average height of man = (18-3) 30.48 = 457.2 cm

$$\therefore d = 1.403 \times 10^{-21} R S_\gamma t \ .$$

The total dose received at any time is then:

$$D \text{ (rems)} = \int_0^t 1.403 \times 10^{-21} R S_\gamma t \, dt = 7.015 \times 10^{-22} R S_\gamma t^2 \ .$$

Based on the assumption of a 25 rem total dose, the maximum time an individual could stand at this point is:

$$t_m = \sqrt{\frac{25}{7.015 \times 10^{-22} R S_\gamma}}$$

$$t_m = \sqrt{\frac{3.564 \times 10^{22}}{R S_\gamma}} \ .$$

The solution to this equation is shown in Figure (5) as a function of steam leak rate. It can be readily seen that in comparison with the ingestion hazard there is little personnel safety hazard from this source. Since there is essentially no difference between the core and blanket results or between the results at either 400 or 40 days, only the core results at 400 days operation are plotted in Figure (5).

The second case can be estimated using the maximum ground concentration as calculated by Sutton's equation, neglecting the additional dilution of the steam killer, and assuming night conditions. Thus,

$$D = \frac{10^6 \times 3.7 \times 10^4 \times 1.6 \times 10^{-6} \times 1.13 \times 2\pi\ EC(x,y)t}{1293 \times 100 \times 4\pi}$$

$$= 0.26\ EC(x,y)t$$

where, D = Dose, rems

E = Effective energy $= E_\gamma + \frac{E_\beta}{3} = 0.7 + \frac{0.4}{3} = 0.83\ \frac{\text{Mev}}{\text{dis.}}$

$C(x,y)$ = Concentration, curies/meter^3 $= 1.731 \times 10^{-18}\ S_\beta R$

t = Exposure time, sec.

For a maximum external dose of 25 rem, the maximum exposure time is then,

$$t_m = \frac{331.2}{R} \quad .$$

This equation is also plotted in Figure (5) as t_m vs. the leakage rate corresponding to the proper $C(x,y)$.

The radiation hazard from long pipes containing either radioactive steam or condensate can be evaluated by considering the piping as an infinite cylindrical volume source. The dose rate from such a source can be given by:

$$D\left(\frac{r}{\text{min}}\right) = \frac{30\ B\ S_v R_o^2\ \mu_e}{(a + z)}\quad F(\theta, b_2)$$

where, B = Buildup factor

R_o = Radius of the pipe, cm

μ_e = Energy absorption coefficient for air, cm^{-1}

a = Distance from the cylinder, cm

z = Self-absorption distance of the cylinder, cm

θ = Angle subtended by the end of the cylinder, for the infinite cylinder, $\theta = \frac{\pi}{2}$.

$$b_2 = \sum_{i=1}^{n} \mu_i t_i + \mu_s z$$

t = Thickness of each absorbing medium between the cylinder and the dose point, cm

μ_i = Mass absorption coefficient of each absorbing medium, cm^{-1}

μ_s = Mass absorption coefficient of the active steam or condensate, cm^{-1}

S_v = Gamma source strength, Mev/cm^3-sec-Mw .

Assuming 1020 lb of fuel solution transferred to the steam system, the gamma source strength is,

$$S_v = 1.330 \times 10^{-7} \rho S_\gamma \quad (\text{Mev/sec-cm}^3\text{-Mw})$$

where, ρ = Density of radioactive fluid, g/cm^3

S_γ = Photons/sec-Mw .

Assuming that S_γ is equal to 11% of the photon source as calculated by the Wigner-Way equation for 400 day reactor operation, that the density of the steam is that corresponding to steam at atmospheric pressure and that the density of the condensate is equal to room temperature water, the dose rate for 4 and 6" Sch. 80 steam piping and 4" Sch 40 condensate piping is given below:

(1) From 4" Sch 80 steam piping,

$$D = \frac{0.2004}{a} \left(\frac{r}{min}\right)$$

(2) From 6" Sch 80 steam piping,

$$D = \frac{0.4036}{a} \left(\frac{r}{min}\right)$$

(3) From 4" Sch 40 condensate piping,

$$D = \frac{307.2}{(1.19 + a)} \left(\frac{r}{min}\right) .$$

Assuming that the maximum emergency exposure is 25 r , Figure (6) shows the time required to accumulate this dose per Mw of reactor power as a function of the distance from the contaminated piping.

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EXPOSURE TIME REQUIRED TO GIVE 25 REM FROM BONE SEEKERS AS A FUNCTION OF LEAK RATE THROUGH THE HRT STEAM VALVES 537 OR 538 FOLLOWING A HEAT EXCHANGER TUBE RUPTURE

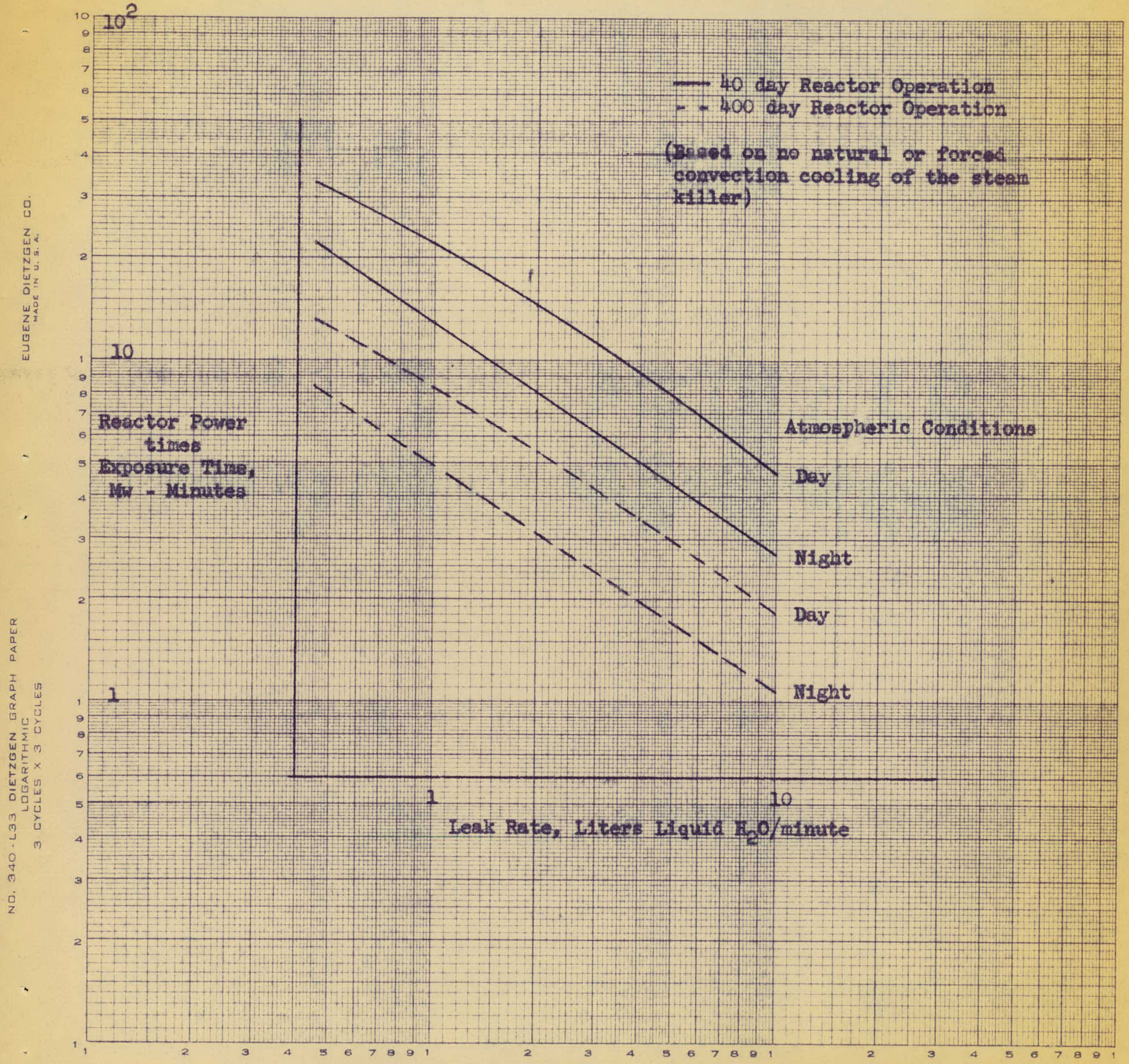

Figure 1.

EXPOSURE TIME REQUIRED TO GIVE 50 REM TO THE THYROID AS A FUNCTION OF LEAK RATE THROUGH THE HRT STEAM VALVES 537 OR 538 FOLLOWING A HEAT EXCHANGER TUBE RUPTURE

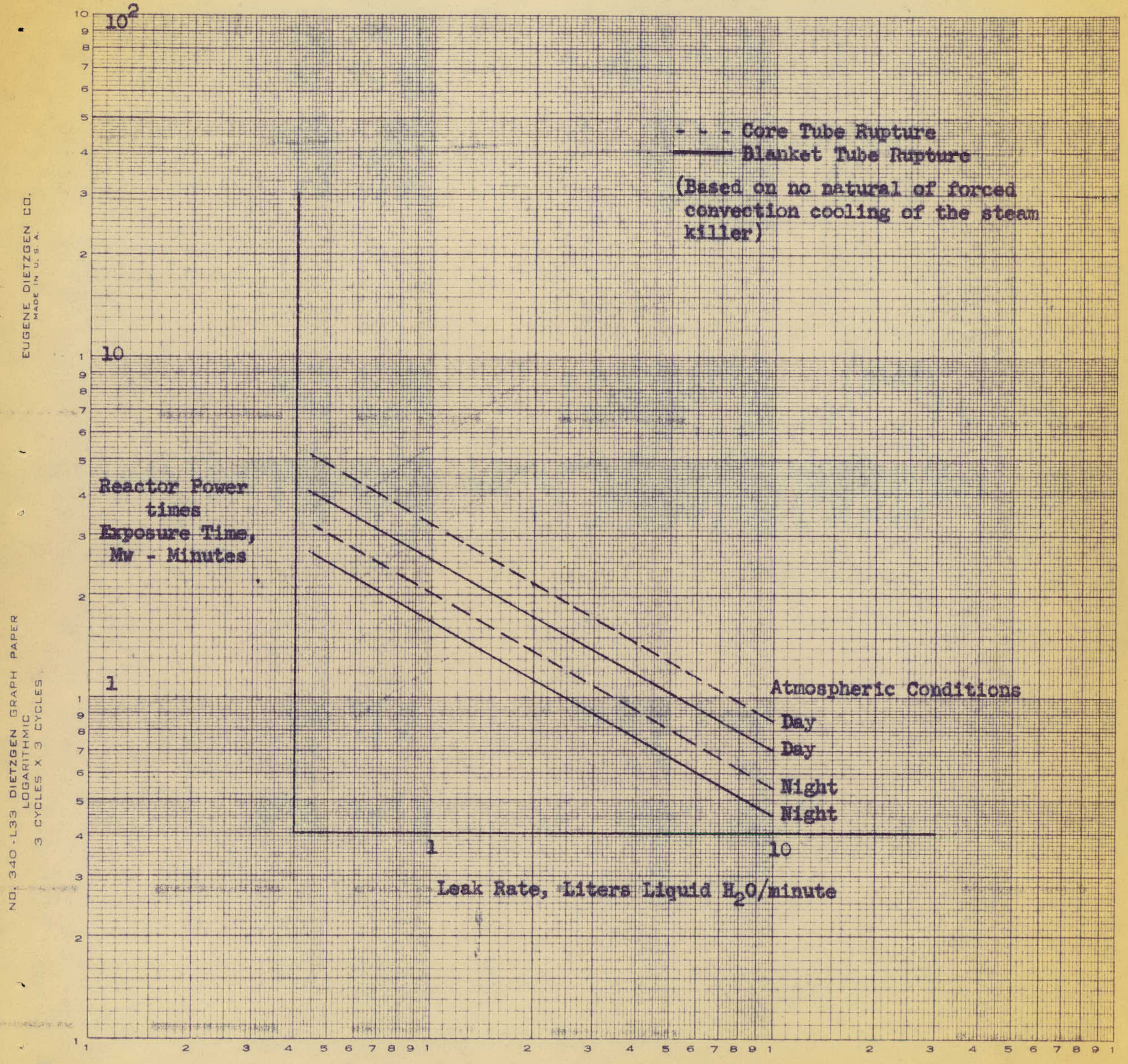

Figure 2.

EXPOSURE TIME REQUIRED TO GIVE 25 REM FROM BONE SEEKERS AS A FUNCTION OF LEAK RATE THROUGH THE HRT STEAM VALVES 537 OR 538 FOLLOWING A HEAT EXCHANGER TUBE RUPTURE

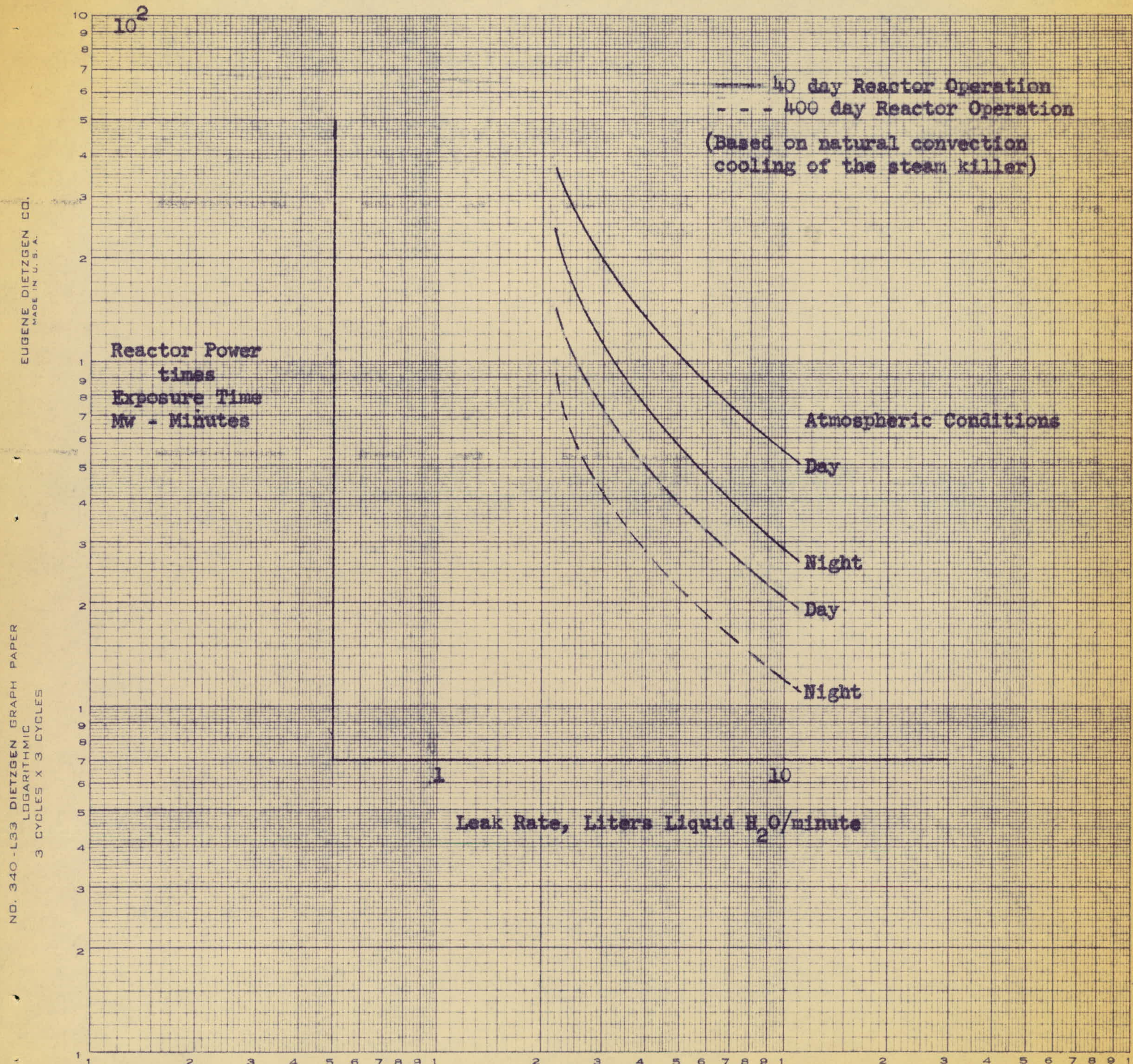

Figure 3.

EXPOSURE TIME REQUIRED TO GIVE 50 REM TO THE THYROID AS A FUNCTION OF LEAK RATE THROUGH THE HRT STEAM VALVES 537 OR 538 FOLLOWING A HEAT EXCHANGER TUBE RUPTURE

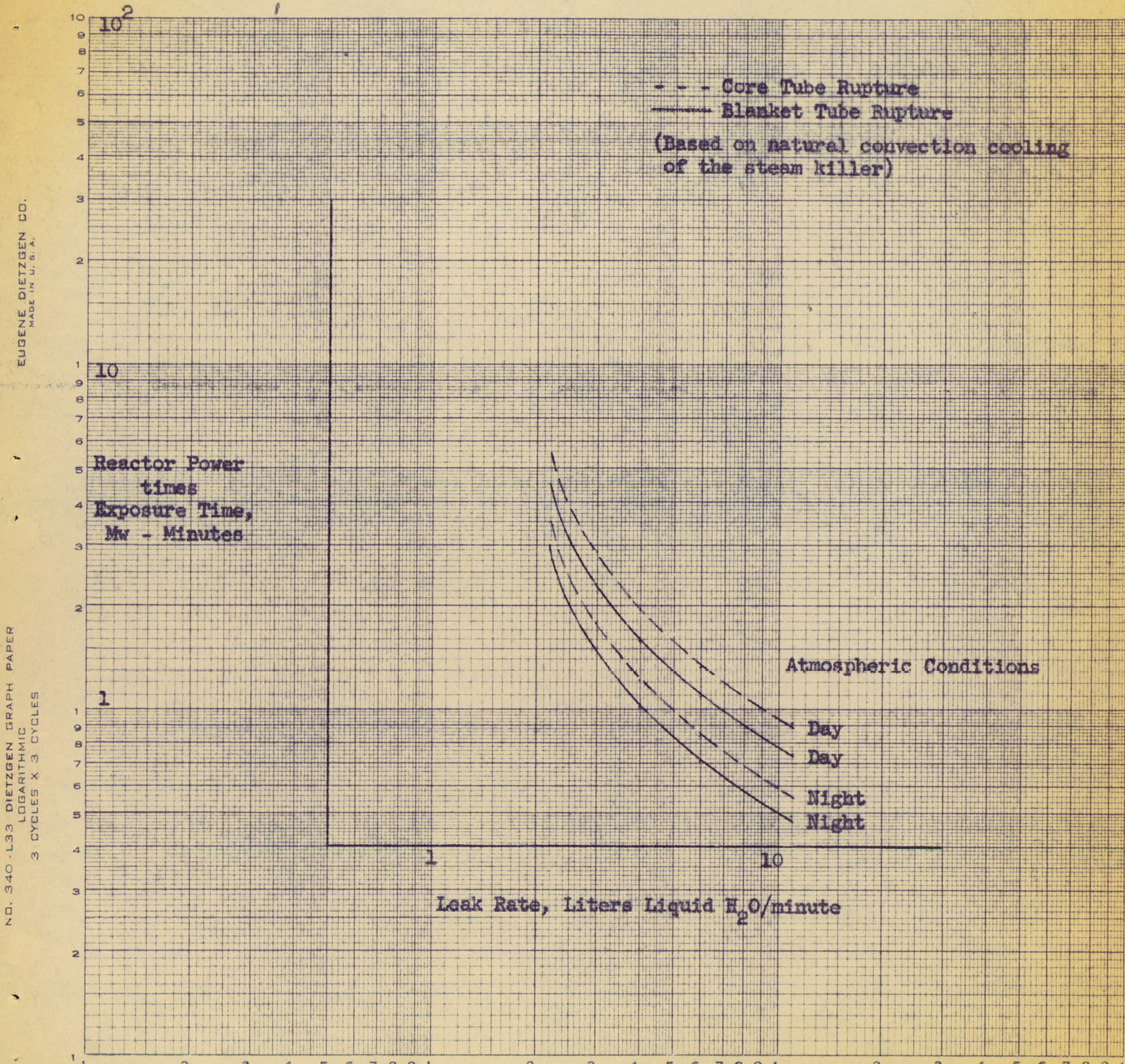

Figure 4.

EXPOSURE TIME REQUIRED TO GIVE 25 REM WHOLE BODY DOSE BY EXTERNAL EXPOSURE AS A FUNCTION OF LEAK RATE THROUGH HRT STEAM VALVES 537 OR 538 FOLLOWING A HEAT EXCHANGER TUBE RUPTURE

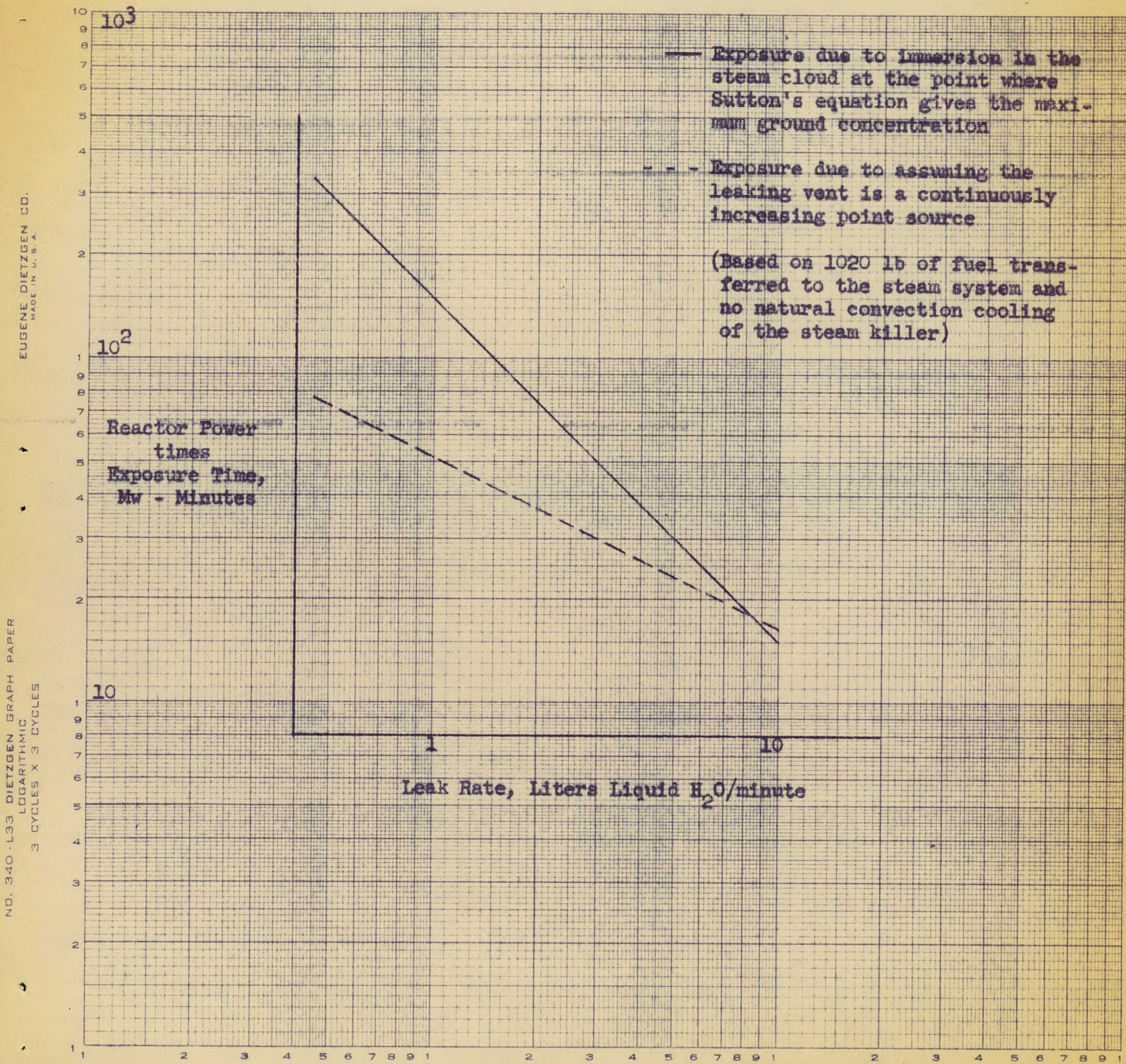

Figure 5.

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EXPOSURE TIME REQUIRED TO RECEIVE 25 REM WHOLE BODY DOSE AS A FUNCTION OF DISTANCE FROM CONTAMINATED HRT STEAM AND CONDENSATE LINES FOLLOWING A HEAT EXCHANGER TUBE RUPTURE

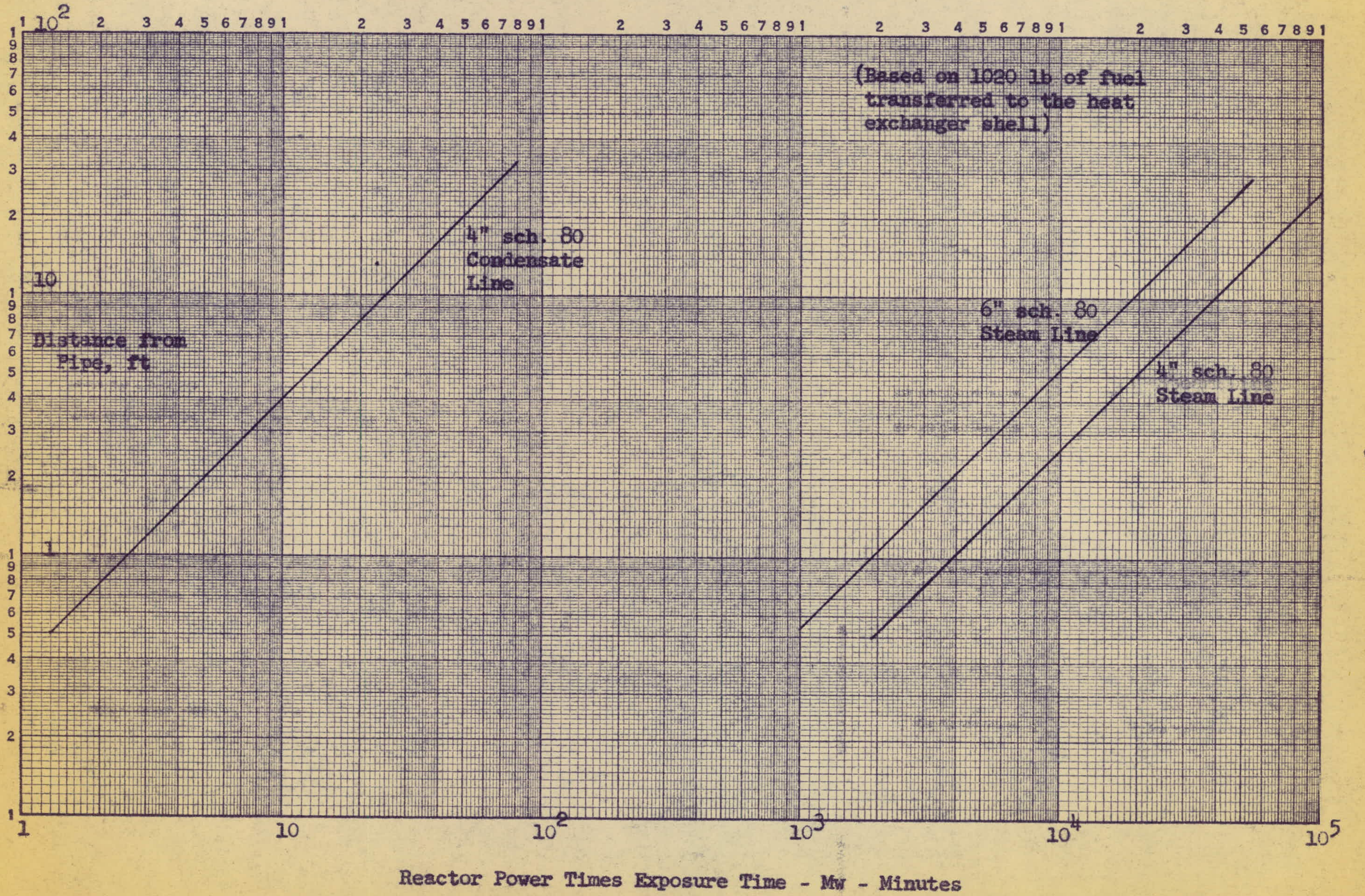

Figure 6.

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