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CENTRAL FILES NUMBER

CF-56-6-142

External Distribution Auth.
COPY NO. 10

DATE: June 22, 1956

SUBJECT: Gaseous Radioactivity From HRT Fuel Storage Tanks

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SUMMARY

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A study has been made to determine the amount of gaseous radioactivity from the fuel solution when it is stored in the outer dump tanks. The main source of gaseous activity is the decay of the fission products Br-83, I-133 and I-135 into Kr-83, Xe-133 and Xe-135 respectively. Assuming long term operation of the reactor at 10 Mw. some activity values are:

<u>Time After Reactor Shutdown, hrs.</u>	<u>Radiation From Gases Leaving Fuel Storage Tanks to Stack curies/sec.</u>	<u>At one foot distance from Line 165 in East Valve Pit, r/hr.</u>
1	108	200
10	40	120
24	9.4	33

The radioactivity of the gases leaving the reflux condenser is much too great to be sent directly to the stack. For time periods after shutdown greater than 24 hours the gaseous activity may be found from Figure 1. The radiation release is directly proportional to long term power, so the amount of radiation after operation at 5 Mw. is one-half the above values.

Since the radiation release to the stack must be kept low (~ 20 curies/day or less), it is recommended that a recombiner be used in the fuel storage system to remove deuterium and oxygen from the gaseous stream leaving the outer dump tanks. The radioactive gases can then be either held indefinitely in the low pressure system or sent through the main charcoal beds, before release to the stack. The only safe alternative to the recombiner is to hold the fuel solution in the inner dump tanks for a period of about 10 days for 5 Mw power (11 days for 10 Mw). The rate of radiation release after this period is less than 20 curies/day and can be sent directly to the stack.

INTRODUCTION

The original design of the outer dump tank storage system called for a catalytic recombiner of the type used in the HRE. The off gas, after passing through this recombiner and being relieved of radiolytic deuterium and oxygen, was to be sent through the main cold traps and charcoal beds before being vented to the stack. This recombiner was tested on a hydrogen flow similar to that expected in the off gas stream from the outer dump tanks and was found to be inadequate due to flashbacks and detonations which pulverized some of the pellets. Other types of recombiners were proposed (1) and some were tested. Small catalyst thimble assemblies placed in the reflux condenser was one proposal. Tests proved this design unsatisfactory because of detonations which pulverized the catalyst pellets. A second alternate, a platinized tube inserted through part of the length of the condenser was tested also. It was found that the tube had to be heated (to about 325°C) well above the temperature of the condensing vapors (~100°C) before any appreciable recombination was effected. In this case electrical heating units would probably be needed to keep the tube hot enough to be effective. Another type catalytic recombiner proposed was a natural circulation recombiner. This recombiner has been designed and a program for testing it, has been initiated. Because of its size, however, it may prove difficult to place it inside the shield close to the outer dump tanks. It was decided, therefore, to eliminate the recombiner on the outer dump tank reflux condenser vent line on the following basis:

- 1) Development of a completely satisfactory recombiner appeared improbable.
- 2) The outer dump tanks would be used only intermittently and loss of D₂O due to decomposition by energy from fission product decay would be relatively small while the fuel was stored here.
- 3) Since boiling occurs in the inner dump tanks for at least an hour (after reactor shutdown), essentially all the radioactive gases will be stripped out of the fuel solution before it is transferred to the outer dump tanks.

With the elimination of the recombiner on the outer dump tank vent, however, it was no longer considered safe to send the off gas through the main charcoal beds, as it would contain large amounts of explosive deuterium and oxygen. Therefore, in the present design of the fuel storage system of the HRT, the off gas is sent directly to the stack through line 134, the hold-up tank (Item 22), and lines 147 and 165.

At the time the recombiner was eliminated from the design, no check was made to determine if there would be any significant gaseous activity from the fuel solution when stored in the outer dump tanks. The purpose of this study is to estimate the amount and type of this gaseous activity and to recommend means for handling it.

Activity of Off-Gas from Outer Dump Tanks

The active gases involved, after the fuel has been transferred to the outer dump tanks, are krypton-83, and xenon isotopes 133 and 135. The source of these gases are bromine-83 and iodine 133 and 135, which are transferred along with the fuel solution. The simplified reactions are: (2)

Radiation in the off gas stream from the outer dump tanks has been estimated as a function of time after reactor shutdown on the following assumptions:

1. Long term reactor operation at 10 Mw power. (To determine the radiation for 5 Mw operation merely divide the values presented by 2).
2. All gases (radiolytic and radioactive) are stripped from the fuel solution in the inner dump tanks.
3. All the bromine and iodine fission products (present at time fuel is transferred to the outer dump tanks) accompany the fuel solution either suspended or dissolved.
4. Radiolytic gas production rates are those given in CF-55-8-77. (3)

Results are given in Table I. Radiation is plotted versus time in Fig. 1.

TABLE I

5.

Gaseous Radiation and Radiolytic Gas Production in the Outer Dump Tanks

Time After Reactor Shutdown hrs.	Radiolytic Gas Production Rate, ft ³ /sec	Radiation Release to Stack curies/sec.	Radiation at 1 ft. distance from Line 165 in east valve put. r/hr.
1	0.00996	108	197
10	.00629	40.2	118
24 (1 day)	.00526	9.43	32.4
48 (2 days)	.00459	0.92	3.11
100	.00399	0.037	0.044
168 (7 days)	.00360	3.5×10^{-3}	3.3×10^{-3}
336 (14 days)	.00314	1.94×10^{-5}	3.2×10^{-5}
1000	.00253	3.1×10^{-15}	3.8×10^{-15}

Derivation of equations for estimating the gaseous activity from the outer dump tanks is given in Appendix A.

Holdup of radioactive gases before release to stack

As seen by Table I and Fig. 1, if the fuel solution is transferred to the outer dump tanks within ~ 10 days the gaseous activity is too great to be vented directly to the stack. Some method must be found, then, to hold up these radioactive gases before releasing them to the stack. One method of handling the problem is to hold the fuel in the inner dump tanks until the iodine and bromine have decayed to a safe level. Figure 1 shows this time to be about 11 days after reactor operation at 10 Mw. (or 10 days after 5 Mw. operation).

Holding the fuel in the inner dump tank for this length of time, however, severely limits the usefulness of the outer dump tanks. A second method of handling the problem is to close the vent lines from the outer dump tanks while the fuel solution is stored there. With the vent lines closed, however, pressure will build up in the outer dump tank system due to the production of radiolytic gases at the rates shown in Table I. The rate of radiolytic gas evolution can be estimated from

$$\dot{V}_g = \frac{dn}{dt} = \alpha G P(t) \quad (4)$$

where $\dot{V}_g$ = rate of radiolytic gas evolution in dump tanks

n = number of moles of radiolytic gas evolved

t = time

α = conversion factor

$P(t)$ = fission decay power in the HRT fuel solution which is a function of time

G = rate of D_2O decomposition for fission fragment decay energy
(=0.5 molecules D_2O)

100 ev

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The fission decay power can be represented by the equation of Wigner and Way

$$P(t) = 0.076 P_0 t^{-0.2} \quad (5)$$

where P_0 = long term power of reactor

Let $\left\{ \begin{array}{l} n \text{ be the number of lb-mols of radiolytic gas released in time interval } (t-t_1) \\ P_0 \text{ be the long term power in Mw.} \\ t \text{ be the time after shutdown, in sec.} \\ t_1 \text{ be the time after shutdown when fuel is transferred to outer dump tanks.} \end{array} \right.$

Then, substituting eq (5) in eq (4), integrating and solving for n

$$n = 1.30 \times 10^{-5} P_0 (t^{0.8} - t_1^{0.8}) \quad (6)$$

The volume in the outer dump tank system available for the radiolytic gases to expand into is assumed to be that of the reflux condenser and the lines leading to the cut-off valve. This volume is

Reflux condenser -	3.93 ft^3
Lines	$\underline{.83 \text{ ft}^3}$
	4.76 ft^3

(This is actually an optimistic assumption since about 98% of the gases evolving from the dump tanks is D_2O vapor, and some volume of the reflux condenser is needed to condense this vapor). It is assumed that when the pressure reaches 500 psi in the dump tank system it will be necessary to vent the gases. The number of lb mols of gas needed to raise the pressure to 500 psi in the dump tanks is given by the gas law.

$$n = \frac{PV}{RT} = 0.330 \text{ lb. mol.} \quad (7)$$

where $P = 500 \text{ psi}$

$$V = 4.76 \text{ ft}^3$$

$$R = 10.73 \text{ psi-ft}^3/(\text{lb.-mol } ^\circ\text{R})$$

$$T = 212^\circ\text{F} \rightleftharpoons 672^\circ\text{R.}$$

Substituting this value for n in equation (6) the time required for the pressure to build up to 500 psi can be computed in terms of t_1 and P_0 . Some times are given in Table II.

Table II
Time Required for Pressure in Outer Dump Tank System
to Reach 500 psi (with no venting)

t_1 , hrs.	Time to Build Pressure to 500 psi	
	for $P_0=10$ Mw.	For $P_0=5$ Mw.
1	5.8	11.6
10	7.6	15.2
24	8.9	17.8
48	10.0	20.0
100	11.6	23.2

The amount of radiation (in curies) which must be vented (for $P_0 = 10$ Mw) in this case is given as a function of time in Figure (2). Again the activity is much too great (for reasonable build-up pressures) to be vented directly to the stack. Equations for estimating the radiation of Figure (2) are derived in Appendix A.

A third method to handle the radiation problem is to provide a special charcoal bed for the outer dump tanks. It is considered inadvisable to use the main charcoal beds, because of the large flow and explosive nature of the radiolytic gas. The design of a special charcoal bed might prove attractive if it could be made small enough ($< \sim 15$ -20 ft. of 1" piping) to be placed in the east valve pit. A bed this small could easily be built to withstand a possible radiolytic gas explosion. The holdup volume (for xenon) of a given amount of charcoal, however, varies inversely with the total gas flow rate through the bed. Since the radiolytic gas flow rate is large compared to the flow rate of oxygen through the main charcoal beds (~ 1 liter (STP)/min) it is very improbable that a bed designed for the outer dump tanks will be smaller in volume than the main beds.

Since the bed will not be used continuously it will be profitable to estimate the volume of charcoal needed to provide a xenon breakthrough time of one day as a function of bed temperature, with time after shutdown as a parameter. If the adsorption rate of xenon on charcoal is assumed to be very rapid so that equilibrium is reached instantly, and if radioactive decay is ignored, a vertical adsorption front will move through the bed. The time required for this front to arrive at the end of the bed is the breakthrough time and is given theoretically by ⁽⁴⁾

$$t_B = \frac{HP}{f} \frac{V}{f} \quad (8)$$

where t_B = breakthrough time, hrs.

$$H = \frac{\sqrt{x_e}}{P x_e}$$

$\sqrt{x_e}$ = volume of xenon adsorbed per unit weight of charcoal, $\frac{\text{ft}^3(\text{STP})}{\text{lb.}}$

P_{xe} = pressure of xenon, mm Hg.

P = total pressure, mm Hg.

V = bed volume, ft^3

ρ = bulk density of charcoal, lbs/ft^3

f = total flow rate of gas, $\text{ft}^3(\text{STP})/\text{hr}$.

For a breakthrough time of 24 hrs (1 day) the average value for f can be found using equation (6)

$$f_{\text{avg.}} = \frac{359 \left\{ 1.30 \times 10^{-5} P_o \left[(t_1 + 86,400)^{0.8} - t_1^{0.8} \right] \right\}}{24}$$

$$\text{or } f_{\text{avg.}} = 1.94 \times 10^{-4} P_o \left[(t_1 + 86,400)^{0.8} - t_1^{0.8} \right] \quad (9)$$

The bulk density for charcoal is taken as $25 \text{ lbs}/\text{ft}^3$ and the total pressure as one atmosphere or 760 mm Hg. Solving equation (8) for V and substituting equation (9) for f

$$V = \frac{2.45 \times 10^{-7} P_o \left[(t_1 + 86,400)^{0.8} - t_1^{0.8} \right]}{H} \quad (10)$$

The value of H will depend upon the temperature of the bed. Values of H used in this calculation were taken from CF-55-9-12⁽⁵⁾ and are given below:

Temperature of Bed, $^{\circ}\text{C}$	$H_{xe} \frac{\text{ft}^3 x_e \text{ absorbed}}{\text{lb(charcoal)-mm Hg}}$
-60	0.14
0	.026
50	.0067
100	.0019

The volume of the charcoal bed, V , (found from eq. (10)) is plotted versus bed temperature for various values of t_1 in Figure 3. The long term power before shut-down is assumed to 10 Mw. (For 5 Mw the bed volume should be divided by 2).

If the non-adsorbed gas has no effect on the rate of transport of the adsorbed gas, then the holdup time of the bed will equal the breakthrough time. This is assumed here and Fig. 3, therefore, represents holdup time also.

Consider, for example, the following case:

Let $t_1 = \text{one day}$

$T = 50^\circ\text{C}$ bed temperature

$P_0 = 10 \text{ Mw}$

In this case it would be reasonable to want a holdup time of 10 days in the charcoal bed. From Fig. 3 the volume of bed needed for one day holdup is 2.4 ft^3 . For 10 days holdup the volume would be about ten times as great or 24 ft^3 . This is equivalent to 120 ft. of 6" schedule 40 pipe filled with charcoal.

The values for the bed volume given in Figure 3 should be considered as indicative of the order of magnitude, only, since they are based on the theoretical equation for the breakthrough time of xenon. The effect of other gases present, particularly deuterium and oxygen, have been neglected except in calculating the total gas flow rate. More reliable equations to use would be ⁽⁴⁾:

For breakthrough time

$$t_B = \frac{K_B V}{f} \quad (11)$$

and For holdup time, t_H ,

$$t_H = \frac{K_H V}{f} \quad (12)$$

where K_B = experimentally determined constant (dimensionless) evaluated by passing the adsorbable gas through a bed free of this gas.

K_H = experimentally determined constant (dimensionless) evaluated by passing the adsorbable gas through a bed already saturated with the gas.

The calculations indicate that a very large bed would be required to holdup the xenon until it had decayed to a safe level of activity permissible in the stack. Another big disadvantage is that a highly explosive mixture of deuterium and oxygen is flowing through the bed. As the xenon decays, cesium is formed. Enough cesium may be deposited on the charcoal to catalyze the recombination process, and initiate an explosion in the bed. The use of a charcoal bed on a gas stream containing deuterium and oxygen should be considered hazardous.

A fourth method of handling the radioactivity from the storage tanks is through the use of a recombiner. The off gases from this recombiner can then be sent through the main charcoal beds as was considered earlier, or else they can be held in the outer dump tank system until the activity is sufficiently low to vent directly to the stack. The recombiner, which shows the most promise at the present time is a natural circulation recombiner. Such a recombiner has been designed and the material

is available to build it. Operating data on a natural circulation recombiner is desirable as this type recombiner is being considered for homogeneous reactor designs of the future. My recommendation is to proceed with the natural circulation recombiner program and if it proves applicable, to use it on the fuel outer dump tanks.

If the natural circulation recombiner proves inadequate or is too large to be placed inside the shield, it may be necessary to use the platinized tube insert in the reflux condenser. The design in this case should include electrical heating units for the tube and means for repair or replacement of the units.

A third type of recombiner which might prove applicable is a flame recombiner. Such a recombiner was used on the HRE. The gas leaving the reflux condenser is essentially a stoichiometric mixture of deuterium and oxygen and a flame recombiner should work well under these conditions.

APPENDIX A
Derivation of Equations to Estimate Radiation from
Outer Dump Tanks.

The number of atoms of Br-83, I-133 and I-135 present at time of reactor shut-down can be estimated from the equation (for equilibrium)

$$\frac{dN}{dt} = 0 = \gamma \sum_f \phi - \lambda N \quad 1-A$$

where N = number of atoms

γ = fission yield of isotope

$\sum_f$ = macroscopic cross section of fuel

ϕ = neutron flux

λ = decay constant

Solving for N (at equilibrium)

$$N_{eq} = \frac{\gamma \sum_f \phi}{\lambda} \quad 2-A$$

If the fuel solution is transferred to the outer dump tanks after a time, t_1 , the number of parent isotopes present is given by

$$N(t_1) = N_{eq} e^{-\lambda t_1} \quad 3-A$$

Some values of interest here are:

Isotope	$\gamma, \frac{\text{atoms}}{\text{fission}} (2)$	$\lambda, \text{sec}^{-1} (2)$	$N_{eq}, \text{atoms (for } P_0=10 \text{ Mw)}$
Br-83	0.00468	8.37×10^{-5}	1.89×10^{19}
I-133	0.0662	9.25×10^{-6}	2.42×10^{21}
I-135	0.0560	2.89×10^{-5}	6.55×10^{20}

In deriving the isotope equations let

r_i = rate of formation of gaseous isotope i , atoms/sec

$\mathcal{V}$ = volumetric flow rate (total) of gas, ft^3/sec , (see Table I).

V_T = total volume hold-up in lines running from the outer dump tanks reflux condenser to the east valve pit (outside main shield). $\cong 0.83 \text{ ft}^3$.

f = fraction of iodine decaying to xenon

γ_i = rate at which radioactive isotope i leaves the shielded area, atoms/sec

subscripts 13 = refer to X_e -133 isotope with 2.3 day half life

23 = refer to X_e -133 isotope with 5.27 day half life

15 = refer to X_e -135 isotope with 15.6 min. half life

25 = refer to X_e -135 isotope with 9.13 hr half life

Kr = refer to Kr-83 isotope

Br = refer to Br-83 isotope

I_3 = refer to I-133

I_5 = refer to I-135

The rate of formation of Kr-83 equals the rate of decay of Br-83

$$r_{kr} = N_{Br}^{(t)} \lambda_{Br} = \left\{ N_{Br(eq)} e^{-\lambda_{Br} t} \right\} \lambda_{Br} \quad 4-A$$

Xenon isotopes are formed from I-133 and I-135 according to equations (2) and (3). The rates are

$$r_{13} = f_{13} \lambda_{I_3} N_{eq}(I_3) e^{-\lambda_{I_3} t} \quad 5-A$$

$$r_{23} = f_{23} \lambda_{I_3} N_{eq}(I_3) e^{-\lambda_{I_3} t} \quad 6-A$$

$$r_{15} = f_{15} \lambda_{I_5} N_{eq}(I_5) e^{-\lambda_{I_5} t} \quad 7-A$$

$$r_{25} = f_{25} \lambda_{I_5} N_{eq}(I_5) e^{-\lambda_{I_5} t} \quad 8-A$$

Case I - Outer Dump Tank Vent Valves Open

The rates at which Kr-83, 2.3 day X_e -133 and 15.6 min X_e -135 leave the shielded area (i.e. enter the east valve pit) are

$$\gamma_{Kr} = r_{Kr} e^{-\lambda_{Kr} \frac{V_T}{V}} \quad 9-A$$

$$\gamma_{13} = r_{13} e^{-\lambda_{13} \frac{V_T}{V}} \quad 10-A$$

$$\gamma_{15} = r_{15} e^{-\lambda_{15} \frac{V_T}{V}} \quad 11-A$$

Since 2.3 day X_e -133 and 15.6 min X_e -135 decay into 5.27 day X_e -133 and 9.13 hr X_e -135, respectively, there is an additional term in the rate equations for these isotopes. The half-life of 2.3 day X_e -133 is long compared to the time $\frac{V_T}{v}$ so for X_e -133 this additional source will be neglected. Then

$$\gamma_{23} = r_{23} e^{-\lambda_{23} \frac{V_T}{v}} \quad 12-A$$

In the case of X_e -135, however, the decay of 15.6 min X_e -135 into 9.13 hr X_e -135 during the time $\frac{V_T}{v}$ cannot be neglected. To determine the importance of this source, let

V = volume

X_{e15} = concentration of 15.6 min. X_e -135, atoms/unit volume

$\frac{V}{v}$ = time after decay of Iodine in fuel solution

Consider the element dV in volume holdup. Then atoms of 9.13 hr X_e -135 formed in $dV = X_{e15} \lambda_{15} dV$

But

$$X_{e15} = \frac{r_{15} e^{-\lambda_{15} \frac{V}{v}}}{v}$$

Atoms of 9.13 hr X_e -135 leaving shielded area which were formed in $dV =$

$$\begin{aligned} &= \left[X_{e15} \lambda_{15} dV \right] e^{-\lambda_{25} \left(\frac{V_T - V}{v} \right)} \\ &= \frac{r_{15} \lambda_{15}}{v} e^{-\left\{ \frac{V}{v} (\lambda_{15} - \lambda_{25}) + \frac{V_T}{v} \lambda_{25} \right\}} dV \end{aligned}$$

Then the total number of atoms of 9.13 hr X_e -135 leaving the shielded area per unit time, which were formed in $V_T =$

$$\begin{aligned} &= \frac{r_{15} \lambda_{15}}{v} e^{-\frac{V_T}{v} \lambda_{25}} \int_0^{V_T} e^{\frac{V}{v} (\lambda_{25} - \lambda_{15})} dV \\ &= \frac{r_{15} \lambda_{15} e^{-\frac{V_T}{v} \lambda_{25}}}{\lambda_{25} - \lambda_{15}} \left[e^{\frac{V_T}{v} (\lambda_{25} - \lambda_{15})} - 1 \right] \end{aligned}$$

The rate (total) at which 9.13 hr X_e -135 atoms leave the shielded area is

$$\gamma_{25} = r_{25} e^{-\lambda_{25} \frac{V_T}{V}} + \frac{r_{15} \lambda_{15} e^{-\frac{V_T}{V} \lambda_{25}}}{\lambda_{25} - \lambda_{15}} \left[e^{\frac{V_T}{V} (\lambda_{25} - \lambda_{15})} - 1 \right] \quad 13-A$$

Let c = rate of radiation release, curies/sec.

$$C = \text{number of curies.} = 3.7 \times 10^{10} \text{ C} \frac{\text{disintegrations}}{\text{sec.}}$$

The rate of radiation release to the stack then is

$$c = \frac{\sum_i \gamma_i \lambda_i}{3.7 \times 10^{10}} \quad 14-A$$

Some values of constants used in determining radiation are given below (2)

<u>Isotope</u>	<u>Half-Life</u>	<u>Decay Constant, sec⁻¹</u>	<u>f</u>
Kr-83	114 min.	1.01×10^{-4}	1
X_e -133	2.3 day	3.49×10^{-6}	0.024
X_e -133	5.27 day	1.52×10^{-6}	0.976
X_e -135	15.6 min.	7.40×10^{-4}	0.30
X_e -135	9.13 hr.	2.11×10^{-5}	0.70

Some gamma radiation is given off from the gases emanating from the fuel solution. Assuming a line source (1/2" pipe) the radiation at a distance of one foot from the line is given by

$$D_L = 17.8 C_L E \quad 15-A$$

where D_L = radiation dose in r/hr.

C_L = rate of radiation release, curies/ft of pipe.

E = energy of γ -emission, mev/photon.

Case II - Outer Dump Tanks Vent Valves Closed.

If the outer dump tanks are closed off while the fuel is stored there the following process will occur:

- 1) The pressure will build up due to radiolytic gas production.
- 2) Radioactive Kr-83, Xe-133, and Xe-135 will build up from the decay of Br-83, I-133 and I-135 respectively.

The rise in pressure is fast enough so that the system must be vented periodically (see Table II). To determine the amounts of radioactivity which will be present as a function of time, the rates of activity buildup can be found from the isotope build-up equations. The rates at which Kr-83, 2.3 day Xe-133 and 15.6 min. Xe-135 buildup are found from the differential equation

$$\frac{dN_i}{dt} = N_j \lambda_j - N_i \lambda_i = N_{oj} \lambda_j e^{-\lambda_j t} - N_i \lambda_i \quad 16-A$$

where subscript i refers to gaseous (daughter) isotope

j refers to parent isotope.

N_o = number of parent atoms present at time fuel is transferred to outer dump tanks (i.e. $N_o = N_{eq} e^{-\lambda t_1}$)

t = time, seconds, measured from time the fuel is transferred to the outer dump tanks.

Solving equation 16-A for N_i

$$N_i = \frac{f_i N_{oj} \lambda_j}{\lambda_i - \lambda_j} \left[e^{-\lambda_j t} - e^{-\lambda_i t} \right] \quad 17-A$$

Let subscript 1 refer to 2.3 day Xe-133 and 15.6 min Xe-135

2 refer to 5.27 day Xe-133 and 9.13 hr Xe-135

The rates at which 5.27 day Xe-133 and 9.13 hr Xe-135 build up are given by

$$\begin{aligned} \frac{dN_{i2}}{dt} &= f_{i2} N_j \lambda_j + N_{i1} \lambda_{i1} - N_{i2} \lambda_{i2} \\ &= f_{i2} N_{oj} \lambda_j e^{-\lambda_j t} + \frac{f_{i1} N_{oj} \lambda_j \lambda_{i1}}{\lambda_{i1} - \lambda_j} \left[e^{-\lambda_j t} - e^{-\lambda_{i1} t} \right] - N_{i2} \lambda_{i2} \end{aligned} \quad 18-A$$

16.

Solving for N_{12}

$$N_{12} = \frac{A}{\lambda_{12} - \lambda_j} \left[e^{-\lambda_j t} - e^{-\lambda_{12} t} \right] - \frac{B}{\lambda_{12} - \lambda_{11}} \left[e^{-\lambda_{11} t} - e^{-\lambda_{12} t} \right] \quad 19-A$$

$$\text{where } A = N_{0j} \lambda_j \left[\frac{\lambda_{11} - f_{12} \lambda_j}{\lambda_{11} - \lambda_j} \right]$$

$$B = \frac{f_{11} N_{0j} \lambda_j \lambda_{11}}{\lambda_{11} - \lambda_j}$$

The total number of curies at time t is

$$C(t) = \frac{\sum_i N_i(t) \lambda_i}{3.7 \times 10^{10}}$$

20-A

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Figure 1

Figure 2

Approximate Volume of Charcoal Required For a Breakthrough Time or Holdup Time of One Day Versus Temperature of Bed

(For Gases Directly off the Outer Dump
Tanks of the HRT)

Volume, ft.³

Figure 3