MASTER

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YANKEE ATOMIC ELECTRIC COMPANY
RESEARCH AND DEVELOPMENT PROGRAM

FISSION AND CORROSION PRODUCT
ACTIVITIES IN MAIN COOLANT AND
ATMOSPHERE OF THE VAPOR CONTAINER

MAY 15, 1958

WESTINGHOUSE ELECTRIC CORPORATION
ATOMIC POWER DEPARTMENT

PITTSBURGH, 30

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Yankee Atomic Electric Company
Research And Development Program

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FISSION AND CORROSION PRODUCT
ACTIVITIES IN MAIN COOLANT
AND ATMOSPHERE OF THE VAPOR CONTAINER

by

H. S. Kresny

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For The Yankee Atomic Electric Company
Under Research and Development Subcontract
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I. Abstract

Fission products, which may leak from the fuel and activated corrosion products from stainless steel surfaces influence the design of several systems which support the main coolant system. Since the radioactivity in the main coolant resulting from these impurities must be limited to reasonable levels during operation, a purification system becomes important. Air conditioning of the vapor container as a result of possible main coolant leakage may be necessary during and after operation to remove airborne activity. After shutdown treatment and disposal of active effluents becomes the function of a waste disposal system.

Activities are tabulated, by individual isotopes, for 10,000 hours of full power operation.

II. Introduction

In order to formulate a basis for the design of those systems directly concerned with the removal and processing of radioactivity in the Yankee Atomic Electric Plant, the sources of activity and their nature must be known. The purpose of this report is to give the calculated magnitude of these sources and to show how they affect the design of the following systems:

- a. Main Coolant Purification System
- b. Radioactive Waste Disposal System
- c. Vapor Container Air Conditioning System

These systems support the main coolant system and function as follows:

- a. The Purification System receives, by continuous bleed from the main coolant, fission products, corrosion products, and a small percentage of the chemical shutdown additives.
- b. The Waste Disposal System receives all radioactive effluents and contains, treats, and disposes of radioactive waste from the plant.
- c. The Vapor Container Air Conditioning System removes airborne activity from the plant container which may result from leakage of main coolant. The system limits the airborne activity to an optimum level which can be reduced to tolerance within 8 to 10 hours after reactor shutdown.

The overall purpose of these systems is to limit any radioactivity which might leave the plant to the maximum permissible tolerances prescribed by the Atomic Energy Commission.⁽⁴⁾

There are two major sources of activity in the plant which affect the design of the aforementioned systems. These sources are fission products in the fuel and corrosion products from the stainless steel surfaces in contact with the main coolant.

1. Fission Products

As a result of the fission of U-235 contained in the fuel, fission fragments are formed which by beta and gamma emission decay to fission products. Although the stainless steel fuel cladding is carefully inspected and tested some leakage of fission products may occur through minor defects. These defects can be in the form of pinholes, small cracks or other minor imperfections in the cladding.

2. Corrosion Products

Effectively two sources of corrosion products contribute to the main coolant radioactivity. These are:

- a. Products of corrosion from normally inactive surfaces in low or zero neutron flux regions.
- b. Products of corrosion which have their origin on surfaces located in high neutron flux regions.

Both types present the same problem. The difference is the effective flux which induces the activities and the irradiation time. This difference is discussed further in this report.

Both the fission products and the corrosion products add to the main coolant radioactivity increasing the total above the intrinsic N-16 activity. If these impurity activities were allowed to build up unchecked, they would eventually become a shielding problem. The use of a purification system therefore becomes important not only to help prevent fouling of heat transfer surfaces and clogging of moving parts but also to limit the coolant impurity activity to a level less than the N-16 equilibrium level.

III. Plant Design Data

Core(*)

"Active" Heat Transfer Surface, ft ²	17,300
Fuel Rods	
UO ₂ Fuel Pellets, diameter, in.	0.300
Outside Diameter, in.	0.335
Tube Wall Thickness, in.	0.015
Number per Cross Section	23,218
Rods per Fuel Assembly	305 & 306
Total Number of Fuel Assemblies	76
Power (heat) MW.	480
Lifetime, Hr.	10,000
Core Active Height, (Between Fuel Ends) in.	102
Water Volume, in ³ .	223,000
Average Thermal Neutron Flux in Core, n/cm ² /sec,	2.77×10^{13}
Average Fast Neutron Flux in Core, n/cm ² /sec,	2.6×10^{14}
(Calculated from Wanda Code output data)	

Plant

Water Volume of Main Coolant, ft ³	2,910
Total Wetted Surface Area of Main Coolant, ft ²	100,000
Plant Container Volume, ft ³	800,000

* Yankee Atomic Electric Company, Reference Design (5)

IV. Basis for Calculating the Activities in the Main Coolant

A. Fission Products

The accumulation of fission products resulting from the fission of U-235 in the fuel must be considered in the design of the overall reactor plant. Apart from their contribution to neutron absorption, they are a potential source of activity in the main coolant, vapor container and ultimately in the waste disposal system. Shielding of components and piping, vapor container air conditioning, waste disposal system, and purification system designs are in part or wholly dependent upon the amount of fission products in the main coolant.

1. Assumptions

- a. One percent of the fuel rods have defects and release fission products to the main coolant for the full lifetime of the core.
- b. There is no independent fission yield for the secondary members of a chain unless otherwise noted.
- c. The values of the escape rate coefficient, λ , found for PWR fuel rods⁽⁶⁾ are applicable to the Yankee fuel rods.
- d. No fission products having fission yields less than 0.1% are considered.
- e. The water replacement rate is negligible.
- f. Time of operation is 10,000 hrs.
- g. The purification flow rate is 10 GPM with a resin efficiency of 100%.
- h. All calculations are based on the original reference core⁽⁵⁾ with an active length between fuel ends of 8.5 ft.
- i. Fission products resulting from the fission of Plutonium in the fuel do not alter the activities calculated for the fission products of U-235.

2. Nomenclature

Subscript i - First members of chain

Subscript j - Second members of chain

N_c = Number of atoms in defective fuel rods.

N_w = Concentration of atoms in main coolant, atoms/ml

F = Fission rate, fission/sec/rod

Y = Fission yield, atoms/fission.

λ = Decay constant, sec^{-1}

ν = Escape rate coefficient, sec^{-1}
 σ = Thermal neutron absorption cross section, cm^2
 ϕ = Average thermal flux in core - 2.77×10^{13} , $\text{n/cm}^2\text{-sec}$
 t = Time of operation, sec
 V_w = Main Coolant volume, 8.2×10^7 ml
 Q = Purification flow rate, ml/sec
 ω = Water replacement rate, sec^{-1}
 n = Number of rods having defects

3. Activity in Fuel

The rate of change of fission products in the fuel, using the method described by Kesten and Lindsay⁽⁷⁾, is given by:

$$(1.) \frac{dN_{ci}}{dt} = nFY_i - (\lambda_i + \nu_i + \sigma_i\phi) N_{ci}$$

For first members

$$(2.) \frac{dN_{cj}}{dt} = nFY_j + \lambda_i N_{ci} - (\lambda_j + \nu_j + \sigma_j\phi) N_{cj}$$

For second members

The fission product activity at any time t in the fuel is given by:

$$(3.) \lambda_i N_{ci} = \frac{nFY_i \lambda_i}{\lambda_i + \nu_i + \sigma_i\phi} \left[1 - e^{-(\lambda_i + \nu_i + \sigma_i\phi)t} \right] \text{dis/sec}$$

$$(4.) \lambda_j N_{cj} = \frac{nFY_i \lambda_i \lambda_j}{(\lambda_i + \nu_i)(\lambda_j + \nu_j + \sigma_j\phi_c)} \left[1 - e^{-(\lambda_i + \nu_i)t} \right] \text{dis/sec}$$

4. Escape Rate Coefficients

The escape rate coefficient, ν , contained in the equations of fission product buildup in the fuel describes the escape of the fission products from the fuel to the main coolant. Several tests⁽⁶⁾ conducted in the X-1 Loop at the NRX Reactor, Atomic Energy of Canada Limited, determined the magnitude of this parameter for fission products escaping through small defects in the PWR fuel cladding. The results of these tests are shown in Figure 1 and Table 1.

Three mechanisms govern the release of fission products from the fuel rods. These are discussed in the order of their importance.

a. Diffusion

The fission products concentrated in the fuel pellets will diffuse to the surface of the fuel by a process which is proportional to the concentration of the isotopes in the fuel. If any defects are present in the fuel cladding, fission products will diffuse through these small cracks or pinholes and accumulate in the main coolant.

The rate of escape by the diffusion type mechanism is given by:

$$(5.) \quad \frac{dN_d}{dt} = \gamma N_c$$

Where N_d = Total atoms in water as a result of the diffusion escape mechanism.

N_c = Total atoms of isotope N in the fuel.

γ = Escape rate coefficient in sec^{-1}

b. Fission Product Recoil

Fission product recoil from the surface of the fuel is not important when only small defects exist in the cladding. The rate at which fission products recoil from the surface of the fuel is given by: (6)

$$(6.) \quad \frac{dN_r}{dt} = \frac{FY l_f \xi (2 - \xi)}{d}$$

where

N_r = Total atoms in water as a result of the recoil escape mechanism.

F = Fissioning rate per rod

Y = Fission yield of isotope N

l_f = Recoil length of fission product in fuel

d = Diameter of fuel

ξ = h/l_s if $h \leq l_s$; if $h > l_s$, $\xi = 1$

h = Radial clearance between fuel and cladding at operating conditions

l_s = Recoil range of fission products in steam

Table 1

ESCAPE RATE COEFFICIENTS⁽⁶⁾

Group	Elements	τ sec ⁻¹
I	Cs, I, Xe, Kr, Rb, Br	1.3×10^{-8}
II	Sr, Ba	1.0×10^{-11}
III	Zr, Ce, other rare earths	1.6×10^{-12}
IV	Te	1.0×10^{-9}
V	Mo	2×10^{-9}

ESCAPE RATE COEFFICIENT ν , VS
TIME FROM START OF TEST *

FIGURE 1

• Reproduced from WAPD-TM-29 Radiochemistry of Third PWR Fuel Material
Test X-1 Loop, NRX Reactor - February 1, 1957

c. Fuel Fragmentation

Small fragments of UO_2 can break from the pellets and carry associated fission products from the fuel to the main coolant. This mechanism will not contribute significantly to the activity of the main coolant, because high density UO_2 (90% of theoretical) is stable under the conditions imposed by a defect in the cladding.

The results of the tests conducted in the NRX Reactor indicate that the diffusion process best describes the fission product activity in the system. As a consequence all isotopes of the same element and their daughters having half lives greater than 1/4 hour have, within experimental error, the same escape rate coefficient. The present data indicate that fission products can be placed in three distinct groups according to their escape rate coefficients. Only Tellurium and Molybdenum thus far, do not fit into this grouping. Table 1 gives values for the escape rate coefficient which represents only that fraction of the total released activity that is in solution at any given time, excepting the value for Tellurium. It has been found in neutral pH systems that the Tellurium which escapes from the fuel is rapidly deposited on pipe surfaces so that little if any is ever found in the main coolant. Therefore the escape rate for Te represents the total Te escaping and being deposited on the pipe surfaces.

Although the escape rate coefficients shown in Table 1 apply to PWR fuel elements, the similarity of the fuel used in PWR and Yankee justifies the use of these coefficients. In both cases the fuel is UO_2 , sintered and pressed to above 90% of theoretical density. Since the diffusion mechanism seems to control the fission product activity leaving the fuel and the fuel composition and dimensions are almost identical it can be assumed that the mode of escape from the Yankee fuel rods will be the same as from PWR fuel rods. The difference in cladding material should not affect the escape since the defect represents very little additional resistance to escape compared with diffusion through the fuel.

Since the elements of Group I are weakly adsorbed on pipe surfaces⁽⁶⁾, these values for λ represent the total activity which escapes from the core. The greater fraction of the elements in Group II and V that escape are deposited on the loop surfaces. Therefore the accuracy of the calculation of Sr, Ba, Mo activities in the main coolant using these escape rate coefficients depends on the area/volume ratio of the loop. The approximate loop parameters for the X-1 Loop and the Yankee main coolant system are shown in Table 2.

Table 2

Loop Parameters and Area - Volume Ratios

<u>Loop</u>	<u>Area (wetted)</u>	<u>Volume</u>	<u>Area/Volume</u>
Yankee	100,000 ft ²	2,910 ft ³	34
X-1	99 ft ²	1.84 ft ³	54

The main coolant activity calculations do not take into account the effect of the area/volume ratio difference between Yankee and the X-1 Loop.

5. Radioactivity in the Main Coolant

The rate of change of the activity resulting from the escape of the fission products from the fuel is given by the following equations:

$$(7.) \quad \frac{dN_{wi}}{dt} = \frac{\gamma_i N_{ci}}{V_w} - (\lambda_i + \frac{Q}{V_w} + \int + \phi_a) N_{wi}$$

For first members.

$$(8.) \quad \frac{dN_{wj}}{dt} = \frac{\gamma_j N_{cj}}{V_w} + \lambda_i N_{wi} - (\lambda_j + \frac{Q}{V_w} + \int + \phi_a) N_{wj}$$

For second members.

The activity in the main coolant at any time t is:

$$(9.) \quad \lambda_i N_{wi} = \frac{n F Y_i \gamma_i \lambda_i}{V_w (\lambda_i + \gamma_i + \phi_a)} \left\{ \left[\frac{1}{\frac{Q}{V_w} + \int - \gamma_i} - \frac{1}{\lambda_i + \frac{Q}{V_w} + \int + \phi_a} \right] \left(e^{-(\lambda_i + \frac{Q}{V_w} + \int + \phi_a)t} - e^{-(\lambda_i + \gamma_i + \phi_a)t} \right) + \frac{1}{\lambda_i + \frac{Q}{V_w} + \int + \phi_a} \times \right. \\ \left. \left(1 - e^{-(\lambda_i + \gamma_i + \phi_a)t} \right) \right\} \frac{\text{dis}}{\text{ml} - \text{Sec}}$$

For first members.

$$\begin{aligned}
(10.) \quad \lambda_j N_{wj} = & \frac{\lambda_j nF}{V_w} \left\{ \frac{\nu_j Y_j}{B_j} \left[\frac{1 - e^{-(C_j + A_j)t}}{C_j + A_j} \right. \right. \\
& - \left. \frac{e^{-B_j t} - e^{-(C_j + A_j)t}}{C_j + A_j - B_j} \right] + \frac{\lambda_i Y_i}{B_i} \left[\nu_j \left(\frac{1 - e^{-(C_j + A_j)t}}{B_j(C_j + A_j)} \right. \right. \\
& + \left. \frac{e^{-B_j t} - e^{-(C_j + A_j)t}}{C_j + A_j - B_j} \right) \left(\frac{1}{B_j - B_i} - \frac{1}{B_j} \right) \\
& - \left. \frac{e^{-B_i t} - e^{-(C_j + A_j)t}}{(C_j + A_j - B_i)(B_j - B_i)} \right] + \nu_i \left(\frac{1 - e^{-(C_j + A_j)t}}{(C_j + A_j)(C_i + A_i)} \right. \\
& - \left. \frac{e^{-B_i t} - e^{-(C_j + A_j)t}}{(C_j + A_j - B_i)(C_i + A_i - B_i)} + \frac{e^{-(C_i + A_i)t} - e^{-(C_i + A_i)t} - e^{-(C_j + A_j)t}}{C_j + A_j - C_i - A_i} \right. \\
& \left. \left. \times \left[\frac{1}{C_i + A_i - B_i} - \frac{1}{C_i + A_i} \right] \right) \right\} \frac{\text{dis}}{\text{ml} - \text{Sec}}
\end{aligned}$$

For second members.

$$\begin{aligned}
\text{Where} \quad A_i &= \int_i + \frac{Q}{V_w} & B_i &= \lambda_i + \nu_i + \omega_i \phi & C_i &= \lambda_i + \omega_i \phi \\
A_j &= \int_j + \frac{Q}{V_w} & B_j &= \lambda_j + \nu_j + \omega_j \phi & C_j &= \lambda_j + \omega_j \phi
\end{aligned}$$

These equations can be simplified as follows:

1. For the rare gases (Kr, Xe) the purification resin is ineffective and the term Q/V_w must be neglected.
2. In most systems leakage is negligible and so $\int$ may be neglected.
3. Except for the special case of Xe 135 which has a large thermal neutron absorption cross section, the burnout term $\omega \phi$ may be neglected.

4. For isotopes whose half lives are much smaller than the time of operation, the equations can be simplified by assuming equilibrium conditions exist in the water (production equals decay).

For cases 2 and 4 above, equations 9 and 10 can be written as:

$$(9a.) \lambda_i N_{wi} = \frac{nF Y_i \gamma_i}{V_w (\lambda_i + Q/V_w)} \frac{\text{dis}}{\text{ml-Sec}}$$

$$(10a.) \lambda_j N_{wj} = \frac{\lambda_j nFY}{V_w (\lambda_j + Q/V_w)} \left[\frac{\gamma_j}{\lambda_j} + \frac{\gamma_i}{\lambda_i + Q/V_w} \right] \frac{\text{dis}}{\text{ml-Sec}}$$

The results of calculations using these equations are tabulated in Table 5 together with the nuclear properties of the isotopes and the effects of decay and purification rates on each isotope.

B. Corrosion Products

As in any circulating water system, some corrosion of the surfaces in contact with the flowing medium will occur. In the Yankee main coolant loops all the surfaces exposed to the main coolant are stainless steel and the corrosion products will therefore be constituents of stainless steel. The corrosion rate in the plant is minimized by the addition of a corrosion inhibitor.

Two sources of active corrosion products exist in the reactor plant:

- a. Corrosion products released to the main coolant from normally inactive surfaces in the low or zero neutron flux regions.
- b. Corrosion products which originate on surfaces located in regions of high flux, such as the fuel cladding.

1. Assumptions

- a. The corrosion rate is constant from startup to shutdown.
- b. The corrosion release rate is 10 mg/dm²/mo.
- c. No deposition on the pipe and component walls is considered in these calculations.

- d. The corrosion release rate of the individual corrosion products is proportional to the elemental concentration in the stainless steel.
- e. The solubility of the corrosion products is 100%.
- f. Time of operation is 10,000 hrs.
- g. The purification flow rate is 10 GPM with a resin efficiency of 100%.
- h. All calculations are based on the original reference core (5) with an active length between fuel ends of 8.5 ft.

2. Nomenclature

N	= Parent atoms of N_w in the water, atoms/ml.
N_w	= Concentration of active atoms resulting from activation of parent atoms in water, atoms/ml.
N_p^c	= Parent atoms of Na^c in metal, atoms/cc of metal.
Na^c	= Concentration of active atoms in metal exposed to high neutron flux, atoms/cc of metal.
Na^w	= Concentration, in water, of active atoms released from metal exposed to high neutron flux, atoms/ml.
λ	= Corrosion release rate, gm/cm ² - Sec.
f	= Conversion factor, gm/cm ² - Sec. to atoms/Sec.
F	= Corrosion release rate, cm ³ /Sec.
λ	= Decay constant, Sec ⁻¹
σ_a	= Neutron absorption cross section for parent atoms, cm ² /atom.
$\bar{\Phi}$	= Time average neutron flux, n/cm ² -Sec.
Φ	= Average neutron flux in core, n/cm ² /Sec.
t	= Time of operation, Sec.
V_w	= Main coolant water volume, ml.
Q	= Purification flow rate, m./Sec.
ρ_{ss}	= Density of Stainless Steel, gm/cc.
f_n	= Natural abundance of N_p .
N_A	= Avogadro's constant.
M	= Atomic weight.
f_s	= Abundance of element in stainless steel.
K	= Release rate of active nuclides from metal surfaces, atoms/cc-Sec.

3. Corrosion From Normally Inactive Surfaces

The corrosion products which originate on the loops, steam generator, pumps, etc., are not active at the time they are released to the main coolant. As they pass through the high flux region around the core these nuclides are activated by neutron capture and decay by beta and gamma emission. The equations which describe this process are:

a. Inactive atoms in coolant.

$$(11.) \quad \frac{dN}{dt} = \frac{f\lambda}{V_W} - \left(\frac{Q}{V_W} + \sigma_a \bar{\phi} \right) N$$

Then

$$(12.) \quad N = \frac{f\lambda/V_W}{\frac{Q}{V_W} + \sigma_a \bar{\phi}} \left(1 - e^{-\left(\frac{Q}{V_W} + \sigma_a \bar{\phi} \right) t} \right) \frac{\text{atoms}}{\text{cc}}$$

b. Active atoms in coolant.

$$(13.) \quad \frac{dN_W}{dt} = \sigma_a \bar{\phi} N(t) - \left(\lambda + \frac{Q}{V_W} \right) N_W$$

and

$$(14.) \quad \lambda N_W = \lambda \sigma_a \bar{\phi} \left(\frac{f\lambda/V_W}{\frac{Q}{V_W} + \sigma_a \bar{\phi}} \right) \left\{ \frac{1}{\lambda + \frac{Q}{V_W}} \left(1 - e^{-\left(\lambda + \frac{Q}{V_W} \right) t} \right) - \frac{1}{\lambda - \sigma_a \bar{\phi}} \left(e^{-\left(\frac{Q}{V_W} + \sigma_a \bar{\phi} \right) t} - e^{-\left(\lambda + \frac{Q}{V_W} \right) t} \right) \right\} \frac{\text{dis}}{\text{ml-sec}}$$

After some time of operation, the rate of increase of activity is equal to the rate of decrease due to decay and removal by the purification system; consequently, equation (14) reduces to:

$$(15.) \quad \lambda N_W = \lambda \sigma_a \bar{\phi} \left(\frac{f\lambda/V_W}{\frac{Q}{V_W} + \sigma_a \bar{\phi}} \right) \frac{1}{\lambda + \frac{Q}{V_W}} \frac{\text{dis}}{\text{ml-sec.}}$$

The time averaged neutron flux, $\bar{\phi}$, is obtained by multiplying the average thermal flux in the high flux region (ϕ) by the ratio of the time spent by the nuclide in the high flux region (T) to the total cycle time (γ).

Then

$$(16.) \quad \bar{\phi} = \phi \frac{T}{\gamma} \quad (\text{n/cm}^2 - \text{Sec})$$

4. Corrosion From Surfaces Located in High Flux Regions

The core cladding, thermal shields, cladding on the reactor vessel walls, etc. are exposed to a high thermal neutron flux which induces activity in the steel before corrosion takes place. As a consequence many of the nuclides are radioactive before leaving the surface of the metal. The equations which describe this process are:

a. Active Nuclides in the Metal

$$(17.) \quad \frac{dN_a^c}{dt} = \mathcal{C}_a \phi N_p^c - \lambda N_a^c - K$$

The release rate of the active nuclides from the metal surface, K , is relatively small and may be neglected.

Then

$$(18.) \quad N_a^c = \frac{\mathcal{C}_a \phi N_p^c}{\lambda} (1 - e^{-\lambda t}) \quad \frac{\text{atoms}}{\text{cc of metal}}, \text{ and}$$

$$(19.) \quad N_p^c = \frac{\rho_{ss} \times f_n \times f_s \times N_A}{M} \quad \frac{\text{parent atoms}}{\text{cc of metal}}$$

b. For the Active Nuclides in the Water

$$(20.) \quad \frac{dN_a^w}{dt} = \frac{F}{V_w} N_a^c - \lambda N_a^w - \frac{Q}{V_w} N_a^w$$

$$(21.) \quad \lambda N_a^w = \frac{\lambda F}{V_w} \left(\frac{\mathcal{C}_a \phi N_p^c}{\lambda} \right) \left[\frac{1}{\lambda + \frac{Q}{V_w}} (1 - e^{-(\lambda + \frac{Q}{V_w}) t}) + \frac{1}{\frac{Q}{V_w}} (e^{-(\lambda + \frac{Q}{V_w}) t} - e^{-(\lambda) t}) \right] \quad \frac{\text{dis}}{\text{Sec} - \text{ml}}$$

5. Sources of Activity in the Stainless Steel

In the Yankee Plant all surfaces exposed to the main coolant are type 304 stainless steel. The percent analysis of this type is shown in Table 3.

Table 3

Percent Analysis of Type 304 Stainless Steel

Chromium	18-20%
Nickel	8-12
Carbon	0.08 max.
Manganese	2.00 max.
Silicon	1.00 max.
Iron	Remainder

Typical Impurities Content

Tantalum	0.01%
Niobium	0.01
Copper	0.1-0.25
Molybdenum	0.15-0.40
Tin	0.015
Boron	0.0012
Cobalt	0.2-0.3

The elements which make the major contribution to the main coolant corrosion product activity are Manganese, Cobalt, Iron and Chromium. The activity contribution of the important nuclides is given in Table 4.

The nuclides Mn-54 and Co-58 result from the fast (np) reaction with Fe-54 and Ni-58 respectively. The equations for corrosion product activities given in this section are applicable to these reactions with the following modifications.

1. The fast neutron flux instead of the thermal neutron flux must be substituted in the equations.
2. The neutron absorption cross section for the fast (np) reaction must be used.

When substituting the fast flux in the equations only the flux above the threshold energy for the reaction should be used. However since there is some uncertainty concerning the fast (np) reaction cross section for Mn-54 and Co-58 the total average fast flux was applied in these calculations. This approach predicts a higher activity contribution for these two isotopes.

Table 4

Activity Contributions of Corrosion Products

Nuclide	Thermal neutron absorption cross section of Parent Barns (corrected)	Activity from high flux region $\mu\text{c/cc}$	Activity from pipes and components $\mu\text{c/cc}$
Na-24 (8)	0.53		1.5×10^{-1}
Cr-51	10.4	7.9×10^{-1}	8.8×10^{-3}
Mn-54	0.056 (9)	1.16×10^{-1}	1.8×10^{-4}
Fe-55	1.43	1.2×10^{-1}	9.2×10^{-5}
Mn-56	9.7	1.5×10^{-1}	3.7×10^{-1}
Co-58	0.140 (9)	8.4×10^{-1}	3.8×10^{-3}
Fe-59	3.0	5.2×10^{-2}	5.1×10^{-4}
Co-60 (10m)	11.7	1.9×10^{-3}	6.4×10^{-2}
Co-60 (5yr)	12.3	7.7×10^{-2}	1×10^{-4}
Cu-64	2.9	1.23×10^{-2}	6.9×10^{-3}
Cu-66	1.45	2.68×10^{-5}	2.26×10^{-3}
Ta-182	14.3	2.8×10^{-4}	1×10^{-5}

The Na-24 activity given in Table 4 has been inferred from activity measurements taken at the Naval Reactor Testing Facility, Arco, Idaho, and appear in graphical form in reference (8). This activity is probably the result of trace impurities in the makeup water and in the main coolant.

ACTIVITIES IN THE YANKEE ATOMIC ELECTRIC PLANT MAIN COOLANT SYSTEM
FIRST MEMBER AND EFFECTIVE FIRST MEMBER FISSION PRODUCTS

TABLE 5

Isotope	Half Life	Decay Const. (sec ⁻¹)	Fission Yield %	γ Energy (MEV) Ref.	% of Disintegration Ref.	Total Gamma Energy (MEV) Ref.	Equilibrium Main Coolant Activity (Q=10 GPM) μc/cc	γ Source From Equil. Main Coolant (γ/cc/sec.)	Main Coolant Activity After 1 day Decay (μc/cc)	Main Coolant Activity After 1 week Decay (μc/cc)	Main Coolant Activity After 1 month Decay (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=50 G.P.M. (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=100 G.P.M. (μc/cc)
Kr 85	10.27 yr	2.14 x 10 ⁻⁹	0.3	0 (1)	0 (1)	0 (1)	1.51	0	1.51	1.51	1.51	1.51	1.51
Sr 90	28 yr	7.85 x 10 ⁻¹⁰	5.9	0 (1)	0 (1)	0 (1)	1.15 x 10 ⁻⁴	0	1.15 x 10 ⁻⁴	1.15 x 10 ⁻⁴	1.15 x 10 ⁻⁴	5.8 x 10 ⁻⁵	1.15 x 10 ⁻⁵
Ru 106	1.0 yr	2.20 x 10 ⁻⁸	0.38	0 (1)	0 (1)	0 (1)	5.4 x 10 ⁻⁵	0	5.4 x 10 ⁻⁵	5.31 x 10 ⁻⁵	5.08 x 10 ⁻⁵	2.7 x 10 ⁻⁵	5.7 x 10 ⁻⁵
Cs 137	26.6 yr	8.27 x 10 ⁻¹⁰	5.8	0 (1)	0 (1)	0 (1)	8.9 x 10 ⁻²	0	8.77 x 10 ⁻²	8.77 x 10 ⁻²	8.77 x 10 ⁻²	4.4 x 10 ⁻²	8.8 x 10 ⁻³
Br 84	30 min	3.85 x 10 ⁻⁴	1.1	1.9 (1) .89 (1)	16 (2) 9 (2)	2.4 (1)	8.3 x 10 ⁻³	49 28				7.7 x 10 ⁻³	7 x 10 ⁻³
Kr 85	4.4 hrs	4.41 x 10 ⁻⁵	1.5	.305 (1) .15 (1)	20 (1) 80 (1)	0.181 (1)	9.6 x 10 ⁻²		2.25 x 10 ⁻³			9.6 x 10 ⁻²	9.6 x 10 ⁻²
Kr 87	78 min	1.48 x 10 ⁻⁴	2.7	2.3 (1) 1.89 (1)	25 (1) 25 (1)	0.56 (1)	1.9 x 10 ⁻¹	1.76 x 10 ³ 1.76 x 10 ³				1.9 x 10 ⁻¹	1.9 x 10 ⁻¹
Kr 88	2.8 hrs	6.95 x 10 ⁻⁵	3.7	2.4 (1) 2.19 (1) 1.85 (1) 1.55 (1) 0.85 (1)	35 (1) 18 (1) 15 (1) 14 (1) 23 (1)	2.07 (1)	2.4 x 10 ⁻¹	3.1 x 10 ³ 1.6 x 10 ³ 1.3 x 10 ³ 1.3 x 10 ³	9.4 x 10 ⁻⁴			2.4 x 10 ⁻¹	2.4 x 10 ⁻¹
Rb 89	15.4 min	7.5 x 10 ⁻⁴	4.8	0 (1)	0 (1)	0 (1)	3.2 x 10 ⁻²	0				3.1 x 10 ⁻²	2.9 x 10 ⁻²
Sr 91	9.7 hr	1.99 x 10 ⁻⁵	5.9	1.41 (1) 1.03 (1) 0.75 (1) 0.66 (1) 0.64 (1)	7 (1) 33 (1) 7 (1) 22 (1) 33 (1)	0.845 (1)	1 x 10 ⁻³	2.6 12 2.6 8.1 12	1.84 x 10 ⁻⁴			4.7 x 10 ⁻⁴	2.9 x 10 ⁻⁴
Sr 92	2.7 hr	7.13 x 10 ⁻⁵	6.1	1.38 (2)	0 (1)	0 (1)	3.7 x 10 ⁻⁴	0				2.7 x 10 ⁻⁴	2 x 10 ⁻⁴
Y 93	10 hr	1.93 x 10 ⁻⁵	6.5	0.7 (1)	100 (1)	0.7 (1)	2.3 x 10 ⁻⁴	8.5				1.1 x 10 ⁻⁴	6.5 x 10 ⁻⁵
Y 94	16.5 min	7.0 x 10 ⁻⁴	6.5	1.4 (1)	100 (1)	1.4 (1)	1 x 10 ⁻⁵	0.37				9.5 x 10 ⁻⁶	9.1 x 10 ⁻⁶
Zr 95	63 days	1.27 x 10 ⁻⁷	6.4	0.717 (1)	98 (1)	0.733 (1)	7.4 x 10 ⁻⁴	28	7.35 x 10 ⁻⁴	6.79 x 10 ⁻⁴	5.4 x 10 ⁻⁴	1.5 x 10 ⁻⁴	7.4 x 10 ⁻⁵
Zr 97	17 hr	1.13 x 10 ⁻⁵	6.2	(1)	(1)	0.75 (1)	3.7 x 10 ⁻⁴	13.7	1.5 x 10 ⁻⁴			1.4 x 10 ⁻⁴	8.1 x 10 ⁻⁵
Mo 99	67 hr	2.88 x 10 ⁻⁶	6.1	0.780 (1) 0.740 (1)	Assume 16 Assume 16	.24 (1)	5.7 x 10 ⁻¹	3.4 x 10 ³ 3.4 x 10 ³	2.2 x 10 ⁻²	5 x 10 ⁻³		1.53 x 10 ⁻¹	8 x 10 ⁻²
Mo 101	14.6 min	7.91 x 10 ⁻⁴	5.0	0.96 (1) 0.19 (1)	70 (1) 100 (1)	0.864 (1)	6.23 x 10 ⁻³	160				6.1 x 10 ⁻³	5.7 x 10 ⁻³
Mo 102	12 min	9.63 x 10 ⁻⁴	4.2	0 (1)	0 (1)	0 (1)	4.3 x 10 ⁻³					4.2 x 10 ⁻³	4 x 10 ⁻³
Ru 103	41 days	1.96 x 10 ⁻⁷	2.9	0.498 (1)	95 (1)	0.473 (1)	4.6 x 10 ⁻⁴	17				8.3 x 10 ⁻⁵	4.6 x 10 ⁻⁵
Rh 105	36.5 hr	5.27 x 10 ⁻⁶	0.9	0.322 (1)	10 (1)	0.032 (1)	1 x 10 ⁻⁴		6.49 x 10 ⁻⁵			3 x 10 ⁻⁵	1.6 x 10 ⁻⁵

ACTIVITIES IN THE YANKEE ATOMIC ELECTRIC PLANT MAIN COOLANT SYSTEM
FIRST MEMBER AND EFFECTIVE FIRST MEMBER FISSION PRODUCTS

TABLE 5

Isotope	Half Life	Decay Const. (Sec ⁻¹)	Fission Yield %	γ Energy (MEV) Ref.	% of Disintegration Ref.	Total Gamma Energy (MEV) Ref.	Equilibrium Main Coolant Activity (Q=10 GPM) μc/cc	γ Source From Equil. Main Coolant (γ/cc/Sec.)	Main Coolant Activity After 1 day Decay (μc/cc)	Main Coolant Activity After 1 week Decay (μc/cc)	Main Coolant Activity After 1 month Decay (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=50 G.P.M. (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=100 G.P.M. (μc/cc)
I 131	8.05 d	9.96 x 10 ⁻⁷	2.9	.72 (1) 0.64 (1) 0.36 (1) 0.28 (1)	3 (1) 9 (1) 80 (1) 5.3 (1)	0.39 (1)	1.6	1.76 x 10 ³ 5.3 x 10 ³	1.5	8.9 x 10 ⁻¹	1.22 x 10 ⁻¹	3.5 x 10 ⁻¹	0.176
Te 132	77 hr	2.5 x 10 ⁻⁶	4.4	0.23 (1)	100 (1)	0.23 (1)	2.2 x 10 ⁻¹		1.77 x 10 ⁻¹	4.84 x 10 ⁻²	3.3 x 10 ⁻⁴	5.5 x 10 ⁻²	2.9 x 10 ⁻²
I 133	20.8 hr	9.25 x 10 ⁻⁶	6.5	1.4 (1) 0.85 (1) 0.53 (1)	1 (1) 5 (1) 94 (1)	0.56 (1)	2.1	7.8 x 10 ² 3.9 x 10 ³ 7.3 x 10 ⁴	9.85 x 10 ⁻¹	1.05 x 10 ⁻²		9.7 x 10 ⁻¹	0.42
Te 134	44 min	2.63 x 10 ⁻⁴	6.7	0 (1)	0 (1)	0 (1)	1.5 x 10 ⁻²					1.3 x 10 ⁻²	1.2 x 10 ⁻²
I 135	6.68 hr	2.89 x 10 ⁻⁵	5.9	1.8 (1) 1.27 (1)	50 (1) 50 (1)	1.54 (1)	9.3 x 10 ⁻¹	1.7 x 10 ³ 1.7 x 10 ³	7.82 x 10 ⁻²			5.1 x 10 ⁻¹	0.33
Xe 138	17 min	6.79 x 10 ⁻⁴	5.5	0 (1)	0 (1)	0 (1)	4.5 x 10 ⁻²	0				4.5 x 10 ⁻²	4.5 x 10 ⁻²
Cs 139	9.5 min	1.22 x 10 ⁻³	5.9	0 (1)	0 (1)	0 (1)	2.6 x 10 ⁻²	0				2.6 x 10 ⁻²	2.6 x 10 ⁻²
Ba 140	12.8 d	6.27 x 10 ⁻⁷	6.3	0.54 (1) 0.30 (1) 0.16 (1) 0.08 (1)	30 (1) 10 (1) 10 (1) 100 (1)	0.24 (1)	3.7 x 10 ⁻³	41	3.55 x 10 ⁻³	2.57 x 10 ⁻³	7.52 x 10 ⁻⁴	7.8 x 10 ⁻⁴	4.1 x 10 ⁻⁴
Ba 141	18 min	6.42 x 10 ⁻⁴	5.9	0 (1)	0 (1)	0 (1)	4.6 x 10 ⁻⁵	0				4.4 x 10 ⁻⁵	4.1 x 10 ⁻⁵
Ce 143	32 hr	6.01 x 10 ⁻⁶	6.2	0.66 (1) 0.36 (1) 0.29 (1) 0.13 (1)	15 (1) 12 (1) 61 (1) 12 (1)	0.33 (1)	4 x 10 ⁻⁴	2.3	2.35 x 10 ⁻⁴	1.16 x 10 ⁻⁵		1.2 x 10 ⁻⁴	6.6 x 10 ⁻⁵
Ce 144	290 d	2.76 x 10 ⁻⁸	6.1	0.13 (1) 0.10 (1)	10 (1) 10 (1)	0.043 (1)	5.8 x 10 ⁻⁴		5.87 x 10 ⁻⁴	1.01 x 10 ⁻⁵	5.4 x 10 ⁻⁴	1.2 x 10 ⁻⁴	5.8 x 10 ⁻⁵

ACTIVITIES IN THE YANKEE ATOMIC ELECTRIC PLANT MAIN COOLANT SYSTEM
FIRST MEMBER AND EFFECTIVE FIRST MEMBER FISSION PRODUCTS

TABLE 5

Isotope	Half Life	Decay Const. (Sec ⁻¹)	Fission Yield %	γ Energy (MEV) Ref.	% of Disintegration Ref.	Total Gamma Energy (MEV) Ref.	Equilibrium Main Coolant Activity (Q=10 GPM) μc/cc	γ Source From Equil. Main Coolant (γ/cc/Sec.)	Main Coolant Activity After 1 day Decay (μc/cc)	Main Coolant Activity After 1 week Decay (μc/cc)	Main Coolant Activity After 1 month Decay (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=50 G.P.M. (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=100 G.P.M. (μc/cc)
Pr 145	6 hr	3.21 x 10 ⁻⁵	4.2	0 (1)	0 (1)	0 (1)	8.6 x 10 ⁻⁵					4.2 x 10 ⁻⁵	3.2 x 10 ⁻⁵
Pr 146	24.4 hr	4.73 x 10 ⁻⁴	3.3	1.49 (1)	33 (1)	1.12 (1)	5.3 x 10 ⁻⁶	6.4 x 10 ⁻²				5.2 x 10 ⁻⁶	4.8 x 10 ⁻⁶
				0.75 (1)	22 (1)			4.3 x 10 ⁻²					
				0.46 (1)	100 (1)								
Total Act.							7.69 μc/cc	no removal of Kr and Xe	4.37 μc/cc	2.56 μc/cc	1.72 μc/cc	4.25 μc/cc	3.21 μc/cc no removal of Kr and Xe

ACTIVITIES IN THE YANKEE ATOMIC ELECTRIC PLANT MAIN COOLANT SYSTEM
SECOND MEMBER AND EFFECTIVE SECOND MEMBER FISSION PRODUCTS

TABLE 5

Isotope	Half Life	Decay Const. (Sec ⁻¹)	Fission Yield %	γ Energy (MEV) Ref.	% of Disintegration Ref.	Total Gamma Energy (MEV) Ref.	Equilibrium Main Coolant Activity (Q=10 GPM) μc/cc	γ Source From Equil. Main Coolant (γ/cc/Sec.)	Main Coolant Activity After 1 day Decay (μc/cc)	Main Coolant Activity After 1 week Decay (μc/cc)	Main Coolant Activity After 1 month Decay (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=50 G.P.M. (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=100 G.P.M. (μc/cc)
Rb 88	17.8 min	6.49 x 10 ⁻⁴	3.7	2.8 (1)	Assume 8.5	0.47 (1)	2.5 x 10 ⁻¹	7.9 x 10 ²				1.77 x 10 ⁻¹	1.3 x 10 ⁻¹
				1.86 (1)	Assume 8.5			7.9 x 10 ²					
				0.9 (1)	Assume 8.5			7.9 x 10 ²					
Sr 89	54 d	1.48 x 10 ⁻⁷	4.8	0 (1)	0	0 (1)	3.7 x 10 ⁻³	0	3.55 x 10 ⁻²	3.28 x 10 ⁻²	2.43 x 10 ⁻²	7.4 x 10 ⁻³	3.8 x 10 ⁻³
Y 90	64.5 hrs	2.98 x 10 ⁻⁶	5.9	1.4 (1)	0.4 (1)	0 (1)	9.5 x 10 ⁻⁴	1.4 x 10 ⁻¹	7.34 x 10 ⁻⁴	1.57 x 10 ⁻⁴		1.16 x 10 ⁻⁴	5.2 x 10 ⁻⁵
Y 91	51 min	2.26 x 10 ⁻⁴	2.4	0.55 (1)	100 (1)	0.55 (1)	4.4 x 10 ⁻⁴	16				1.89 x 10 ⁻⁴	1.02 x 10 ⁻⁴
Y 91	58 d	1.38 x 10 ⁻⁷	5.9	1.22 (1)	0.3 (1)	0 (1)	7.55 x 10 ⁻⁴	8.4 x 10 ⁻²	7.46 x 10 ⁻⁴	6.95 x 10 ⁻⁴	5.3 x 10 ⁻⁴		
Y 92	3.6 hr	5.35 x 10 ⁻⁵	6.1	0.6 (1)	(1)	0 (1)	4.4 x 10 ⁻⁴	16				2.32 x 10 ⁻⁴	
Nb 95	35 d	2.29 x 10 ⁻⁷	6.4	0.75 (1)	100 (1)	0.75 (1)	7.6 x 10 ⁻⁴	28	6.35 x 10 ⁻⁴	2.1 x 10 ⁻⁴		1.57 x 10 ⁻⁴	
Nb 97	72 min	1.6 x 10 ⁻⁴	6.2	0.75 (1)	100 (1)	0.75 (1)	3.6 x 10 ⁻⁴	13.3				1.30 x 10 ⁻⁴	7.4 x 10 ⁻⁵
				0.67 (1)	100 (1)	1.42 (1)		13.3					
Tc 101	14 min	8.25 x 10 ⁻⁴	5.0	0.3 (1)	100 (1)	0.3 (1)	9.6 x 10 ⁻³					9 x 10 ⁻³	8.3 x 10 ⁻³
Rh 106	30 Sec	2.31 x 10 ⁻²	0.38	2.41 (1)	0.25 (1)	0.25 (1)	7 x 10 ⁻⁶	6.5 x 10 ⁻⁴				7 x 10 ⁻⁶	
				1.55 (1)	0.5 (1)			1.3 x 10 ⁻³					
				1.05 (1)	2 (1)			5.2 x 10 ⁻³					
				0.87 (1)	1 (1)			2.6 x 10 ⁻³					
				0.62 (1)	12 (1)			3.1 x 10 ⁻²					
				0.51 (1)	25 (1)			6.5 x 10 ⁻²					
I 132	2.4 hr	8.02 x 10 ⁻⁵	4.4	2.2 (1)	2 (1)	1.99 (1)	4.5 x 10 ⁻¹	3.34 x 10 ²	4.3 x 10 ⁻⁴			2.24 x 10 ⁻¹	1.55 x 10 ⁻¹
				1.96 (1)	5 (1)			8.4 x 10 ²					
				1.40 (1)	11 (1)			1.8 x 10 ³					
				1.16 (1)	8 (1)			1.4 x 10 ³					
				0.96 (1)	20 (1)			3.34 x 10 ³					
				0.78 (1)	75 (1)			1.3 x 10 ⁴					
				0.67 (1)	100 (1)			1.7 x 10 ⁴					

ACTIVITIES IN THE YANKEE ATOMIC ELECTRIC PLANT MAIN COOLANT
SECOND MEMBER AND EFFECTIVE SECOND MEMBER FISSION PRODUCTS

TABLE 5

Isotope	Half Life	Decay Const. (Sec ⁻¹)	Fission Yield %	γ Energy (MEV) Ref.	% of Disintegration Ref.	Total Gamma Energy (MEV) Ref.	Equilibrium Main Coolant Activity (Q=10 GPM μc/cc)	γ Source From Equil. Main Coolant (γ/cc/Sec.)	Main Coolant Activity After 1 day Decay (μc/cc)	Main Coolant Activity After 1 week Decay (μc/cc)	Main Coolant Activity After 1 month Decay (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=50 G.P.M. (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=100 G.P.M. (μc/cc)
				0.62 (1)	6 (1)			1.0 × 10 ³					
				0.53 (1)	25 (1)			4.3 × 10 ³					
Xe 133	5.27 d	1.52 × 10 ⁻⁶	6.5	0.081 (1)	100 (1)	0.081 (1)	24		21.2	9.6	4.9 × 10 ⁻¹	24	24
Xe 133	2.3 d	3.49 × 10 ⁻⁶	0.16	0.23 (1)	100 (1)	0.23 (1)	2.74 × 10 ⁻¹						
I 134	52.5 min	2.2 × 10 ⁻⁴	7.6	1.78 (1)	35 (1)	1.27 (1)	1.85 × 10 ⁻¹	2.3 × 10 ³				1.56 × 10 ⁻¹	1.35 × 10 ⁻¹
				1.1 (1)	35 (1)			2.3 × 10 ³					
				0.86 (1)	30 (1)			2.0 × 10 ³					
Xe 135	9.13 hr	2.11 × 10 ⁻⁵	6.2	0.60 (1)	4 (1)	0.27 (1)	1.51 × 10 ⁰	2.2 × 10 ³				1.51 × 10 ⁰	1.51 × 10 ⁰
				0.37 (1)	1 (1)								
				0.25 (1)	96 (1)								
Cs 138	32 min	3.62 × 10 ⁻⁴	5.8	1.44 (1)	100 (1)	2.01 (1)	1.4 × 10 ⁻¹	5.2 × 10 ³				1.28 × 10 ⁻¹	1.14 × 10 ⁻¹
				0.98 (1)	43 (1)			2.2 × 10 ³					
				0.46 (1)	33 (1)								
Ba 139	85 min	1.36 × 10 ⁻⁴	6.0	1.43 (1)	19 (1)	0.380 (1)	2.5 × 10 ⁻²	1.8 × 10 ²				2.0 × 10 ⁻²	1.61 × 10 ⁻²
				0.16 (1)	66 (1)								
La 140	40.2 hr	4.79 × 10 ⁻⁶	6.3	3 (1)	1 (1)	2.11 (1)	2 × 10 ⁻³	7.4	1.3 × 10 ⁻³			2.4 × 10 ⁻⁴	1.03 × 10 ⁻⁴
				2.5 (1)	5.4 (1)			4.0					
				1.6 (1)	94 (1)			70					
				0.82 (1)	29 (1)			21					
				0.99 (1)	39 (1)			29					
				0.33 (1)	5.4 (1)								
La 141	3.7 hr	5.2 × 10 ⁻⁵	6.0	1.5 (1)	5 (1)	0.075 (1)	1.4 × 10 ⁻⁴	2.7 × 10 ⁻¹				9.2 × 10 ⁻⁵	6.2 × 10 ⁻⁵
Pr 143	13.7 d	5.85 × 10 ⁻⁷	6.2	0 (1)	0 (1)	0 (1)	7.8 × 10 ⁻⁴	0	7.5 × 10 ⁻²			1.61 × 10 ⁻⁴	8.2 × 10 ⁻⁵
Pr 144	17.5 min	6.6 × 10 ⁻⁴	6.1	2.19 (1)	1 (1)	0.08 (1)	8 × 10 ⁻⁴	3 × 10 ⁰				1.46 × 10 ⁻⁴	8 × 10 ⁻⁵
				1.48 (1)	2 (1)			6 × 10 ⁰					
				0.70 (1)	4 (1)			1.2 × 10 ¹					
TOTAL ACTIVITY						26.85 μc/cc	no removal of Kr and Xe		21.32 μc/cc	9.63 μc/cc	5.15 × 10 ⁻¹ μc/cc	26.23 μc/cc	26.07 μc/cc Total no removal of Kr and Xe

ACTIVITIES IN THE YANKEE ATOMIC ELECTRIC PLANT MAIN COOLANT SYSTEM
CORROSION PRODUCTS

TABLE 5

Isotope	Half Life		Decay Const. (Sec ⁻¹)	γ Energy (MEV)	Ref.	% of Disint- egration	Ref.	Total Gamma Energy (MEV)	Ref.	Equilibrium Main Coolant Activity (Q=10 GPM) μc/cc	γ Source From Equil. Main Coolant (γ/cc/Sec.)	Main Coolant Activity After 1 day Decay (μc/cc)	Main Coolant Activity after 1 week Decay (μc/cc)	Main Coolant Activity After 1 month Decay (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=50 G.P.M. (μc/cc)	Effect of Purification Rate on Main Coolant Activity Q=100 G.P.M. (μc/cc)		
Na 24	15	hr	1.3 x 10 ⁻⁵	2.75 (3)		Assume 100		4.12		1.5 x 10 ⁻¹	5.6 x 10 ³	4.29 x 10 ⁻²	6 x 10 ⁻⁵		1.21 x 10 ⁻²	3.45 x 10 ⁻³		
				1.37 (3)		Assume 100					5.6 x 10 ³							
Cr 51	27	d	3 x 10 ⁻⁷	0.32 (2)		10 (2)		0.03 (2)		8 x 10 ⁻¹	3.6 x 10 ³	8 x 10 ⁻¹	6.8 x 10 ⁻¹	4.4 x 10 ⁻¹	1.55 x 10 ⁻¹	7.9 x 10 ⁻²		
Mn 54	300	d	2.7 x 10 ⁻⁸	0.83 (2)		100 (2)		0.83 (2)		1.16 x 10 ⁻¹	4.3 x 10 ³	1.16 x 10 ⁻¹	1.16 x 10 ⁻¹	1.1 x 10 ⁻¹	2.32 x 10 ⁻²	1.16 x 10 ⁻²		
Fe 55	2.9	yr	7.6 x 10 ⁻⁹	0		0		0		1.2 x 10 ⁻¹	0	1.2 x 10 ⁻¹	1.2 x 10 ⁻¹	1.2 x 10 ⁻¹	2.4 x 10 ⁻²	1.2 x 10 ⁻²		
Mn 56	2.58	hr	7.5 x 10 ⁻⁵	3.0 (2)		0.2 (2)		1.82 (2)		5.2 x 10 ⁻¹	3.8 x 10 ¹	7.8 x 10 ⁻⁴			1.68 x 10 ⁻¹	1.03 x 10 ⁻¹		
				2.7 (2)		0.1 (2)					1.9 x 10 ¹							
				2.1 (2)		20 (2)					3.8 x 10 ³							
				1.81 (2)		30 (2)					5.8 x 10 ³							
				0.85 (2)		100 (2)					1.9 x 10 ⁴							
Co 58	71	d	1.13 x 10 ⁻⁷	0.805 (2)		100 (2)		0.805		8.4 x 10 ⁻¹	3.1 x 10 ⁴	8.4 x 10 ⁻¹	7.9 x 10 ⁻¹	6.3 x 10 ⁻¹	1.68 x 10 ⁻¹	8.4 x 10 ⁻²		
Fe 59	45	d	1.8 x 10 ⁻⁷	1.3 (2)		46		1.2		5.2 x 10 ⁻²	8.8 x 10 ²	5.2 x 10 ⁻²	4.7 x 10 ⁻²	3.3 x 10 ⁻²	1.04 x 10 ⁻²	5.2 x 10 ⁻³		
				1.1 (2)		54					1.0 x 10 ³							
				0.19 (2)		2.8					5.4 x 10 ¹							
Co 60	10.5	min	1.1 x 10 ⁻³	1.33 (2)		0.28 (2)		0		6.6 x 10 ⁻²	0				1.47 x 10 ⁻²	9.65 x 10 ⁻³		
Co 60	5.2	yr	4.2 x 10 ⁻⁹	1.33 (2)		100 (2)		2.5		7.7 x 10 ⁻²	4.6 x 10 ³	7.7 x 10 ⁻²	7.7 x 10 ⁻²	7.7 x 10 ⁻²	1.54 x 10 ⁻²	7.7 x 10 ⁻³		
				1.17 (2)		100 (2)					4.6 x 10 ³							
Cu 64	12.8	hr	1.5 x 10 ⁻⁵	1.35 (2)		0.43 (2)		0.0058		1.9 x 10 ⁻²	4.5	5.2 x 10 ⁻³			5.9 x 10 ⁻³	3 x 10 ⁻³		
Cu 66	5.1	min		1.05 (2)		9 (2)		0.095		2.3 x 10 ⁻³	11.5				4.56 x 10 ⁻⁴	2.44 x 10 ⁻⁴		
Ta 182	112	d	7.1 x 10 ⁻⁸	1.2 (3)		Assume 52		1.2		2.9 x 10 ⁻⁴	5.5	2.9 x 10 ⁻⁴	2.8 x 10 ⁻⁴	2.4 x 10 ⁻⁴	5.64 x 10 ⁻⁵	2.81 x 10 ⁻⁵		
				1.1 (3)		Assume 52					5.5							
TOTAL ACTIVITY										2.76 μc/cc		2.05 μc/cc	1.83 μc/cc	1.41 μc/cc	6.00 x 10 ⁻¹ μc/cc	3.19 x 10 ⁻¹ μc/cc		

V. The Purification System

A. Description

The purpose of the purification system is the removal of impurities from the main coolant, to prevent fouling of heat transfer surfaces, to prevent failure of mechanical devices and to concentrate as much activity on the ion-exchange resins as possible thereby decreasing the main coolant activity.

Impurities found in the coolant of pressurized water reactor systems such as Yankee can be put into two distinct groups:

1. Corrosion products resulting from the interaction of the exposed surfaces with the main coolant.
2. Fission products which may leak out of the fuel cladding.

The basis for calculating the activities in the main coolant are discussed in previous sections. This section gives a brief description of the purification system functions and evaluates the effect of purification on the main coolant activity.

Figure 2 shows a simplified diagram of the function of the purification system, where by filtration and ion exchange the activity in the water is removed. The purified water then returns to the main coolant system thereby reducing the overall activity.

B. Effect of Increased Purification Flow Rate

The flow rate through the ion-exchangers can be varied from 0, 10-100 GPM. The greater the flow the lower will be the main coolant activity. Table 6 shows the effect of purification flow rates on the total main coolant activity.

Table 6

Purification Flow Rates and Main Coolant Activities

	<u>10</u>	<u>50</u>	<u>100</u>	GPM
Fission Products $\mu\text{c/ml}$	34.54	30.48	29.28	
Corrosion Products $\mu\text{c/ml}$	2.76	6×10^{-1}	3.2×10^{-1}	
Total	37.3	31.08	29.6	

A graph of the effect of the purification flow rate on the main coolant activity is shown in Figure 3. The purification flow rate has a markedly greater effect on the corrosion product activities than on the fission product activities which in this case constitute almost the total activity in the water.

This is largely the result of Xe-133 activity in the water. Since the resin is ineffective in removing the rare gases Krypton and Xenon, their activity will not be affected by purification and so will build up to an equilibrium value which is independent of the purification flow rate.

FIGURE 2
YANKEE ATOMIC ELECTRIC PLANT
SIMPLIFIED MAIN COOLANT &
AUXILIARIES DIAGRAM

-15-

YANKEE ATOMIC ELECTRIC PLANT
EFFECT OF PURIFICATION RATE ON MAIN COOLANT ACTIVITY

FIGURE 3

180 661
199 031

VI. The Radioactive Waste Disposal System

A. Function

The waste disposal system receives and processes all radioactive effluents leaving the reactor plant. The design is based on reducing the activity of the liquid wastes sufficiently to permit their reuse as primary plant makeup water. Consequently, little liquid is discharged from the waste disposal system and any liquid leaving the plant will be at or below the tolerances prescribed by AEC Regulations. ⁽⁴⁾

The two major effluents which pass through the waste disposal system are liquids and gases. The fission and corrosion product activity of the main coolant during operation is 37.3 uc/ml of which 27.59 $\mu\text{c/ml}$ is Krypton and Xenon.

Before entering the waste disposal system, the liquid and gaseous effluents may be diluted or the activities may be reduced by increased purification. As a result the total activity from the main coolant may not pass through the system at one time. However, when all the activity from one operating period passes through the system, a total decontamination factor is required such that any activity leaving the plant will be at tolerance.

B. Methods of Disposal

Several methods of disposal are available, each requiring different maximum permissible tolerances. They are:

1. Liquid to liquid disposal
2. Liquid to solid disposal
3. Gaseous to atmospheric disposal

1. Liquid to liquid disposal suggests that radioactive liquids be diluted to the maximum permissible tolerance for disposal prescribed by the AEC Regulations ⁽⁴⁾ and passed into a body of water large enough to receive the liquid. In this case the maximum permissible concentration in water for the gross fission products is $1 \times 10^{-7} \mu\text{c/ml}$.
2. Liquid to solid disposal might be employed where disposal to a large body of water is impractical. In this case the activity can be contained in a solid medium for ultimate burial or disposal at sea. The limitations for such disposal methods are the maximum number of microcuries which can be shipped at one time and the maximum radiation from the container. The "Handbook of Federal Regulations Applying to the Transportation of Radioactive Materials, July, 1955" gives the radiation tolerance of 10 mr/hr, 1 meter from the nearest point on the source or 200 mr/hr at the surface of the container, whichever is limiting.

3. Radioactive gases, such as Krypton and Xenon which are discharged to the atmosphere must be diluted sufficiently to meet the maximum allowable concentrations in air given in the AEC Regulations.⁽⁴⁾

In order to decrease the radioactivity leaving the waste disposal system, it may be warranted to hold up the liquids and gases so that the short lived isotopes can decay to lower or possibly negligible levels of activity. The effect of decay on the main coolant activity is shown in Table 7.

Table 7

The Effect of Decay on the Main Coolant Activity

Time after Reactor Shutdown	<u>1 day</u>	<u>1 week</u>	<u>1 month</u>
Fission Product Activity $\mu\text{c/ml}$	25.68	12.19	2.24
Corrosion Product Activity $\mu\text{c/ml}$	2.05	1.83	1.41
Total $\mu\text{c/ml}$	27.73	14.02	3.65

If during operation the purification rate is increased, more activity will be concentrated on the ion-exchange resin, decreasing the burden on the waste disposal system. The effect of increased purification is shown in Table 6. At a purification rate of 100 GPM the main coolant equilibrium activity is reduced to 29.6 $\mu\text{c/ml}$. Of this 2.0 $\mu\text{c/ml}$ will remain in the water, 24 $\mu\text{c/ml}$ is Xe-133, and the remaining rare gases constitute 3.6 $\mu\text{c/ml}$. In this case the largest portion of the activity is gaseous and can probably be diluted to the atmosphere and released at the maximum permissible tolerance for air.⁽⁴⁾

VII. Vapor Container Air Conditioning System

A. Source of Airborne Activity

As in any pressurized plant, some leakage of fluid may occur past valve stems, gaskets, etc. In the Yankee Atomic Electric Plant all possible precautions to limit such leakage to the vapor container have been taken. All valves within the vapor container have either controlled leak off, or are capped to prevent leakage. The main coolant piping is welded throughout and the main circulating pumps are the canned rotor type.

In spite of these precautions, there is still a possibility that some leakage of water may occur. Since the leaking water may be radioactive as a result of corrosion product activation and fission product escape through fuel cladding, some means of atmospheric dilution or filtration must be employed to prevent excessive buildup of airborne activity in the vapor container. For this purpose an airborne activity removal system will be used to remove airborne activity from the vapor container atmosphere. This system will hereafter be referred to as the Air Conditioning System.

B. Basic Assumptions

1. One percent of the fuel rods have defects and release fission products to the main coolant for the full lifetime of the core.
2. The rate of corrosion release from the stainless steel surfaces in contact with the main coolant is $10 \text{ mg/dm}^2/\text{mo.}$
3. The purification flow rate is 10 GPM.
4. Main coolant leakage to the vapor container is at the rate of one liter per hour.
5. The fission product concentration in the leaking main coolant is equal to the equilibrium concentration in the main coolant system. Activated corrosion products are assumed to remain within the main coolant system.

C. Isotopes of Major Importance

To find the relative importance of the isotopes which may be found in the plant container atmosphere a calculation of the holdup of activity in the plant without any form of removal is helpful. The equations used for this calculation are shown below.

$$(22.) \quad \frac{dN_g}{dt} = \frac{L}{V_g} N_w - \lambda N_g$$

$$(23.) \quad \lambda N_g = \frac{L}{V_g} N_w (1 - e^{-\lambda t}) \quad \left(\frac{\text{dis}}{\text{ml} \cdot \text{Sec}} \right)$$

N_g = Airborne activity, atoms/ml

t = Time of operation, sec

L = Leak rate, ml/sec

V_g = Plant container volume, ml

N_w = Main coolant equilibrium activity, atoms/ml water

λ = Decay constant, Sec^{-1}

For the long lived isotopes such as Kr-85 which have long half lives and do not reach an equilibrium level in the main coolant. the time dependent solution for N_w , as shown on page (12) must be substituted into equation 22. Only Sr-90 will be above tolerance in the vapor container when using the time dependent solution for N_w for the long lived isotopes.

Table 8 is a comparison of the relative importance of those activities which will be above the maximum permissible concentration in the air given in the AEC Regulations. (4)

Table 8

Isotopes of Major Importance

Isotope	MPC* μc/ml of air	Fraction above MPC For Main Coolant Equilibrium Conditions (1% of fuel rods defected)
I-131	3×10^{-9}	6.6×10^3
I-133	1.4×10^{-8}	2×10^2
Sr-90	2×10^{-10}	1.19×10^2
I-135	5.7×10^{-8}	7
Te-132	2.7×10^{-7}	4.0

* Maximum Permissible Concentration (4)

Table 8 shows that iodine and strontium create the greatest ingestion hazard as a result of the low maximum allowable concentrations for these isotopes. Tellurium should not be present in the plant container in appreciable concentrations since it is readily deposited on the walls of the piping and other components in the main coolant system.⁽⁶⁾ However, for these calculations it was assumed that no deposition of Te-132 occurred.

D. Removal of Airborne Activity

Figures 4 and 5 illustrate the effect of activity removal on the airborne activity levels in the vapor container during operation and after shutdown. These curves are obtained by using the simple exponential equation involving the decay constant and the activity removal rate constant in the exponential. Figure 4 shows that a 6300 CFM removal rate, either by ventilation or filtration and adsorption of active particles, will limit the airborne activity to approximately 50 times above tolerance. By referring to Figure 5 the time to reduce the airborne activity to tolerance is about 8 hours if the same removal rate is used.

E. The Effect of Increased Purification Rates on the Air Conditioning Requirements

The effect of increasing the purification flow on the main coolant activities is shown in Table 9.

Table 9

Effect of Purification Flow Rates on Iodine and Strontium in the Main Coolant

<u>Isotope</u>	<u>Effect of Purification Rate</u>		
	Purification Rate (GPM)		
	10	50	100
	Factor (Effect)		
I-131	1.0	0.22	0.11
Sr-90	1.0	0.5	0.1

Since the Air Conditioning rate is proportional to both the leakage rate from the main coolant system and the main coolant activity (see equations on page 12) a purification rate of 100 gpm will lower the ventilation requirements by almost a factor of 10.

YANKEE ATOMIC ELECTRIC PLANT
AIRBORNE ACTIVITY REMOVAL FROM VAPOR CONTAINER AFTER SHUTDOWN

FIGURE 5

VIII. Acknowledgment

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IX. Bibliography

- (1) Blomeke, J. O. and Todd, Mary F., Uranium-235 Fission - Product Production as a Function of Thermal Neutron Flux, Irradiation Time and Decay Time. Part 1, Volume 1, ORNL-2127.
- (2) Way, K., King, R. W., McGinnis, C. L. and van Lierhout, R. Nuclear Level Schemes., USAEC, September, 1955.
- (3) Chart of Nuclides, KAPL, April, 1956.
- (4) AEC Regulations (10 CFR Part 20), "Standards for Protection Against Radiation". (1957).
- (5) Yankee Atomic Electric Company Reactor, Reference Design, YAEC-1, July 20, 1956.
- (6) Frank, Paul W., Vogel, Kenneth H. and Cohen, Paul, Radiochemistry of Third PWR Fuel Material Test X-1 Loop NRX Reactor, WAPD-TM-29, February, 1957.
- (7) Kesten, A. S. and Lindsay, W. T., Fission Product Activity Levels in PWR Primary Coolant and Reactor Plant Container Air., WAPD-PWR-CP-2245 July, 1956.
- (8) Rockwell, T., Reactor Shielding Design Manual USAEC, March, 1956.
- (9) Rochlin, R. S., Fission Neutron Activation Cross Sections, Presented before the 2nd Winter Meeting of the American Nuclear Society, New York, N. Y., October, 1957.