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SUBJECT: Activity Due to N^{16} and N^{17} in the HFIR Primary Coolant

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Summary

The concentrations of and activities due to N^{16} and N^{17} in the HFIR primary coolant water have been calculated. At the pressure vessel exit, the N^{16} activity is 3.9×10^6 dis/sec-ml and the N^{17} activity is 6.9×10^2 dis/sec-ml. Comparison of the N^{16} activity with the data obtained from the ORR water system indicates that the calculated results are slightly conservative.

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Introduction

The presence of N^{16} and N^{17} in the HFIR water coolant-moderator must be considered in the design of shielding for the primary cooling system. These short-lived isotopes are produced from the O^{16} and O^{17} in the water by high energy neutrons in n,p reactions. N^{16} has a half life of 7.35 sec, and emits 6.13 Mev gamma photons in 75.9% of its disintegrations and 7.10 Mev gamma photons in 6.1% of its disintegrations.¹ N^{17} has a half life of 4.15 sec and emits 1 Mev neutrons in almost all of its disintegrations.^{1,2}

Method of Calculation

The rate of production of N^{16} and N^{17} in the HFIR may be calculated by the use of effective threshold energies and effective cross sections.³ In this method, the rate of reaction between the oxygen and the fast neutrons is approximated by the relation:

$$\text{Reaction Rate} = \int_0^{\infty} \Sigma(E) \phi(E) dE \approx \Sigma(E') \int_{E'}^{\infty} \phi(E) dE$$

where $\Sigma(E)$ = macroscopic cross section at energy E
 $\phi(E)$ = neutron flux at energy E
 E' = effective threshold energy
 $\Sigma(E')$ = effective cross section
 $= 0$ for $E < E'$
 $= N \sigma(E')$ for $E \geq E'$

Roys and Shure¹ measured these effective values for the $O(n,p)N$ reactions and give the following results:

Reaction	E'	$\sigma(E')$
$O^{16}(n,p)N^{16}$	11.7 Mev	59 mb
$O^{17}(n,p)N^{17}$	10.0 Mev	4.2 mb

A schematic sketch of the HFIR primary cooling system is as follows:

3.

Neglecting the water flow in the region between the beryllium reflector and the pressure vessel's wall, this system may be represented by the following block diagram:

A material balance for the concentration of N^{16} or N^{17} in each region may be written. In particular, for a region j :

$$\frac{dN_j}{dt} = (\bar{\Sigma\phi})_j - \lambda N_j$$

where N_j = concentration of isotope in region j
 $(\bar{\Sigma\phi})_j$ = rate of production of isotope in region j
 λ = decay constant of the isotope
 t = time

Integrating this equation,

$$N_j = \left[N_j^0 - \frac{(\bar{\Sigma\phi})_j}{\lambda} \right] e^{-\lambda t} + \frac{(\bar{\Sigma\phi})_j}{\lambda}$$

where N_j^0 = initial concentration of isotope in region j .

This relation may be used as a continuity equation to determine the initial isotope concentration in a region immediately downstream of region j . Assuming a liquid holdup time in region j of t_j , the isotope concentration in the fluid entering region $j + 1$ is

$$N_{j+1}^0 = \left[N_j^0 - \frac{(\bar{\Sigma\phi})_j}{\lambda} \right] e^{-\lambda t_j} + \frac{(\bar{\Sigma\phi})_j}{\lambda}$$

Combining these continuity equations for the entire primary coolant circuit, the isotope concentration in the water entering the external region (that portion of the primary cooling system where the isotope production is negligible) is

$$N_e^0 = \frac{M}{1 - Le^{-\lambda t_e}}$$

where N_e^0 = initial concentration of isotope in region e
(the external region)
 t_e = liquid holdup time in region e
 M = a function of the irradiation levels and holdup times
various parts of the reactor
 L = a function of the holdup times in various parts of the
reactor.

The exact definition of the quantities M and L are shown in Appendix A. It should be noted as the holdup time in the external circuit t_e becomes very large such that

$$Le^{-\lambda t_e} \ll 1,$$

then $N_e^0 = M$.

Effective Neutron Fluxes

Since the threshold energy for the $O(n,p)N$ reactions are high (above 8.5 Mev)⁴, the source of neutrons available for these reactions are assumed to be uncollided fission neutrons. It is assumed the fission neutron spectrum can be represented by the Watt relation⁴, which is

$$n(E) = \sqrt{\frac{2}{\pi e}} \sinh \sqrt{2Ee^{-E}}$$

where $n(E)$ is the fraction of neutrons at energy E
 E is the neutron energy in Mev.

To obtain the effective neutron flux distribution along the island axis, it is assumed that the fission sources in the annular fuel space are uniform and isotropic. Therefore, the contribution of uncollided neutrons to a specific point from a source in a volume element dV is,

$$N(E) \bigg|_{dV} = \frac{e^{-\sum_{i=1}^m \Sigma_{Ti} \rho_i}}{4\pi \rho^2}$$

where Σ_{Ti} = total microscopic section in material i

ρ_i = distance through material i

ρ = total distance from the fission source to the specific point.

If the geometry of the HFIR fuel is as shown in the following sketch, the contribution of the uncollided neutrons to a specific point on the island axis, P_o , may be computed by integrating the above relation.

First, integrating the volume source into a line source, let

$$\rho = r \sec \theta$$

$$dV = r d\alpha dr dz = r^2 d\alpha dr d\theta .$$

$$N(E) \left|_{dL} = \int_0^{\tan^{-1} \frac{h_1}{r}} N(E) \left|_{dV} + \int_0^{\tan^{-1} \frac{h_2}{r}} N(E) \left|_{dV} .$$

But,

$$\int_0^{\tan^{-1} \frac{h_1}{r}} N(E) \left|_{dV} = \int_0^{\tan^{-1} \frac{h_1}{r}} \frac{n(E) e^{-[\Sigma_{Tw} R_o + \Sigma_{Tc}(r-R_o)] \sec \theta}}{4\pi (r \sec \theta)^2} r d\alpha dr dz$$

$$= \frac{n(E)}{4\pi} d\alpha dr \int_0^{\tan^{-1} \frac{h_1}{r}} e^{-[\Sigma_{Tw} T_o + \Sigma_{Tc}(r-R_o)] \sec \theta} d\theta$$

where Σ_{Tw} = total cross section of island
 Σ_{Tc} = total cross section of fuel region.

Defining,

$$F(\tan^{-1} \frac{h_1}{r}, \Sigma_{Tw} R_o + \Sigma_{Tc}(r-R_o)) = \int_0^{\tan^{-1} \frac{h_1}{r}} e^{-[\Sigma_{Tw} R_o + \Sigma_{Tc}(r-R_o)] \sec \theta} d\theta$$

the above expression becomes

$$\int_0^{\tan^{-1} \frac{h_1}{r}} N(E) \Big|_{dv} = \frac{n(E)}{4\pi} d\alpha dr F(\tan^{-1} \frac{h_1}{r}, \Sigma_{Tw} R_o + \Sigma_{Tc}(r-R_o))$$

An analogous expression can be derived for the contribution to point P_o from the volume of fuel below P_o . Integrating these line sources for $0 \leq \alpha \leq 2\pi$ and $R_o \leq r \leq R_1$, the high energy neutron flux at P_o is

$$N(E) = \frac{n(E)}{2} \int_{R_o}^{R_1} [F(\tan^{-1} \frac{h_1}{r}, \Sigma_{Tw} R_o + \Sigma_{Tc}(r-R_o)) + F(\tan^{-1} \frac{h_2}{r}, \Sigma_{Tw} R_o + \Sigma_{Tc}(r-R_o))] dr$$

For the energy range 10 - 16 Mev, good averages of the total cross sections to be used are⁵

H	0.80 barns
O	1.40 "
Al	1.6 "
U ²³⁵	8.0 "

Using these values, the macroscopic cross section for the water in the island region Σ_{TW} is $9.82 \times 10^{-2} \text{ cm}^{-1}$ and that in the fuel region Σ_{TC} is $10.02 \times 10^{-2} \text{ cm}^{-1}$. These two cross sections have approximately the same numerical values. A good average is $9.92 \times 10^{-2} \text{ cm}^{-1}$.

Substituting this averaged total macroscopic cross section $\Sigma_T \text{ avg}$ for the cross sections in the above relation and integrating,

$$N(E) = \frac{n(E)}{2 \Sigma_T \text{ avg}} \left[G_1(\Sigma_T \text{ avg } h_1, b_1) + G_1(\Sigma_T \text{ avg } h_2, b_1) - G_0(\Sigma_T \text{ avg } h_1, b_0) - G_0(\Sigma_T \text{ avg } h_2, b_0) \right]$$

$$\text{where } G_i(\Sigma_T \text{ avg } h_j, b_i) = \int_0^{R_i} F = \tan^{-1} \frac{h_j}{r}, \Sigma_T \text{ avg } R_i) dr$$

$$b_i = \Sigma_T \text{ avg } R_i$$

Results using this relation are shown in Figure 1.

Figure 1. Effective Neutron Flux Distribution
along the Island Axis

To calculate the effective neutron fluxes in various parts of the reactor, use was made of results computed by Cheverton⁶, using 16 region, 34 group, diffusion theory (GNU code). The highest energy group considered by this code is the range from 4 to 10 Mev, which is below the energies of interest here. In this energy range, the averaged neutron fluxes are as follows:

Region	Averaged Neutron Flux in the Energy Range 4 Mev < E < 10 Mev	
		neutrons sec-cm ²
Island	1.31×10^{14}	"
Fuel	1.43×10^{14}	"
Shim	7.75×10^{13}	"
Reflector	4.14×10^{12}	"

To convert the above results from the energy range of 4 Mev to 10 Mev to those in the energy ranges of interest, use was made of the Watt formula⁴ for the fission neutron spectrum. At the higher neutron energies, this relation can be approximated by

$$n(E) = \frac{e^{(\sqrt{2E} - E)}}{\sqrt{2\pi e}}$$

Using this relation, the effective neutron flux may be found by the relation,

$$\frac{\int_{E'}^{\infty} \phi(E) dE}{\int_4^{10} \phi(E) dE} = \frac{\int_{E'}^{\infty} e^{(\sqrt{2E} - E)} dE}{\int_4^{10} e^{(\sqrt{2E} - E)} dE}$$

This conversion factor is considered conservative since there probably are some scattered neutrons in the energy range of 4 Mev to 10 Mev. The conversion factor for the $O^{16}(n,p)N^{16}$ reaction ($E' = 11.7$ Mev) is 2.972×10^{-3} and that for the $O^{17}(n,p)N^{17}$ reaction ($E' = 10.0$ Mev) is 1.148×10^{-2} . The effective fluxes for these two reactions are, therefore:

Region	Effective Neutron Flux for the $O^{16}(n,p)N^{16}$ Reaction		Effective Neutron Flux for the $O^{17}(n,p)N^{17}$ Reaction	
Island	3.89×10^{11}	$\frac{\text{neuts}}{\text{cm}^2\text{-sec}}$	1.50×10^{12}	$\frac{\text{neuts}}{\text{cm}^2\text{-sec}}$
Fuel	4.26×10^{11}	"	1.64×10^{12}	"
Shim	2.30×10^{11}	"	8.89×10^{11}	"
Reflector	1.23×10^{10}	"	4.75×10^{10}	"

For comparison purposes, the effective neutron fluxes at the island centerline were computed by the extrapolation of the results computed by Cheverton using the GNU code and by the direct integration of the fission neutrons produced in the fuel region. Results of the GNU method for the energy range of 10 Mev to infinity are:

	4 Mev $\leq E \leq$ 10 Mev		10 Mev $\leq E \leq \infty$	
Maximum along island centerline	1.48×10^{14}	$\frac{\text{neuts}}{\text{cm}^2\text{-sec}}$	1.70×10^{12}	$\frac{\text{neuts}}{\text{cm}^2\text{-sec}}$
Average along island centerline	1.17×10^{14}	"	1.34×10^{12}	"

Results by the direct integration method, shown in Figure 1, for the energy range of 10 Mev to infinity are:

	$N(E)$	$10 \text{ Mev} < E < \infty$
Maximum along island centerline	2.93 n(E)	$1.21 \times 10^{12} \frac{\text{neuts}}{\text{cm}^2\text{-sec}}$
Average along island centerline	2.48 n(e)	$1.02 \times 10^{12} \quad "$

It can be seen that the results using the GNU code are higher and, therefore, more conservative.

For the inlet and outlet regions of the core, the uncollided neutron flux is assumed to be significant for three relaxation lengths beyond each end of the core. Using a value of $9.92 \times 10^{-2} \text{ cm}^{-1}$ for the total cross section, this length is $3/(9.92 \times 10^{-2})$ or 30.2 cm. The flux distribution along the island centerline shown in Figure 1 indicates that the ratio of the uncollided neutron flux at the ends of the active core region to the average uncollided neutron flux is $1.48/2.48$ or 0.596. It is assumed that this ratio is constant for all the regions in the HFIR core. Therefore, the effective neutron fluxes at the ends of the active length are:

Region	Effective Neutron Flux for the $^{16}\text{O}(n,p)^{16}\text{N}$ Reaction		Effective Neutron Flux for the $^{17}\text{O}(n,p)^{17}\text{N}$ Reaction	
Island	2.32×10^{11}	$\frac{\text{neuts}}{\text{cm}^2\text{-sec}}$	8.96×10^{11}	$\frac{\text{neuts}}{\text{cm}^2\text{-sec}}$
Fuel	2.54×10^{11}	"	9.79×10^{11}	"
Shim	1.37×10^{11}	"	5.30×10^{11}	"
Reflector	7.34×10^9	"	2.83×10^{10}	"

These neutron fluxes are regarded as plane sources for the regions beyond the ends of the active core. The average effective neutron fluxes in these regions then can be found by the relation,

$$\frac{S_A \int_0^{30.2} e^{-\Sigma_T x} dx}{l} = \frac{S_A}{\Sigma_T(30.2)} \left[1 - e^{-\Sigma_T(30.2)} \right] \approx \frac{S_A}{3} ,$$

since $\Sigma_T = 9.92 \times 10^{-2} \text{ cm}^{-1}$ and $\Sigma_T(30.2) = 3$. S_A is the effective neutron flux at the end of the active core. Therefore, the average effective neutron fluxes in these regions are:

Region	Effective Neutron Flux for the $^{16}\text{O}(n,p)^{16}\text{N}$ Reaction		Effective Neutron Flux for the $^{17}\text{O}(n,p)^{17}\text{N}$ Reaction	
		$\frac{\text{neuts}}{\text{cm}^2\text{-sec}}$		$\frac{\text{neuts}}{\text{cm}^2\text{-sec}}$
Island plenum	7.73×10^{10}		2.99×10^{11}	
Fuel plenum	8.47×10^{10}	"	3.26×10^{11}	"
Shim plenum	4.58×10^{10}	"	1.77×10^{11}	"

Because the beryllium reflector extends beyond the end of the active core 3 in., the "reflector plenum" was divided into the beryllium portion and the water portion for calculation purposes. Assuming the total cross section of beryllium to be 0.1926 cm^{-1} and using the techniques shown above, the average effective neutron fluxes in the reflector regions above and below the active core are:

Portion	Effective Neutron Flux for the $^{16}\text{O}(n,p)^{16}\text{N}$ Reaction		Effective Neutron Flux for the $^{17}\text{O}(n,p)^{17}\text{N}$ Reaction	
		$\frac{\text{neuts}}{\text{cm}^2\text{-sec}}$		$\frac{\text{neuts}}{\text{cm}^2\text{-sec}}$
Beryllium	3.85×10^9		1.48×10^{10}	
Water	6.84×10^8	"	2.60×10^9	"

Volumetric Production of N^{16} and N^{17}

The oxygen concentration in the coolant water is assumed to be 3.27×10^{22} atoms/cc, and the atomic percent of each oxygen isotope in the water is:

O^{16}	99.759 atomic %
O^{17}	0.037 "
O^{18}	0.204 "

Using the effective microscopic cross sections shown above, the effective macroscopic cross sections are:

<u>Reaction</u>	<u>Effective Cross Section, $\Sigma(E')$</u>
$^{16}_0(n,p)^{16}_0$	$1.924 \times 10^{-3} \text{ cm}^{-1}$
$^{17}_0(n,p)^{17}_0$	$5.08 \times 10^{-8} \text{ "}$

The production of N^{16} and N^{17} may be then calculated for each region in the reactor. Results are shown in Table 1.

Flow Rates and Holdup Time for Each Region

The flow rate and the velocity of the primary coolant through each region of the HFIR are shown in Table 2. Calculations and assumptions in obtaining these quantities are shown in Appendix B. From these quantities, the fraction of the total flow and holdup time in each region, which are shown also in Table 2, may be obtained.

Volume of the External System

Volumes of the coolant in the various components of the HFIR primary coolant system have been estimated by R. E. Schappel¹⁰ to be:

Pressure vessel	4960	gal
Decay vessel	15000	"
Heat exchangers	4200	"
Piping	5840	"
total:	30,000	gal

The volume of the cooling system exterior to the pressure vessel is then 25,040 gal. As shown in Appendix C, it is assumed for calculation purposes that the "effective holdup volume" in the pressure vessel above the core inlet region is 239 gal and that below the core outlet regions 191 gal. Hence, the volume of the external system is assumed to be 25,470 gal. Assuming a total flow rate of 15,250 gpm, the holdup time in the external system is 100.2 sec.

Table 1

N¹⁶ and N¹⁷ Production in the NFIR

Region*	N ¹⁶ Production		N ¹⁷ Production	
	0	atoms sec · cc water	0	atoms sec · cc water
urH ₂ O	1.32×10^6	"	1.32×10^2	"
urBe	7.41×10^6	"	7.52×10^2	"
us	8.81×10^7	"	8.99×10^3	"
uf	1.63×10^8	"	1.66×10^4	"
ui	1.49×10^8	"	1.52×10^4	"
r	2.37×10^7	"	2.43×10^3	"
s	4.43×10^8	"	4.52×10^4	"
f	8.20×10^8	"	8.33×10^4	"
i	7.48×10^8	"	7.62×10^4	"
lrBe	7.41×10^6	"	7.52×10^2	"
lrH ₂ O	1.32×10^6	"	1.32×10^2	"
ls	8.81×10^7	"	8.99×10^3	"
lf	1.63×10^8	"	1.66×10^4	"
li	1.49×10^8	"	1.52×10^4	"

* Letters for each region are defined in Appendix A and in the sketch on page 3.

Table 2

Flow Rate and Holdup Time for Each Region of the HFIR

Region*	Flow Rate	Velocity	Fraction of Total Flow	Holdup Time
e	15,250 gpm	-	1.0000	-
urH ₂ O	1,000	0.296 fps	0.0656	2.502 sec
urBe	1,000	5.94	0.0656	0.04210
us	1,345	44	0.0882	0.02251
uf	11,100	21.3	0.7277	0.04653
ui	1,806	24.9	0.1185	0.03980
τ	1,000	5.94	0.0656	0.2526
s	1,345	44	0.0882	0.03409
f	11,100	40	0.7277	0.03750
i	1,806	30	0.1185	0.05000
lrBe	1,000	5.94	0.0656	0.04210
lrH ₂ O	1,000	0.296	0.0656	2.502
ls	1,345	44	0.0882	0.02251
lf	11,100	21.3	0.7277	0.04653
li	1,806	24.9	0.1185	0.03980

* Letters for each region are defined in Appendix A and in the sketch on page 3.

N¹⁶ Concentration and Activities in the Primary Coolant

Using the assumptions and equations derived above, the N¹⁶ concentrations and activities in the coolant water discharging from the pressure vessel were calculated, and the results are shown in Figure 2. It is assumed that the holdup volume in the pressure vessel between the point where the N¹⁶ production becomes negligible and the pressure vessel exit is 191 gal. At the point where production becomes negligible, the N¹⁶ concentration in the primary coolant is 4.1×10^7 atoms/ml, and at the pressure vessel exit, the N¹⁶ concentration in the primary coolant is 3.8×10^7 atoms/ml. These values are equivalent to 3.9×10^6 dis/sec-ml and 3.6×10^6 dis/sec-ml, respectively. Figure 3 shows the buildup of N¹⁶ in the coolant in the various regions of the HFIR core. As expected, most of this active isotope is produced in the island and fuel regions.

Comparison with the N¹⁶ Production on the ORR

The N¹⁶ activities in the ORR cooling water were measured at a sample station to be:¹¹

Reactor Power	N ¹⁶ Activity
17 Mw	5.53×10^3 dis/sec-ml
20 Mw	7.70×10^3 "

This sample station is located 37.2 sec downstream from the reactor core^{12,13} and, therefore, the activities at the ORR core exit are:

Reactor Power	N ¹⁶ Activity
17 Mw	1.85×10^5 dis/sec-ml
20 Mw	2.59×10^5 "

The active core length in the ORR is 2 ft and coolant flow rate is 15,000 gpm¹⁴ which is equivalent to a velocity of:¹⁵

$$v = \frac{0.0916 \times 15,000}{60} = 22.9 \text{ fps}$$

Figure 3

Calculated N^{16} Concentrations
in Various Regions of the HFIR Core

The volume of the fuel region in the ORR neglecting the beryllium reflector and the experiments is about 3.71 ft³. With these data and assuming that the total cross sections are the same for both the ORR and the HFIR at these higher energies, the N¹⁶ activities in the water discharging from the cores of the two reactors approximately related by the following equation:

$$\frac{(N^{16})_{\text{HFIR}}}{(N^{16})_{\text{ORR}}} = \frac{(\text{Power})_{\text{HFIR}} (\text{Vol})_{\text{ORR}} (1 - e^{-\lambda \frac{L}{V}})_{\text{HFIR}}}{(\text{Power})_{\text{ORR}} (\text{Vol})_{\text{HFIR}} (1 - e^{-\lambda \frac{L}{V}})_{\text{ORR}}}$$

$$= \frac{100 (3.71) (1 - e^{-0.0943 \frac{1.5}{40}})}{(\text{Power})_{\text{ORR}} (2.02) (1 - e^{-0.0943 \frac{2.0}{22.9}})}$$

$$= \frac{79.2}{(\text{Power})_{\text{ORR}}}$$

where $(\text{Power})_{\text{ORR}} = \text{Mw}$. Using the N¹⁶ activities measured for the ORR in this relation, the HFIR N¹⁶ activities are:

ORR Power	HFIR N ¹⁶ Activity
17 Mw.	8.62 x 10 ⁵ dis/sec-ml
20 Mw	1.125 x 10 ⁶ "

These quantities are lower than those calculated above by a factor of about 4. It appears, therefore, the method and assumptions used in these calculations are conservative.

N¹⁷ Concentrations and Activities in the Primary Coolant

Again using the assumptions and equations derived above, the N¹⁷ concentrations and activities in the water discharging from the pressure vessel were calculated and are shown in Figure 4. At the point in the pressure vessel where production becomes negligible, the N¹⁷ concentration in the primary coolant is 4.1×10^3 atoms/ml, and at the pressure vessel exit, the N¹⁷ concentration is 3.7×10^3 atoms/ml. These values are equivalent to 6.9×10^2 dis/sec-ml and 6.2×10^2 dis/sec-ml, respectively. The buildup of N¹⁷ in the coolant in the various regions of the HFIR could be calculated using the same equations, but these calculations were not performed here.

Conclusions

The activity in the cooling water discharging from the HFIR pressure vessel due to N¹⁶ is calculated to be 3.9×10^5 dis/sec-ml, and that due to N¹⁷ is calculated to be 6.9×10^2 dis/sec-ml.

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Appendix A

Derivation and Definition of the Quantities L and M in the Equation,

$$N_e^0 = \frac{M}{1 - L e^{-\lambda t_e}}$$

Let f_i = fraction of the total coolant flow passing through the island region

f_f = fraction of the total coolant flow passing through the fuel region

f_s = fraction of the total coolant flow pass through the shim region

f_r = fraction of the total coolant flow passing through the beryllium reflector region

The water in between the beryllium reflector and the pressure vessel's wall is assumed to be stagnant for these calculations.

The following subscripts refer to these respective regions:

e = 'external region' (the region where there is no production of the active isotope)

urH₂O = water portion of the upper plenum over the beryllium reflector

urBe = portion of the beryllium reflector above the active core

us = portion of the upper plenum above the shim region

uf = portion of the upper plenum above the fuel region

ui = portion of the upper plenum above the island region

r = beryllium reflector region along the active core length

s = shim region

f = fuel region (active region)

i = island region

lrBe = portion of the beryllium reflector below the active core

ℓ_{rH_2O} = water portion of the lower plenum below the beryllium reflector

ℓ_s = portion of the lower plenum below the shim region

ℓ_f = portion of the lower plenum below the fuel region

ℓ_i = portion of the lower plenum below the island

The initial concentration of the active isotope in two adjacent regions j and $j + 1$ are related by

$$N_{j+1}^0 = N_j^0 e^{-\lambda t_j} + \left[1 - e^{-\lambda t_j} \right] \frac{(\bar{\Sigma}\phi)_j}{\lambda}$$

Combining these relations for the various regions and defining the following terms,

$$A_1 = \left[1 - e^{-\lambda t_{urH_2O}} \right] \frac{(\bar{\Sigma}\phi)_{urH_2O}}{\lambda}$$

$$A_2 = \left[1 - e^{-\lambda t_{urBe}} \right] \frac{(\bar{\Sigma}\phi)_{urBe}}{\lambda}$$

$$B = \left[1 - e^{-\lambda t_{us}} \right] \frac{(\bar{\Sigma}\phi)_{us}}{\lambda}$$

$$C = \left[1 - e^{-\lambda t_{uf}} \right] \frac{(\bar{\Sigma}\phi)_{uf}}{\lambda}$$

$$D = \left[1 - e^{-\lambda t_{ui}} \right] \frac{(\bar{\Sigma}\phi)_{ui}}{\lambda}$$

$$E_1 = \left[1 - e^{-\lambda t_r} \right] \frac{(\bar{\Sigma}\phi)_r}{\lambda}$$

$$E_2 = \left[1 - e^{-\lambda t_{\ell rBe}} \right] \frac{(\bar{\Sigma}\phi)_{\ell rBe}}{\lambda}$$

$$F = \left[1 - e^{-\lambda t_s} \right] \frac{(\bar{\Sigma}\Phi)_s}{\lambda}$$

$$G = \left[1 - e^{-\lambda t_f} \right] \frac{(\bar{\Sigma}\Phi)_f}{\lambda}$$

$$H = \left[1 - e^{-\lambda t_i} \right] \frac{(\bar{\Sigma}\Phi)_i}{\lambda}$$

$$J = f_r \left[1 - e^{-\lambda t_{rH_2O}} \right] \frac{(\bar{\Sigma}\Phi)_{rH_2O}}{\lambda} + f_s \left[1 - e^{-\lambda t_{ls}} \right] \frac{(\bar{\Sigma}\Phi)_{ls}}{\lambda} \\ + f_f' \left[1 - e^{-\lambda t_{lf}} \right] \frac{(\bar{\Sigma}\Phi)_{lf}}{\lambda} + f_i \left[1 - e^{-\lambda t_{li}} \right] \frac{(\bar{\Sigma}\Phi)_{li}}{\lambda}$$

$$K = f_r E_1 e^{-\lambda t_{rBe}} e^{-\lambda t_{rH_2O}} + f_r E_2 e^{-\lambda t_{rH_2O}} \\ + f_s E e^{-\lambda t_{ls}} + f_f Ge^{-\lambda t_{lf}} + f_i He^{-\lambda t_{li}} + J$$

$$L = f_r e^{-\lambda t_{urH_2O}} e^{-\lambda t_{urBe}} e^{-\lambda t_r} e^{-\lambda t_{rBe}} e^{-\lambda t_{rH_2O}} + f_s e^{-\lambda t_{us}} e^{-\lambda t_s} e^{-\lambda t_{ls}} \\ + f_f e^{-\lambda t_{uf}} e^{-\lambda t_f} e^{-\lambda t_{fs}} + f_i e^{-\lambda t_{ui}} e^{-\lambda t_i} e^{-\lambda t_{li}}$$

$$M = f_r \left[A_1 e^{-\lambda t_{urBe}} + A_2 \right] e^{-\lambda t_r} e^{-\lambda t_{rBe}} e^{-\lambda t_{rH_2O}} + f_s Be^{-\lambda t_s} e^{-\lambda t_{ls}} \\ + f_f C e^{-\lambda t_f} e^{-\lambda t_{ff}} + f_i D e^{-\lambda t_i} e^{-\lambda t_{li}} + K$$

the following equation is obtained

$$N_e^0 = \frac{M}{1 - Le^{-\lambda t_e}}$$

Appendix B

Calculation of the Flow Rates and Velocities
through the Various Regions of the HFIR

Island

For heat transfer purposes, it is assumed that the required velocity through the island is 30 fps. The island is within a shroud which has an inside radius of 2.722 in.⁸ The sample for the island contains 19 3/8 in. OD tubes inside a 4 5/8 in. ID and 4 7/8 in. OD shroud.⁸ Therefore, the cross sectional area for the flow of the water is

$$\pi [(2.722)^2 - (2.438)^2] + \pi (2.313)^2 - \frac{\pi}{4} (19)(0.375)^2 = 19.31 \text{ in.}^2$$

and the required flow rate is 1806 gpm.

Fuel

The required velocity for heat transfer purposes in the fuel region is 40 fps,⁶ and the cross sectional area available for the coolant flow is 0.6180 ft².⁹ Therefore, the water flow rate through the fuel region of the reactor is 11,100 gpm.⁹

Shim

The shim plates for the HFIR are two cylindrical shells around the core, each 1/4 in. thickness. The water gap between these two plates is 1/16 in. thick and the distances between these plates and the core and the beryllium reflector are each 1/16 in. It is assumed that for flow calculation purposes, the available pressure difference is 53 psi, which is the same as that for the fuel, and the shim length is 18 in. The velocity in the annular space V_a is related to the available pressure difference Δp by the relation

$$\begin{aligned} \frac{\Delta p}{\rho} &= \text{inlet loss} + \text{outlet loss} + \text{friction loss} \\ &= 0.5 \frac{V_a^2}{2g_c} + 1.0 \frac{V_a^2}{2g_c} + f \frac{4L}{D_e} \frac{V_a^2}{2g_c} \end{aligned}$$

where p = pressure difference
 ρ = water density
 V_a = water velocity
 g_c = conversion factor ($F = \frac{1}{g_c}$ ma)
 f = Fanning friction factor
 L = length
 D_e = equivalent diameter
 $= D_2 - D_1$ for an annular space
 D_2 = outside diameter
 D_1 = inside diameter

Solving this equation by trial-and-error procedures, the velocity through the shim region is found to be 44 fps.

The coolant flow area in the shim region is calculated to be 0.0681 ft². Hence, the flow rate through the shim region is 1345 gpm.

Beryllium Reflector

It is assumed that five volume percent of the beryllium reflector is occupied by water⁶ and that the coolant flow rate through this reflector is 1000 gpm. The total cross section area of the reflector is 7.51 ft²⁹ and the velocity is, therefore, 4.94 fps.

Island Inlet and Outlet Regions

This inlet and outlet regions of the island are assumed to be entirely water for the purposes of these calculations, which is a conservative assumption.

The cross section area of both of these regions is $\pi(2.722)^2$ or 23.29 in.², and the fluid velocity is

$$\frac{(19.31)(30)}{(23.29)} = 24.9 \text{ fps}$$

Fuel Inlet and Outlet Regions

Again, the conservative assumption that the inlet and outlet regions of the HFIR fuel are composed entirely of water is made. The available cross sectional area available for flow in these regions is 1.161 ft², and the fluid velocity is

$$\frac{(0.6180)(40)}{(1.161)} = 21.3 \text{ fps} .$$

Shim Inlet and Outlet Regions

Since the shim control plates extend beyond the active core length, the same coolant velocity is assumed for the inlet and outlet region which is 44 fps.

Beryllium Reflector Inlet and Outlet Regions

The inlet and outlet regions of the beryllium reflector are divided into the beryllium portion and the water portion. The velocity in the beryllium portion is the same as that in the beryllium reflector along the active core length which is 5.94 fps. The flow area in the water portion is assumed to be 7.51 ft² and the fluid velocity in this portion is

$$\frac{(5.94)(7.51)(0.05)}{(7.51)} = 0.296 \text{ fps} .$$

Appendix C

Calculation of the "Effective Holdup Volumes"
in the HFIR Pressure Vessel

The primary coolant enters the reactor vessel at the top and flows downward through the core and out through the exit at the bottom of the vessel. For the upper part of the pressure vessel, it is assumed the coolant flows in the form of a tee.

It is assumed that the top of the tee is a horizontal cylinder 96 in. long which has a volume of 70.6 gal. The vertical portion of the tee is assumed to be a 30 in. cylinder 55 in. long which has a volume of 169 gal. (The 30 in. diameter for the vertical portion of the tee was selected as a reasonable number in view of the relatively large cross section area of and the reduced flow through the beryllium reflector.) Adding the total "effective holdup volume" in the inlet portion of the pressure vessel is 239 gal.

For the lower portion of the pressure vessel, it is assumed that coolant flows in the form of two adjoining cylinders.

The upper cylinder of the exit region has a volume of 123 gal and the lower cylinder has a volume of 68 gal. Therefore, the total "effective holdup volume" in the exit portion of the pressure vessel is 191 gal.

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