TRITIUM AND HYDROGEN TRANSPORT IN LMFBR SYSTEMS: EBR-II, CRBR, AND FFTF

by

T. A. Renner and C. C. McPheeters

Chemical Engineering Division

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NOMENCLATURE

$A$ Effective area for tritium/hydrogen permeation through sodium containment material, cm$^2$

$F_{CG}$ Leakage flow rate of cover gas, cm$^3$(STP)/s

$F_{CT}$ Sodium flow rate through cold trap, kg/s

$K_p$ Temperature-dependent equilibrium constant for the reaction $H_2 + T_2 \rightarrow 2HT$

$K_{SH}$ Sieverts' Law constant for hydrogen in sodium, (atoms H/kg Na)/atm$^{1/2}$

$K_{ST}$ Sieverts' Law constant for tritium in sodium, (atoms T/kg Na)/atm$^{1/2}$

$t$ Sodium containment wall thickness, cm

$N_H$ Quantity of hydrogen in cold trap, atoms H

$N_T$ Quantity of tritium in cold trap, atoms T

$P_r(t)$ Reactor operating power level, MW(thermal)

$P_{T(P_H)}$ Permeability of tritium (or hydrogen) through sodium containment materials, (atoms T or H/cm)/cm$^2$-s-(atoms T or H/kg Na)

$S_H$ Rate of introduction of hydrogen to secondary coolant circuit sodium due to steam generator corrosion, atoms H/s

$S_{HP}$ Rate of introduction of hydrogen to primary coolant circuit sodium due to sources other than permeation through the intermediate heat exchanger, atoms H/s

$S_T$ Release rate of tritium to primary coolant circuit sodium, atoms T/s

$T$ Temperature, K unless otherwise specified

$\tau$ Time, s

$W_p$ Mass of primary coolant circuit sodium, kg

$W_s$ Mass of secondary coolant circuit sodium, kg

$W_w$ Mass of water in steam system, kg

$x_H$ Hydrogen concentration in sodium, atoms H/kg

$x_T$ Tritium concentration in sodium, atoms T/kg

$\eta$ Cold trap efficiency

Acronyms

CAPS Cell Atmosphere Purification System

CRBR Clinch River Breeder Reactor

DHX Dump heat exchanger

EBR-II Experimental Breeder Reactor No. II

FFTF Fast Flux Test Facility

IHTS Intermediate heat transport system (used interchangeably with secondary coolant circuit)

IHX Intermediate heat exchanger

ISTM In-sodium tritium meter

LMFBR Liquid-metal-cooled fast breeder reactor

PHTS Primary heat transport system (used interchangeably with primary coolant circuit)

PSAR Preliminary safety analysis report

SG Steam generator
TRITIUM AND HYDROGEN TRANSPORT IN LMFBR SYSTEMS: EBR-II, CRBR, AND FFTF

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ABSTRACT

A tritium and hydrogen transport model has been employed to simulate concentration profiles, tritium losses to auxiliary containment systems, and cold trap burdens for EBR-II, CRBR, and FFTF. Experimental data from EBR-II were found to correlate well with calculated tritium and hydrogen profiles. A major change relative to previous transport models, namely, the inhibiting effect of oxide coatings on tritium permeation through reactor structural surfaces, has been incorporated into the current model. Tritium release rates to auxiliary systems where oxide barrier effects were included were predicted to be approximately two orders of magnitude lower than those for the reference case where structural surfaces were assumed to be totally oxide-free. Tritium releases during operation of large LMFBRs are expected to present essentially no hazard to the environment.

I. INTRODUCTION

In the design and operation of Liquid-Metal-Cooled Fast Breeder Reactors (LMFBRs), it is imperative to reduce emissions of radionuclides to the environment to the lowest possible levels in conformance with federal regulations. Tritium generated in the reactor core is of particular concern because it is extremely mobile and will diffuse through the fuel and control rod cladding and migrate through the liquid sodium coolant systems. The sodium cold traps are the principal tritium control devices. However, tritium permeation rates through the reactor construction materials must be accurately known, since, at reactor operating temperatures, all three hydrogen isotopes readily penetrate and diffuse through these materials. A generalized model, developed at Argonne National Laboratory to simulate tritium transport in and release from the Experimental Breeder Reactor No. II (EBR-II) and the Fast Flux Test Facility (FFTF), has been extensively upgraded and modified. Two significant alterations have been incorporated into the transport model. Firstly, the inhibiting effect of protective oxide coatings on permeation rates of hydrogen isotopes through reactor structural materials has been included. Secondly, a more refined mathematical treatment of tritium and hydrogen transport across the intermediate heat exchanger (IHX) has been employed.

In this study, the modified model has been utilized to calculate tritium and hydrogen distributions in EBR-II, and predicted profiles were found to correlate well with observed data. Subsequently, calculations were made with the modified model to predict tritium and hydrogen concentrations in the sodium coolant, tritium release rates from individual reactor subsystems, and accumulation rates of tritium and hydrogen in the cold trap systems for CRBR and
II. DESCRIPTION OF THE TRANSPORT MODEL

The tritium and hydrogen transport model, in both the original and the current versions, was based on an LMFBR system similar to that shown schematically in Fig. 1. For such a system, tritium generated in the reactor core is released to the primary sodium coolant and disperses throughout the primary circuit by bulk transport of the coolant. From the primary circuit, tritium may (1) permeate through the stainless steel sodium containment into the inert N₂-1% O₂ cells surrounding the piping, (2) permeate through the intermediate heat exchanger (IHX) tubes into the secondary circuit, (3) escape by leakage from the primary system cover gas, (4) coprecipitate with hydrogen in the primary cold trap(s), and (5) decay naturally to ³He. Likewise, tritium that reaches the secondary circuit through the IHX may (1) permeate through the secondary sodium containment walls into the surrounding air cells, (2) permeate through the walls of the steam generator tubes into the water/steam system, (3) escape by leakage from the secondary system cover gas, (4) coprecipitate with hydrogen in the secondary cold traps, and (5) decay to ³He. A general expression for tritium and hydrogen material balances may be applied to any
of the reactor subsystems:

\[ \text{Net accumulation} = \Sigma \text{Sources} - \Sigma \text{Sinks} \quad (1) \]

Terms and parameters required for the material balance equations are defined, with appropriate symbols and units, in the nomenclature listing at the beginning of this report. Mathematically explicit equations for the rates of change of tritium and hydrogen concentrations in the primary and secondary sodium circuits and in the steam/water system are presented in Appendix A.

The rate of tritium production in the reactor core, and hence the release rate to the primary circuit sodium, depends on the reactor power level and is not a well-characterized experimental quantity:

\[ \text{Tritium source term} = f[P_R(t)] \quad (2) \]

Normally, the power level will not remain constant for an indefinite period of time. For these calculations, however, full-power operation for six months has been assumed. The assumptions used to estimate the tritium source term were as follows:

(1) Nearly 100 % of the tritium produced by fission is released from the fuel pins to the primary sodium; the fission yield is approximately $1.5 \times 10^{-4}$ to $3.5 \times 10^{-4}$ tritium atoms per fission (21-42 Ci/d).\(^{2-5}\)

(2) Activation of boron and lithium impurities in the core and blanket fuel produces approximately 2 Ci/d of tritium.\(^5\)

(3) Tritium generated by activation of boron in the B\(_4\)C control rods is a major contributor to the tritium source term, but the exact amount released to the sodium coolant is not well known. Tritium source terms of 89 Ci/d for CRBR\(^6\) and 40 Ci/d for FFTF\(^7\) have been recommended and are used for all calculations throughout this report.

The rate of permeation through the sodium containment walls is a function of wall thickness, the surface area exposed to tritium, the tritium concentration in the sodium coolant, the Sieverts' Law constant for tritium in sodium, and the permeability of tritium through the reactor construction materials:

\[ \text{Permeation losses} = f[L, A_s, x_T, K_{ST}, P_T] \quad (3) \]

The rate of tritium permeation through the walls of the IHX is also a function of the same variables shown in Eq. (3); however, the driving force for this process is expressed in terms of the difference in tritium concentrations in the primary and secondary sodium circuits, $\Delta x_T$.

The rate of tritium loss due to leakage through primary and secondary cover gas seals depends on the tritium concentration in the cover gas and the cover gas leakage rate. If the cover gas is assumed to be equilibrated with the sodium coolant, the tritium concentration in the gas is a function of the Sieverts' constants for tritium and hydrogen in the coolant, the actual concentration of the two isotopes in the coolant, and the equilibrium constant
for the reaction $\text{H}_2 + \text{T}_2 \rightleftharpoons 2\text{HT}$:

$$\text{Loss from cover gas} = f[F_{CG}, K_{ST}, K_{SH}, x_T, x_H, K_p] \tag{4}$$

The rate of tritium removal by the primary and secondary cold trap systems is a function of sodium flow rate, sodium temperature, the tritium and hydrogen content of the coolant and the cold traps, and the cold trap efficiency:

$$\text{Removal by cold trapping} = f[F_{CT}, T, x_T, x_H, N_T, N_H, n] \tag{5}$$

Finally, the rate of loss due to natural radioactive decay of tritium to $^3\text{He}$ is directly proportional to the total amount of tritium present in the reactor subsystems:

$$\text{Loss by decay} = f[x_T, N_T, W_P, W_S, W_W] \tag{6}$$

III. MODIFICATION AND TESTING OF THE MODEL

A. Protective Oxide Coatings

Two of the potentially more troublesome paths for tritium escape from an LMFBR are the heat transfer surfaces of the steam generator system and the walls of the containment piping for the primary sodium. It is well known that oxide coatings on these surfaces may significantly reduce the permeability of hydrogen isotopes by as much as two or three orders of magnitude. However, directly measured tritium permeation data for unoxidized and oxide-coated metals and alloys are scarce. In earlier tritium transport calculations, the permeation-inhibiting nature of oxide coatings was not taken into account when computing permeation losses with Eq. (3). In order to provide more reliable data for the model, an extensive series of measurements was made of the permeation rate of tritium through unoxidized ("clean") and steam-oxidized Croloy (Fe-21 Cr-1 Mo). This material is a leading candidate for construction of LMFBR steam generators. Recent tritium permeation data of McGuire for oxidized Types 304 and 316 stainless steels, from which the sodium containment vessels and piping will be fabricated, have also been incorporated into the transport model.

B. Tritium Transport across the IHX of EBR-II

An experiment was carried out at EBR-II to provide data from which the tritium permeation rate across the IHX was determined. The IHTS cold trap of EBR-II was bypassed from May 20 to June 8, 1977, and tritium concentration increases in the PHTS and IHTS sodium were recorded with in-sodium tritium meters (ISTMs) that had been recently installed in the reactor. The observed permeation rate was compared with that calculated from a mathematical analysis in which the IHX tubes were divided into 100 segments of equal length. (Further subdivision into more than 100 segments did not improve the results.) From the temperature profile of the IHX tubes, a discreet temperature was assigned to each segment, and the tritium flux across the tube wall was calculated from the physical properties of the construction material (i.e., area, thickness, and tritium permeability in Type 304 stainless steel; see Appendix B). A temperature-averaged tritium permeation rate for a single IHX tube was determined by integrating the tritium fluxes through each segment along the
entire length of the tube. All IHX tubes were assumed to be equivalent for this calculation, and the total tritium permeation rate for the IHX was obtained by multiplying the rate for a single tube by the total number of tubes. The observed tritium permeation rate across the IHX was a factor of three greater than the rate calculated from the segmented-tube model. Since both sides of the tubes are continuously exposed to sodium, this observation suggests that the IHX tubes are probably free of protective oxide films. After scaling up the calculated tritium and hydrogen permeation rates by a factor of three to correspond with the experimental data, the segmented-tube model of the IHX was incorporated into the complete transport model.

EBR-II operating data for the period May 20 to May 28, 1977 were used to test the revised version of the transport-modeling computer code. The initial operating conditions (May 20, 1977) were input to the program, and the tritium and hydrogen distributions were predicted for the nine days during which data were recorded. This calculation represents a transient case, since the secondary cold trap was off-line during the entire period. In Fig. 2, the results of this simulation are compared with the experimental data for tritium and hydrogen levels in the PHTS and IHTS sodium of EBR-II. In this figure, the solid lines represent the profiles predicted with the transport model and the symbols represent the actual operating data. Hydrogen concentration data for

Fig. 2. Tritium and Hydrogen Concentrations in EBR-II Sodium Coolant Systems
the PHTS were not available. Agreement between the calculated and experimental values is good for the time interval studied. These results lend confidence to our predictions of tritium and hydrogen distributions in CRBR (Section IV) and FFTF (Section V) made with the revised model.

C. Sieverts' Law Constant for Tritium in Sodium

Previously, due to a lack of experimental data, the Sieverts' constant for tritium in sodium was assumed to be equal to that for hydrogen in sodium. We have estimated the Sieverts' constant for tritium in sodium on the basis of determinations made by Veleckis et al. of decomposition pressures in the analogous LiH, LiD, and LiT systems and the associated isotope effects. This calculation is described in Appendix B. The physical properties of tritium and hydrogen in liquid sodium, in Types 304 and 316 stainless steels, and in Fe-25Cr-1Mo are also summarized in Appendix B.

D. Tritium Loss by Radioactive Decay

In accounting for the loss of tritium due to natural decay to \(^3\)He, Kumar included in the tritium material-balance equations the decay of the total amount of tritium present in the primary and secondary sodium circuits, the water/steam system, and the cold traps. The resulting tritium concentration-time profiles for the coolant circuits showed sharp rises to maxima followed by gradual declines. However, actual tritium concentrations are expected to attain steady-state plateau values after some time, \(t\). The original analysis has been altered by considering that tritium deposited in any cold trap remains there indefinitely and does not affect the actual tritium levels in other reactor subsystems. After this change was incorporated into the model, the tritium concentrations in the coolant circuits and in the water/steam system attained steady-state values. The decay of tritium deposited in the cold traps must be accounted for, however, in determining the absolute radioactivity burden of the traps when they are disposed of after blockage or regenerated for further use.

IV. TRITIUM AND HYDROGEN TRANSPORT IN CRBR

The updated transport model has been used to predict tritium and hydrogen distributions in CRBR. Rates of tritium loss from reactor containment materials have also been calculated. The predicted tritium and hydrogen profiles and release rates are strongly affected by two factors: (1) the permeation-retarding nature of oxide coatings, particularly on steam generator tubes and sodium coolant piping; and (2) the rate of hydrogen ingress to the secondary coolant circuit due to steam generator corrosion. With regard to the first factor, a reference case has been established in which all structural and heat-transfer surfaces are assumed to be oxide-free. For the reference case, maximum tritium and hydrogen permeation rates through the construction materials as well as upper limit values for tritium release rates from reactor subsystems were obtained. With regard to the second factor, the effectiveness of cold traps is directly dependent on the hydrogen ingress rate from the steam generator. Since tritium is most efficiently removed from the coolant by coprecipitation with hydrogen in the cold traps, large hydrogen influxes from the steam generator should produce high cold-trapping efficiency. However, at the same time, the useful lifetime of sodium cold traps will be greatly reduced by large hydrogen influxes. For economic reasons, then, cold trap...
designs must be optimized, and anticipated tritium and hydrogen burdens in both primary and secondary cold traps must be determined.

The modeling results discussed below have been obtained using the following set of operating conditions for CRBR (see Appendix D):

1. The tritium source term, \( S_T \), is 89 Ci/d \((2.13 \times 10^{16} \text{ atoms T/s})\).
2. The rate of hydrogen influx to IHTS sodium due to steam generator corrosion, \( S_H \), is 3.6 g H/h \((6.05 \times 10^{20} \text{ atoms H/s})\).
3. The rate of hydrogen influx to PHTS sodium from external sources, \( S_{HP} \), is zero; all hydrogen present in PHTS sodium is assumed to diffuse through the IliX from IHTS sodium.
4. The reactor is assumed to operate continuously at full power for a period of 4400 hours (≈6 months) from start-up. (For all cases studied, CRBR tritium and hydrogen levels attained steady-state values before or at six months.)
5. All cold traps are assumed to be 70% efficient at a cold trap temperature of 394 K \((250^\circ\text{F})\).

In Table I, tritium and hydrogen concentrations, rates of tritium loss from reactor containment, and tritium and hydrogen burdens of the cold traps are listed for the reference case and for the normal case where sodium piping and steam generator tubes are coated with permeation-inhibiting oxide films. As can be seen in the table, tritium and hydrogen concentrations in the sodium coolant are nearly identical for both the normal and reference cases. However, the tritium burdens of the cold traps are somewhat greater for the normal case where the rate or tritium loss from sodium containment is lower due to the protective oxide films. The greatest differences between the two cases were observed for rates of tritium release from sodium containment materials to auxiliary systems. As anticipated, permeation of tritium through the walls of the steam generator tubes into the steam/water system was predicted to produce the largest tritium loss; and permeation of tritium through the walls of the PHTS sodium containment, principally the hot leg piping, was predicted to result in the next largest tritium loss. Minor losses from IHTS sodium containment and from primary cover gas leakage were also predicted. The total tritium loss was calculated to be 3.01 Ci/d for the reference case and 21.8 mCi/d for the normal case. Therefore, the presence of oxide films on reactor surfaces is expected to reduce the total tritium release rate by a factor of ≈140.

The above rates of tritium loss from sodium containment must be interpreted with some caution. The values listed in Table I refer to quantities of tritium released to auxiliary reactor systems (see Fig. 1). For example, tritium entering the steam/water system may be subjected to further treatment to reduce its concentration in the plant effluent water stream or tritium permeating through the PHTS and IHTS sodium piping and entering inert gas cells may be removed by such processes as a Cell Atmosphere Purification System (CAPS).
Table I. Tritium and Hydrogen Distributions in CRBR Calculated with the Transport Model for a Cold Trap Temperature of 394 K (250°F)

\[
S_T = 2.13 \times 10^{16} \text{ atoms T/s (89 Ci/d)} \\
S_H = 6.05 \times 10^{20} \text{ atoms H/s (3.6 g H/h)} \\
S_{HP} = 0
\]

Continuous operation for 4400 h (6 months) 70% cold trapping efficiency

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<thead>
<tr>
<th>Reference Case (no oxide coatings)</th>
<th>Normal Case (with oxide coatings)</th>
</tr>
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<tbody>
<tr>
<td><strong>Tritium Release to Auxiliary Systems, mCi/d</strong></td>
<td></td>
</tr>
<tr>
<td>Permeation through SG tube walls</td>
<td>2502</td>
</tr>
<tr>
<td>Permeation through PHTS containment walls</td>
<td>478</td>
</tr>
<tr>
<td>Permeation through IHTS containment walls</td>
<td>30</td>
</tr>
<tr>
<td>PHTS cover gas leakage</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3011</td>
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<tr>
<td><strong>Tritium Concentration in Sodium Coolant, Ci/kg Na</strong></td>
<td></td>
</tr>
<tr>
<td>PHTS</td>
<td>(1.59 \times 10^{-3})</td>
</tr>
<tr>
<td>IHTS</td>
<td>(5.50 \times 10^{-5})</td>
</tr>
<tr>
<td><strong>Hydrogen Concentration in Sodium Coolant, ppb</strong></td>
<td></td>
</tr>
<tr>
<td>PHTS</td>
<td>71</td>
</tr>
<tr>
<td>IHTS</td>
<td>193</td>
</tr>
<tr>
<td><strong>Tritium Content of Cold Traps, Ci</strong></td>
<td></td>
</tr>
<tr>
<td>One PHTS Cold Trap</td>
<td>10505</td>
</tr>
<tr>
<td>Three IHTS Cold Traps</td>
<td>4060</td>
</tr>
<tr>
<td><strong>Hydrogen Content of Cold Traps, kg H</strong></td>
<td></td>
</tr>
<tr>
<td>One PHTS Cold Trap</td>
<td>0.50</td>
</tr>
<tr>
<td>Three IHTS Cold Traps</td>
<td>15.33</td>
</tr>
</tbody>
</table>

Consequently, actual rates of tritium loss to the environment will ultimately be far smaller than those rates given in Table I. With respect to hydrogen removal from the coolant circuits, approximately 16 kg of hydrogen may be expected to accumulate in the cold trap systems in six months. About 97% of this mass should be deposited in the IHTS cold traps. This large hydrogen burden results in IHTS cold trap lifetimes of about one year and underlines the need for effective technology to regenerate and/or refurbish cold traps for commercial breeder reactors.
The effect of lowering the cold trap temperature from 394 to 389 K (250 to 240°F) was also investigated with the transport model. All other operating conditions were the same as described above. Table II presents the tritium and hydrogen distributions for the reference case and for the normal case at this temperature. Hydrogen and tritium burdens in the cold traps are similar.

Table II. Tritium and Hydrogen Distributions in CRBR Calculated with the Transport Model for a Cold Trap Temperature of 389 K (240°F)

<table>
<thead>
<tr>
<th></th>
<th>Reference Case (no oxide coatings)</th>
<th>Normal Case (with oxide coatings)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tritium Release to</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Auxiliary Systems, mCi/d</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeation through SG tube walls</td>
<td>2059</td>
<td>15.10</td>
</tr>
<tr>
<td>Permeation through PHTS containment walls</td>
<td>417</td>
<td>1.52</td>
</tr>
<tr>
<td>Permeation through IHTS containment walls</td>
<td>24</td>
<td>0.14</td>
</tr>
<tr>
<td>PHTS cover gas leakage</td>
<td>1</td>
<td>1.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2501</td>
<td>17.77</td>
</tr>
<tr>
<td><strong>Tritium Concentration in Sodium Coolant, Ci/kg Na</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHTS</td>
<td>$1.39 \times 10^{-3}$</td>
<td>$1.40 \times 10^{-3}$</td>
</tr>
<tr>
<td>IHTS</td>
<td>$4.53 \times 10^{-5}$</td>
<td>$4.99 \times 10^{-5}$</td>
</tr>
<tr>
<td><strong>Hydrogen Concentration in Sodium Coolant, ppb</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHTS</td>
<td>59</td>
<td>59</td>
</tr>
<tr>
<td>IHTS</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td><strong>Tritium Content of Cold Traps, Ci</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One PHTS Cold Trap</td>
<td>11178</td>
<td>11236</td>
</tr>
<tr>
<td>Three IHTS Cold Traps</td>
<td>3602</td>
<td>3960</td>
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<tr>
<td><strong>Hydrogen Content of Cold Traps, kg H</strong></td>
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<td></td>
</tr>
<tr>
<td>One PHTS Cold Trap</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Three IHTS Cold Traps</td>
<td>15.33</td>
<td>15.33</td>
</tr>
</tbody>
</table>
to those predicted for 394 K (250°F), and hydrogen and tritium concentrations in the coolant circuits are somewhat lower. In addition, total releases of tritium to auxiliary systems are reduced by about 18% at the lower cold trap temperature. The results in Table II suggest that sodium cold traps should be operated at the lowest feasible temperature for optimum tritium control.

In the calculations presented in Tables I and II, it was assumed that the rate of hydrogen influx to PHTS sodium from external sources, $S_{HP}$, is zero. However, ordinary reactor maintenance procedures (i.e., refueling, removal of failed fuel assemblies, etc.) and ir-leakage of moisture through cover gas seals may introduce appreciable amounts of hydrogen. When steady-state operation is attained, these external sources should become negligible. To test the effect of external hydrogen sources (other than hydrogen diffusing through the IHX from the IHTS sodium) on tritium release rates to auxiliary systems and on tritium retention in cold traps, $S_{HP}$ values between $10^{15}$ and $10^{20}$ atoms H/s (0.006 and 600 mg H/n) were assumed in the model. All other operating conditions were the same as those listed in Table I for the normal case. In Fig. 3, rates of tritium retention in cold traps and rates of tritium loss to auxiliary systems are plotted as percentages of the tritium source term, $S_T$.

![Fig. 3. Tritium Release Rates from PHTS Sodium Containment and Steam Generator Tubes and Tritium Retention Rates in Cold Traps vs. Hydrogen Source Term, $S_{HP}$ for CRBR.](image-url)
When external hydrogen sources are less than $10^{18}$ atoms H/s (6 mg H/h), tritium release and retention rates remain constant and are identical to the results obtained when $S_{HP}$ is assumed to be zero. Under these conditions, the hydrogen influx from the steam generator, $S_H$, dominates, and $S_{HP}$ is negligible with respect to $S_H$. When $S_{HP}$ is greater than $10^{18}$ atoms H/s, the tritium removal efficiency of the PHTS cold trap increases (i.e., the tritium retention rate approaches 100% of $S_T$ as $S_{HP}$ and $S_H$ become equal in magnitude); correspondingly, tritium releases from the steam generator tubes and PHTS sodium piping decline markedly. The results in Tables I and II and Fig. 3 indicate that tritium releases from sodium containment materials can be maintained at very low levels.

V. TRITIUM AND HYDROGEN TRANSPORT IN FFTF

The transport model was used to predict tritium and hydrogen distributions in coolant circuits and rates of tritium loss from reactor containment for FFTF. Unlike CRBR, FFTF will have no steam generating system. The principal external source of hydrogen addition to IHTS sodium in FFTF will most probably be the dump heat exchangers (DHX). Since no water is present in the DHX, hydrogen can only be introduced by atmospheric corrosion of the steel or by diffusion of atmospheric hydrogen into the sodium. Thus, the hydrogen influx for FFTF will very likely be much smaller than that for CRBR. A value of $S_H$ equal to $1 \times 10^{19}$ atoms H/s (60 mg H/h) and a value of $S_{HP}$ equal to $5 \times 10^{18}$ atoms H/s (30 mg H/h) are assumed for the results shown in Table III. The tritium source term, $S_T$, is 40 Ci/d ($9.57 \times 10^{15}$ atoms T/s). The reactor is assumed to operate at full power for 4400 hours (~6 months) from start-up and the cold traps are assumed to be 70% efficient at a cold-trap temperature of 389 K (240°F).

For the parameters used in these calculations, the loss of tritium from PHTS sodium piping to inert gas cells is predicted to about 1.3 to 1.4 times larger than the loss from the DHX for both the reference and the normal cases. This is a reasonable result because the PHTS hot leg temperature is considerably higher than that of the DHX and permeation losses have an exponential temperature dependence. When total tritium losses to auxiliary systems are compared in Table III, the importance of protective oxide coatings on structural surfaces is again evident, the release rate for the normal case being a factor of ~88 lower than that for the reference case. Hydrogen burdens in the cold traps are much smaller for FFTF than for CRBR because of the lower assumed values of $S_{HP}$ and $S_H$. Reliable experimental determinations of $S_{HP}$ and $S_H$ must be made for FFTF in order to apply the transport model with greater certainty. Previous transport model calculations of Kabele for FFTF are not directly comparable with the predictions of Table III because the effects of oxide coatings were not included at that time and somewhat different operating parameters were assumed. However, both studies indicate that tritium release from sodium containment is not expected to pose any difficulties that cannot be countered effectively with current tritium-control technology.
Table III. Tritium and Hydrogen Distributions in FFTF Calculated with the Transport Model for a Cold Trap Temperature of 389 K (240°F)

\[ S_T = 9.57 \times 10^{15} \text{ atoms T/s (40 Ci/d)} \]
\[ S_H = 1 \times 10^{19} \text{ atoms H/s (60 mg H/h)} \]
\[ S_{HP} = 5 \times 10^{18} \text{ atoms H/s (30 mg H/h)} \]
Continuous operation for 4400 h (~6 months)
70% cold trapping efficiency

<table>
<thead>
<tr>
<th>Reference Case (no oxide coatings)</th>
<th>Normal Case (with oxide coatings)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tritium Release to</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Auxiliary Systems, mCi/d</strong></td>
<td></td>
</tr>
<tr>
<td>Permeation through DHX walls</td>
<td>479</td>
</tr>
<tr>
<td>Permeation through PHTS containment walls</td>
<td>670</td>
</tr>
<tr>
<td>Permeation through IHTS containment walls</td>
<td>74</td>
</tr>
<tr>
<td>PHTS cover gas leakage</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1224</td>
</tr>
<tr>
<td><strong>Tritium Concentration in</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Sodium Coolant, Ci/kg Na</strong></td>
<td></td>
</tr>
<tr>
<td>PHTS</td>
<td>$1.98 \times 10^{-3}$</td>
</tr>
<tr>
<td>IHTS</td>
<td>$3.17 \times 10^{-4}$</td>
</tr>
<tr>
<td><strong>Hydrogen Concentration in</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Sodium Coolant, ppb</strong></td>
<td></td>
</tr>
<tr>
<td>PHTS</td>
<td>49</td>
</tr>
<tr>
<td>IHTS</td>
<td>54</td>
</tr>
<tr>
<td><strong>Tritium Content of</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Cold Traps, Ci</strong></td>
<td></td>
</tr>
<tr>
<td>One PHTS Cold Trap</td>
<td>4777</td>
</tr>
<tr>
<td>Three IHTS Cold Traps</td>
<td>1226</td>
</tr>
<tr>
<td><strong>Hydrogen Content of</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Cold Traps, kg H</strong></td>
<td></td>
</tr>
<tr>
<td>One PHTS Cold Trap</td>
<td>0.14</td>
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<tr>
<td>Three IHTS Cold Traps</td>
<td>0.25</td>
</tr>
</tbody>
</table>

VI. SUMMARY AND CONCLUSIONS

An updated tritium and hydrogen transport model has been successfully applied to EBR-II, and good agreement has been obtained between experimental and calculated tritium and hydrogen profiles. These results lend confidence to predictions made with the model for CRBR and FFTF. The current model may also be applied to future LMFBR systems.
The major influence of oxide coatings in inhibiting tritium permeation through structural materials is a key feature of the model. Under normal conditions, all exterior sodium containment surfaces will be oxidized to some degree. Therefore, accurate tritium permeation data are needed for both oxidized and unoxidized metals and alloys in an LMFBR environment. Protective oxide barriers are expected to be the second most effective means of controlling tritium release, cold trapping being the most important.

The efficiency of tritium removal by cold trapping is strongly dependent on hydrogen sources in the sodium coolant. Because of the predominant coprecipitation mechanism in the cold traps, large hydrogen influxes from the steam generator are beneficial; however, these same large influxes also shorten cold trap lifetimes. Thus, accurate experimental data for hydrogen influx rates are vital. These data would allow cold trap designs to be optimized and the complex interrelationship between hydrogen and tritium in the sodium coolant to be characterized completely by the model.

Tritium losses from sodium containment to auxiliary systems have been found to be very small. Further treatment of effluent gas and water streams to remove tritium will ultimately reduce losses to the environment to extremely small quantities, well below federally mandated levels. This transport modeling study indicates that large LMFBRs can be safely operated with essentially no tritium hazard to the environment.
APPENDIX A

TRITIUM-HYDROGEN TRANSPORT MODEL:
THE MATHEMATICAL SIMULATION

The material balance equations for tritium and hydrogen in the sodium coolant circuits and in the water/steam system of an LMFBR plant may be written as follows:

Tritium

**PHTS Sodium**

\[ g_1 = S_T - c_1 x_1 - c_2 (x_1 - x_2) - c_3 \left( \frac{x_1^2}{K_{ST}} \right) + \left( \frac{c_{15} X_1 X_4}{K_{ST} K_{SH}} \right) - c_4 x_1 \eta_P \left[ 1 - \frac{c_{16}}{(x_1 + x_4)} \right] - c_7 x_1 W_P \]

**IHPS Sodium**

\[ g_2 = c_2 (x_1 - x_2) - x_2 (c_5 + c_6) - c_8 \left( \frac{x_2^2}{K_{ST}} + \frac{c_{18} X_2 X_5}{K_{ST} K_{SH}} \right) - c_9 x_2 \eta_S \left[ 1 - \frac{c_{17}}{(x_2 + x_5)} \right] - c_7 x_2 W_S \]

**Steam/Water System**

\[ g_3 = c_6 x_2 - c_{11} x_3 - c_7 x_3 W_W \]

Hydrogen

**PHTS Sodium**

\[ g_4 = S_{HP} + c_{13} (x_5 - x_4) - c_3 \left( \frac{x_5^2}{K_{SH}} + \frac{c_{15} X_1 X_4}{K_{ST} K_{SH}} \right) - c_4 x_4 \eta_P \left[ 1 - \frac{c_{16}}{(x_1 + x_4)} \right] \]

**IHPS Sodium**

\[ g_5 = S_H - c_{13} (x_5 - x_4) - c_8 \left( \frac{x_5^2}{K_{SH}} + \frac{c_{18} X_2 X_5}{K_{ST} K_{SH}} \right) - c_9 x_5 \eta_S \left[ 1 - \frac{c_{17}}{(x_2 + x_5)} \right] \]
The nomenclature for the above equations is:

- \( c_1 \) Permeation factor for tritium transport through the primary sodium containment (includes PHTS hot and cold legs and walls of the main reactor vessel), \((\text{atoms T/s})/(\text{atoms T/kg Na})\); see Appendix B.

- \( c_2 \) Permeation factor for tritium transport through the IHX, \((\text{atoms T/s})/(\text{atoms T/kg Na})\).

- \( c_3 \) Tritium loss factor due to PHTS cover gas leakage, atoms T/s.

- \( c_4 \) Sodium flow rate in PHTS cold trap, kg Na/s.

- \( c_5 \) Permeation factor for tritium transport through the secondary sodium containment (includes IHTS hot and cold legs), \((\text{atoms T/s})/(\text{atoms T/kg Na})\).

- \( c_6 \) Permeation factor for tritium transport through Creloy (Fe-2 1/4 Cr-1 Mo) steam generator tubes (includes separate terms for superheaters and evaporators), \((\text{atoms T/s})/(\text{atoms T/kg Na})\).

- \( c_7 \) Tritium decay constant, \(1.79 \times 10^{-9} \text{ s}^{-1}\).

- \( c_8 \) Tritium loss factor due to IHTS cover gas leakage, atoms T/s.

- \( c_9 \) Sodium flow rate in IHTS cold traps, kg Na/s.

- \( c_{10} \) Rate of water loss from the steam system, equivalent to the required water make-up rate, kg H\(_2\)O/s.

- \( c_{11} \) Permeation factor for hydrogen transport through the IHX, \((\text{atoms H/s})/(\text{atoms H/kg Na})\).

- \( c_{15} \left(\frac{K_p(T)}{4}\right)^{1/2} \) evaluated at the temperature of the PHTS cover gas.

- \( c_{16} \) Solubility of hydrogen (or tritium) in sodium at the temperature of the PHTS cold trap, atoms H or T/kg Na.

- \( c_{17} \) Solubility of hydrogen (or tritium) in sodium at the temperature of the IHTS cold traps, atoms H or T/kg Na.

- \( c_{18} \left(\frac{K_p(T)}{4}\right)^{1/2} \) evaluated at the temperature of the IHTS cover gas.

- \( \dot{s}_1 \) Rate of change of tritium content of the PHTS sodium, atoms T/s.

- \( \dot{s}_2 \) Rate of change of tritium content of the IHTS sodium, atoms T/s.

- \( \dot{s}_3 \) Rate of change of tritium content of the water/steam system, atoms T/s.
Rate of change of hydrogen content of the PHTS sodium, atoms H/s.

Rate of change of hydrogen content of the IHTS sodium, atoms H/s.

Rate of tritium release to PHTS sodium, atoms T/s.

Rate of introduction of external hydrogen to PHTS sodium, atoms H/s.

Rate of introduction of hydrogen to IHTS sodium due to steam generator corrosion, atoms H/s.

Mass of PHTS sodium, kg Na.

Mass of IHTS sodium, kg Na.

Mass of water in steam generator system, kg H₂O.

Tritium concentration in PHTS sodium, atoms T/kg Na.

Tritium concentration in IHTS sodium, atoms T/kg Na.

Tritium concentration in the water/steam system, atoms T/kg H₂O.

Hydrogen concentration in PHTS sodium, atoms H/kg Na.

Hydrogen concentration in IHTS sodium, atoms H/kg Na.

PHTS cold trap efficiency.

IHTS cold trap efficiency.
APPENDIX B

PHYSICAL PROPERTIES OF TRITIUM AND HYDROGEN IN SODIUM AND IN REACTOR STRUCTURAL MATERIALS

The physical properties of the tritium-hydrogen-sodium-stainless steel-Croloy systems needed for the transport model are discussed in this Appendix. These properties include the permeability of both hydrogen and tritium in SS-316, SS-304, and Fe-2 1/4 Cr-1 Mo (Croloy), the solubility of both isotopes in liquid sodium, the Sieverts' Law constants for both isotopes in liquid sodium, and the temperature-dependent gas-phase equilibrium constant for the reaction, $H_2 + T_2 \rightarrow 2HT$.

Permeabilities of Tritium and Hydrogen in SS-316, SS-304 and Fe-2 1/4 Cr-1 Mo

Webb\(^1\)\(^9\) has tabulated the permeabilities of hydrogen in SS-316 and SS-304. These are exponential functions of the temperature, $T$, and are given by the following expressions:

\[
PH_{316}(T) = \frac{2.2781 \times 10^{18}}{K_{SH}(T)} \exp\left(-\frac{16075}{RT}\right) \frac{\text{atoms H-cm}}{\text{cm}^2 \cdot \text{s} \cdot (\text{atoms H/kg Na})}
\]

\[
PH_{304}(T) = \frac{1.2689 \times 10^{18}}{K_{SH}(T)} \exp\left(-\frac{16100}{RT}\right) \frac{\text{atoms H-cm}}{\text{cm}^2 \cdot \text{s} \cdot (\text{atoms H/kg Na})}
\]

Since directly measured experimental data for tritium permeation in stainless steels are scarce or not available at all, we have corrected the above expressions for $PH_{316}(T)$ and $PH_{304}(T)$ to account for the isotopic mass difference between hydrogen and tritium. Assuming a square-root-of-mass relationship for this correction, the corresponding tritium permeabilities in SS-316 and SS-304 may be written:

\[
PT_{316}(T) = \frac{1.3153 \times 10^{18}}{K_{ST}(T)} \exp\left(-\frac{16075}{RT}\right) \frac{\text{atoms T-cm}}{\text{cm}^2 \cdot \text{s} \cdot (\text{atoms T/kg Na})}
\]

\[
PT_{304}(T) = \frac{7.3263 \times 10^{17}}{K_{ST}(T)} \exp\left(-\frac{16100}{RT}\right) \frac{\text{atoms T-cm}}{\text{cm}^2 \cdot \text{s} \cdot (\text{atoms T/kg Na})}
\]

The permeability of tritium in Fe-2 1/4 Cr-1 Mo (Croloy) has been measured as a function of temperature.\(^12\),\(^13\) The permeability of hydrogen in Croloy over the same temperature range has been calculated from the measured tritium permeability by the square-root-of-mass approximation. These may be written:

\[
PT_{CROLY}(T) = \frac{1.2645 \times 10^{17}}{K_{ST}(T)} \exp\left(-\frac{9300}{RT}\right) \frac{\text{atoms T-cm}}{\text{cm}^2 \cdot \text{s} \cdot (\text{atoms T/kg Na})}
\]

\[
PH_{CROLY}(T) = \frac{2.1901 \times 10^{17}}{K_{SH}(T)} \exp\left(-\frac{9300}{RT}\right) \frac{\text{atoms H-cm}}{\text{cm}^2 \cdot \text{s} \cdot (\text{atoms H/kg Na})}
\]
The permeation factors, \( c_i \), defined in Appendix A for transport of hydrogen or tritium across sodium containment walls, may then be related to the known permeabilities by expressions of the form,

\[
c_i = \frac{P_i A_i}{L_i F_i}
\]

where \( P_i \) is the permeability of the specific material, \( i \), to either tritium or hydrogen, \( A_i \) is the surface area, \( L_i \) is the thickness, and \( F_i \) is a factor that accounts for the presence of protective oxide coatings on the exterior surfaces of the sodium containment. In the absence of any oxide coating, \( F_i \) would be unity. Particular values of \( F_i \) used for EBR-II, CRBR, and FFTF calculations are included in Appendices C, D, and E, respectively.\(^{13,14}\)

**Solubilities of Tritium and Hydrogen in Sodium**

The solubilities of tritium and hydrogen in liquid sodium are needed to predict the effect of cold trap operation at various temperatures. For this purpose, the solubility expression of Vissers et al.\(^2\) was employed:

\[
S(T) = 6.023 \times 10^{20} \exp \left( -\frac{6631.4}{T} + 13.9698 \right) \text{ atoms H/kg Na}
\]

Due to a lack of experimental data for tritium solubility in liquid sodium, its solubility (atoms T/kg Na) was assumed to be equal to the hydrogen solubility at the same temperature, and the above equation for \( S(T) \) was used for both isotopes.

**Sieverts' Law Constants for Hydrogen Isotopes in Liquid Sodium**

The Sieverts' Law constant for hydrogen in sodium was determined by Vissers et al.\(^2\) and is given by the equation

\[
K_{SH}(T) = 1.6604 \times 10^{22} \exp \left( -\frac{280.92}{T} + 1.9802 \right) \text{ atoms H/kg Na-atm}^{1/2}
\]

The Sieverts' Law constant for tritium in sodium has not been measured but may be related to \( K_{SH} \) above. Veleckis et al.\(^1\) have studied the analogous LiH, LiD, and LiT systems and have found that the decomposition pressures are related by

\[
P_{T_2} > P_{D_2} > P_{H_2}
\]

where

\[
\left( \frac{P_{T_2}}{P_{H_2}} \right) = 3^{1/2}
\]

and

\[
\left( \frac{P_{D_2}}{P_{H_2}} \right) = 2^{1/2}
\]
Veleckis et al. also observed that essentially no isotope effect exists for the solubilities of hydrogen and deuterium in lithium. Based on these observations, and our own assumption of equal solubility for tritium and hydrogen in sodium, one may write

\[ K_{ST}^{1/2} = K_{SH}^{1/2} \]

and

\[ K_{ST} = 3^{-1/4} K_{SH} \]

Therefore,

\[ K_{ST}(T) = 1.2616 \times 10^{22} \exp \left( -\frac{280.92}{T} + 1.9802 \right) \frac{\text{atoms T}}{\text{kg Na-atm}^{1/2}} \]

**Equilibrium Constant for Reaction:** \( H_2 + T_2 \rightarrow 2HT \)

In the PHTS and IHTS cover gases, hydrogen isotopes are present as \( H_2, T, \) and \( HT \). The equilibrium constant describing the interaction of these three species is

\[ K_p = \frac{P_{HT}^2}{P_{H_2} P_{T_2}} \]

where \( P_{HT}, P_{H_2}, \) and \( P_{T_2} \) are the partial pressures in the cover gas of \( HT, H_2, \) and \( T_2 \), respectively. The equilibrium constant, \( K_p \), is a function of temperature and has been determined by Jones:

\[ K_p = \exp \left( -\frac{133}{T} + 1.46966 \right) \]

\( K_p \) is used to calculate tritium and hydrogen losses from the cover gas systems.
APPENDIX C

SYSTEMS DATA FOR EBR-II TRITIUM-
HYDROGEN TRANSPORT CALCULATIONS

The systems data for EBR-II were obtained from the System Design Descriptions except where otherwise noted.

Mass of PHTS sodium: $3.2 \times 10^5$ kg

Mass of IHTS sodium: $5.7 \times 10^4$ kg

Mass of water in steam system: $4.5 \times 10^4$ kg

Source term for tritium in PHTS sodium, $S_T$: 
$1.22 \times 10^{14}$ atoms T/s (0.51 Ci/d)

Source term for hydrogen in PHTS sodium, $S_{HP}$: zero

Source term for hydrogen in IHTS sodium, $S_H$: 
$7.95 \times 10^{18}$ atoms H/s (48 mg H/h)

Sodium flow rate in PHTS cold trap: 1.2 Kg/s

Sodium flow rate in IHTS cold trap: 
0.42 kg/s, normally; zero for profiles given in Fig. 2 where cold trap was off-line

Water make-up rate: 0.26 kg/s

Leakage rate of PHTS cover gas: 25 cm$^3$(STP)/s 
(see Ref. 1)

Leakage rate of IHTS cover gas: 0.01 cm$^3$(STP)/s (assumed)

PHTS cold trap efficiency: 70%

IHTS cold trap efficiency: 50%

PHTS containment area: $3.06 \times 10^6$ cm$^2$

IHTS containment area: $3.7 \times 10^6$ cm$^2$

Heat transfer area in IHX: $4.55 \times 10^6$ cm$^2$
Heat transfer area in steam generator:
Superheater: $9.9 \times 10^5 \text{ cm}^2$
Evaporator: $3.96 \times 10^6 \text{ cm}^2$
\[= 4.95 \times 10^6 \text{ cm}^2\]

PHTS containment wall thickness: 1.27 cm
IHTS containment wall thickness: 0.635 cm
IHX tube-wall thickness: 0.124 cm
Steam generator tube-wall thickness: 0.475 cm

Temperature of PHTS containment: 644 K (700°F)
Temperature of IHTS containment: 700 K (800°F)

Logarithmic-mean temperature of IHX tubes:
687 K (777°F)

Superheater tube temperature in steam generator:
721 K (838°F)

Evaporator tube temperature in steam generator:
635 K (684°F)

PHTS cold trap temperature: 389 K (240°F)
IHTS cold trap temperature: 389 K (240°F)
PHTS cover gas temperature: 644 K (700°F)
IHTS cover gas temperature: 700 K (800°F)

F-factors to account for inhibiting effect of oxide coatings on tritium permeation rates through containment materials:

\[F(\text{PHTS containment, SS-304}) = 100\]
\[F(\text{IHTS containment, SS-304}) = 100\]
\[F(\text{IHX, SS-304, oxide-free}) = 1\]
\[F(\text{steam generator tubes, Croloy}) = 150\]
APPENDIX D

SYSTEMS DATA FOR CRBR TRITIUM-HYDROGEN TRANSPORT CALCULATIONS

The systems data for CRBR were obtained from System Design Descriptions and from the Preliminary Safety Analysis Report (PSAR), except where indication to the contrary is given.

Mass of PHTS sodium: $6.19 \times 10^5$ kg

Mass of IHTS sodium: $5.77 \times 10^5$ kg

Mass of water in steam system: $5.0 \times 10^5$ kg (estimated)

Source term for tritium in PHTS sodium, $S_T$: $2.13 \times 10^{16}$ atoms T/s (89 Ci/d)

Source term for hydrogen in PHTS sodium, $S_{HP}$: zero

Source term for hydrogen in IHTS sodium, $S_H$: $6.05 \times 10^{20}$ atoms H/s (3.6 g H/h)

Sodium flowrate in PHTS cold trap: 3.43 kg/s

Sodium flowrate in IHTS cold traps: 10.29 kg/s, total for three traps

Water make-up rate: 2.6 kg/s (estimated)

Leakage rate of PHTS cover gas: 25 cm$^3$(STP)/s (assumed)

Leakage rate of IHTS cover gas: 0.01 cm$^3$(STP)/s (assumed)

PHTS cold trap efficiency: 70%

IHTS cold trap efficiency: 70%

PHTS containment area:

- hot leg: $4.61 \times 10^6$ cm$^2$
- cold leg: $2.65 \times 10^6$ cm$^2$
IHTS containment area:
  hot leg: $1.26 \times 10^7 \text{ cm}^2$
  cold leg: $9.24 \times 10^6 \text{ cm}^2$

Heat transfer area in IHX: $4.45 \times 10^7 \text{ cm}^2$

Heat transfer area in steam generator:
  Superheater: $1.76 \times 10^7 \text{ cm}^2$
  Evaporator: $3.53 \times 10^7 \text{ cm}^2$
  \[5.29 \times 10^7 \text{ cm}^2\]

PHTS containment wall thickness: 1.27 cm

IHTS containment wall thickness: 1.27 cm

IHX tube-wall thickness: 0.114 cm

Steam generator tube-wall thickness: 0.280 cm

Temperature of PHTS containment:
  hot leg: 808 K (995°F)
  cold leg: 661 K (730°F)

Temperature of IHTS containment:
  hot leg: 775 K (936°F)
  cold leg: 616 K (650°F)

Logarithmic-mean temperature of IHX tubes: 727 K (849°F)

Superheater tube temperature in steam generator: 758 K (905°F)

Evaporator tube temperature in steam generator: 675 K (755°F)

PHTS cold trap temperature: 394 K (250°F)

IHTS cold trap temperature: 394 K (250°F)

PHTS cover gas temperature: 808 K (995°F)

IHTS cover gas temperature: 616 K (650°F)
F-factors to account for inhibiting effect of oxide coatings on tritium permeation rates through containment materials:

\[
\begin{align*}
F(\text{PHTS hot leg, SS-316}) &= 300 \\
F(\text{PHTS cold leg, SS-304}) &= 100 \\
F(\text{IHTS hot leg, SS-316}) &= 200 \\
F(\text{IHTS cold leg, SS-304}) &= 100 \\
F(\text{IHX, SS-304, oxide-free}) &= 1 \\
F(\text{steam generator tubes, Croloy}) &= 150
\end{align*}
\]
APPENDIX E

SYSTEMS DATA FOR FFTF TRITIUM-HYDROGEN TRANSPORT CALCULATIONS

The systems data for FFTF were obtained from the System Design Descriptions except where otherwise noted.

Mass of PHTS sodium: $4.89 \times 10^5$ kg

Mass of IHTS sodium: $2.25 \times 10^5$ kg

Source term for tritium in PHTS sodium, $S_T$: $9.57 \times 10^{15}$ atoms T/s (40 Ci/d)

Source term for hydrogen in PHTS sodium, $S_{HP}$: $5 \times 10^{18}$ atoms H/s (30 mg H/h) (estimated)

Source term for hydrogen in IHTS sodium, $S_H$: $1 \times 10^{19}$ atoms H/s (60 mg H/h) (estimated)

Sodium flow rate in PHTS cold trap: 3.43 kg/s

Sodium flow rate in IHTS cold traps: 2.58 kg/s, total for three traps

Leakage rate of PHTS cover gas: 25 cm$^3$(STP)/s (assumed)

Leakage rate of IHTS cover gas: 0.01 cm$^3$(STP)/s (assumed)

PHTS cold trap efficiency: 70%

IHTS cold trap efficiency: 70%

The FFTF plant has one PHTS and three identical IHTSs. The surface areas and wall thicknesses were obtained from Ref. 7. The PHTS and IHTS sodium containments were each considered to consist of two separate sections, a hot leg and a cold leg. The surface areas and wall thicknesses in each section were reduced to an equivalent surface area and a common wall thickness (1 cm). Then, all areas at one temperature were added together to obtain the total area for use in calculating permeation factors, $c_i$ (see Appendix A).
PHTS containment area:
  hot leg: $4.52 \times 10^6$ cm$^2$
  cold leg: $3.73 \times 10^6$ cm$^2$

IHTS containment area:
  hot leg: $6.03 \times 10^6$ cm$^2$
  cold leg: $4.64 \times 10^6$ cm$^2$

Heat transfer area in IHX: $1.0 \times 10^8$ cm$^2$

Heat transfer area in DHX: $1.2 \times 10^8$ cm$^2$

All pipe and tube-wall thicknesses were reduced to a common value of 1 cm

Temperature of PHTS containment:
  hot leg: 839 K (1050°F)
  cold leg: 695 K (792°F)

Temperature of IHTS containment:
  hot leg: 791 K (965°F)
  cold leg: 648 K (707°F)

Logarithmic-mean temperature of IHX tubes:
  739 K (870°F)

Logarithmic-mean temperature of DHX tubes:
  716 K (830°F)

PHTS cold trap temperature: 389 K (240°F)

IHTS cold trap temperature: 389 K (240°F)

PHTS cover gas temperature: 839 K (1050°F)

IHTS cover gas temperature: 648 K (707°F)

F-factors to account for inhibiting effect of oxide coatings on tritium permeation rates through containment materials:

\[
F(\text{PHTS containment, SS-304}) = 100 \\
F(\text{IHTS containment, SS-304}) = 100 \\
F(\text{IHX, SS-304, oxide-free}) = 1 \\
F(\text{DHX, SS-304}) = 100
\]
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7. T. J. Kabele, Parametric Study of the Tritium Distribution in the FFTF, HEDL-TME 74-6 (February 1974).


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