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**Westinghouse Electric Corporation
Fusion Power Systems Department**

**STUDIES OF THE PERMEATION AND DIFFUSION
OF
TRITIUM AND HYDROGEN IN TFTR**

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STUDIES OF
THE PERMEATION AND DIFFUSION OF
TRITIUM AND HYDROGEN IN TFTR

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ABSTRACT

This report documents the main features of studies conducted on the permeation and diffusion of tritium and hydrogen through the stainless steel sections comprising the vacuum vessel of TFTR. The overall conclusion of these studies is that tritium releases to the environment resulting from TFTR operations under normal conditions will be very small, less than one curie per year.

Section 1.0 of the report provides a basis for predicting the magnitudes of the applicable transport properties for tritium-austenitic stainless steel systems as derived from a survey of the technical literature on tritium transport.

Section 2.0 tabulates the key characteristics of the TFTR vacuum vessel that are involved in the permeation and diffusion calculations. Section 3.0 provides information regarding the contemplated plasma scenarios and associated required gas injection quantities, which information is applied in Section 4.0 to form a basis for estimating tritium permeations out of the system during TFTR operations with tritium containing plasmas. The calculations made in Section 4.0 are made on the basis of a quasi-steady state model, which grossly over-states the expected tritium releases.

Section 5.0 examines the tritium level variations in the test cell atmosphere, utilizing the release quantities generated in Section 4.0. It is shown that the highest tritium level encountered is $\sim 10^{-7} \mu\text{Ci}/\text{cm}^3$, which is but two percent of the maximum permissible concentration for controlled areas.

Section 6.0 treats various issues involved in the bakeout of the vacuum vessel, focussing principally on the problems associated with in-situ bakeout and related means to reduce out-gassing from the TFTR vessel and vacuum pumping system hardware. This section summarizes the more relevant quantitative findings derivable from diffusion considerations which center on estimating the expected hydrogen releases during elevated temperature exposures.

Section 7.0 treats the anticipated tritium releases based on a consideration of diffusion transients. The computation model utilizes one-dimensional diffusion through each of the metal

sections of the vessel, based on a simplified "smeared" gas phase tritium concentration throughout the exposure-to-tritium period. Mathematical formulations are presented which are applicable in general to handle any combination of successive exposure and outage periods. However, numerical results are presented only for the first operations of TFTR with tritium and for quasi-steady state conditions. These computations indicate that essentially no tritium releases will occur for normal TFTR operations if the system is "tight". The quasi-steady state calculated annual tritium release in this case amounts to 0.75 curie. This agrees with the 0.66 curie release calculated in Section 4.0.

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TABLE OF SYMBOLS

SECTION 1.0

A	Empirical constant in transport property equation, cm^2/sec for diffusivity, STP $\text{cm}^3 \text{T}_2 / \text{cm}^2 \text{ sec torr}^{1/2}$ for permeability, STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel torr}^{1/2}$ for solubility
B	Empirical constant, $^\circ\text{K}^{-1}$
D	Diffusivity, cm^2/sec
D_e	Effective diffusivity, accounting for grain boundary transport contribution, cm^2/sec
D_g	Diffusivity for grain boundaries, cm^2/sec
S	Solubility, STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel torr}^{1/2}$
T	Absolute temperature, $^\circ\text{K}$
Φ	Permeability, STP $\text{cm}^3 \text{T}_2 / \text{cm}^2 \text{ sec torr}^{1/2}$
Φ_e	Effective permeability, accounting for grain boundary transport contribution, STP $\text{cm}^3 \text{T}_2 / \text{cm}^2 \text{ sec torr}^{1/2}$

SECTION 3.0

a	Plasma minor radius (for ATC studies documented in reference 10), cm
A	Number of surface adsorbed molecules
d	Initial deuterium to tritium mole ratio for torus contained population
F_D	Desired final deuterium mole fraction in the torus residual gas
F_T	Desired tritium mole fraction in the plasma precursor gas
I	Plasma current, MA

n	Number of tritium build-up operations required to achieve F_T , or tritium flush-out operations required to attain F_D
n_e	Electron density in the plasma, particles/cm ³
$n(r)$	Neutral particle content as a function of radial position, particles/cm ³
N_t	Number of tritium atoms in the plasma precursor gas
P	Variable gas pressure in the torus, torr
P_o	Gas pressure in the torus at start of pump-down subsequent to conducting a pulse experiment, torr
r	Radial displacement, measured from plasma center, cm
r_p	Plasma minor radius, cm
R_p	Plasma major radius, cm
t	Number of tritium molecules added per build-up operation or pulse
V_t	Torus interior volume for gas, cm ³
W_o	Energy of primary injected neutral beam deuterium, keV
θ	Pump-down time, sec
τ	Neutral beam injection time, msec

SECTION 4.0

A	Number of surface adsorbed molecules
F_T	Desired tritium mole fraction in the plasma precursor gas
L	Thickness of stainless steel sections of the torus, cm
P	Variable pressure of the gas in the torus, torr
P_o	Initial torus gas pressure at start of pump-down, torr

$\bar{P}_T^{1/2}$

Integral mean square root of the tritium partial pressure in the system over the time interval θ , torr^{1/2}

Q

Total tritium permeated during the time interval θ , μCi

r

Instantaneous tritium permeation rate, $\mu\text{Ci}/\text{sec}$

S

Surface of stainless steel sections of the torus, cm²

t

Number of tritium molecules added per build-up operation or pulse

θ

Variable time, sec

Φ_e

Effective tritium permeability (defined in equation 8), $\mu\text{Ci cm}/\text{cm}^2 \text{ sec torr}^{1/2}$

SECTION 5.0

a

Constant in tritium permeation rate equations, $\mu\text{Ci}/\text{sec}$

b

Time constant in tritium permeation rate equations, sec⁻¹

c

Instantaneous tritium concentration in the cell air, $\mu\text{Ci}/\text{cm}^3$

c_b

Tritium concentration in the test cell air at the conclusion of the 22 build-up operations, prior to initiation of ventilation, $\mu\text{Ci}/\text{cm}^3$

c_B

Final tritium concentration in the test cell air at the end of the tritium build-up operations day, $\mu\text{Ci}/\text{cm}^3$

c_f

Tritium concentration in the test cell air at the conclusion of the 140 tritium flush-out operations, prior to initiation of ventilation, $\mu\text{Ci}/\text{cm}^3$

c_F

Final tritium concentration in the test cell air at the end of the tritium flush-out operations day, $\mu\text{Ci}/\text{cm}^3$

c_o

Tritium concentration in the test cell air immediately prior to initiating tritium build-up operations, $\mu\text{Ci}/\text{cm}^3$

c_p	Tritium concentration in the test cell air at the conclusion of the reference 40 D-T pulsing operations, prior to initiation of ventilation, $\mu\text{Ci}/\text{cm}^3$
c_p	Final tritium concentration in the test cell air at the end of the D-T pulsing operations day, $\mu\text{Ci}/\text{cm}^3$
L	Air inleakage rate into the test cell, cm^3/sec
r	Variable tritium transport rate into the test cell via permeation, $\mu\text{Ci}/\text{sec}$
r_b	Tritium transport rate into the test cell air during the tritium build-up operations, $\mu\text{Ci}/\text{sec}$
r_B	Tritium transport rate into the test cell air during the post-tritium build-up operating day, $\mu\text{Ci}/\text{sec}$
r_f	Tritium transport rate into the test cell air during the tritium flush-out operations, $\mu\text{Ci}/\text{sec}$
r_F	Tritium transport rate into the test cell air during the post-tritium flush-out operating day, $\mu\text{Ci}/\text{sec}$
r_p	Tritium transport rate into the test cell air during the D-T pulsing operations, $\mu\text{Ci}/\text{sec}$
r_p	Tritium transport rate into the test cell air during the post-D-T pulsing operating day, $\mu\text{Ci}/\text{sec}$
R	Amount of tritium released to the environment, μCi
v	Test cell ventilation rate, cm^3/sec
V	Test cell volume, cm^3
θ	Variable time elapsed, sec

SECTION 6.0

C	Instantaneous hydrogen concentration, STP $\text{cm}^3 \text{H}_2/\text{cm}^3 \text{ steel}$
C_o	Initial uniform hydrogen concentration in the as-fabricated steel, STP $\text{cm}^3 \text{H}_2/\text{cm}^3 \text{ steel}$
D	Steel diffusivity for hydrogen at temperature $T^\circ\text{K}$, cm^2/sec
D_b	Steel diffusivity for hydrogen at the bake-out temperature, cm^2/sec
D_p	Steel diffusivity for hydrogen at the D-T pulsing test temperature, cm^2/sec
F_b	Fraction of initially contained hydrogen in the as-fabricated steel still retained after bakeout for time θ_b at temperature T_b
G_b	Instantaneous hydrogen outgassing rate during bakeout at temperature T_b , STP $\text{cm}^3 \text{H}_2/\text{cm}^2 \text{ sec}$
G_p	Instantaneous hydrogen outgassing rate during pulsing tests at temperature T_p , STP $\text{cm}^3 \text{H}_2/\text{cm}^2 \text{ sec}$
G_{p_o}	Initial hydrogen outgassing rate at start of pulsing tests at temperature T_p immediately following a bakeout conducted at temperature T_b for a time interval θ_b , STP $\text{cm}^3 \text{H}_2/\text{cm}^2 \text{ sec}$
i	$\sqrt{-1}$
L	Thickness of steel sections, cm
n	Term index in infinite series
s_1	Infinite series, defined by equations 51a and 52a
s_2	Infinite series, defined by equations 51b and 52b
T	Absolute temperature, $^\circ\text{K}$
T_b	Temperature maintained during bakeout, $^\circ\text{K}$

T_p	Temperature maintained during pulsing operations, °K
x	Variable depth into steel sections, cm
y	Form parameter for series transformations (see equation 49)
z	Form parameter for series transformations (see equation 49)
θ	Variable time, sec
θ_b	Duration of isothermal bakeout at temperature T_b , sec
θ_p	Duration of isothermal pulsing operations at temperature T_p , sec

SECTION 7.0

C	Instantaneous tritium concentration, STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel}$
C^*	Equilibrium tritium concentration, corresponding to a tritium pressure of $\bar{P}_{T_2}$, STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel}$
C_1^*	Equilibrium tritium concentration applicable for first tritium exposure period, STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel}$
C_2^*	Equilibrium tritium concentration applicable for second tritium exposure period, STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel}$
$C_{\epsilon 1}$	Tritium concentration (distribution) at end of first tritium exposure period, STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel}$
$C_{\epsilon i}$	Tritium concentration (distribution) at end of i th tritium exposure period, STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel}$
$C_{\omega 1}$	Tritium concentration (distribution) at end of first outage period, STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel}$
$C_{\omega i}$	Tritium concentration (distribution) at end of i th outage period, STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel}$

D	Effective diffusivity, accounting for grain boundary transport contribution, cm^2/sec
G	Surface diffusion current at steel sections faces, $\text{STP cm}^3 \text{T}_2/\text{cm}^2 \text{sec}$
L	Thickness of stainless steel sections of the torus, cm
n	Term index in infinite series
$\bar{P}_{\text{T}_2}$	Mean tritium pressure during exposure period, torr
Q	Specific diffusion quantity out of a steel section surface during time interval θ , $\text{STP cm}^3 \text{T}_2/\text{cm}^2$
$s_1(\theta)$	Infinite series, defined by equations 51a, 52a
$s_2(\theta)$	Infinite series, defined by equations 51b, 52b
$s_3(\theta)$	Infinite series, defined by equation 60
$s_4(\theta)$	Infinite series, defined by equation 61
S	Surface of stainless steel sections of the torus, cm^2
x	Variable depth into the steel sections measured from the air-exposed side, cm
x'	Dummy variable depth into steel sections, cm
$\bar{X}$	Abbreviation for series solution form of tritium concentration distribution as defined by equation 53, $\text{STP cm}^3 \text{T}_2/\text{cm}^3 \text{steel}$
Γ	Section specific tritium content, $\text{STP cm}^3 \text{T}_2/\text{cm}^2$
Γ_0	Initial section specific tritium content, $\text{STP cm}^3 \text{T}_2/\text{cm}^2$
$\Delta \Gamma_\epsilon$	Change in section specific tritium content during an exposure period of duration ϵ , $\text{STP cm}^3 \text{T}_2/\text{cm}^2$
$\Delta \Gamma_\omega$	Change in section specific tritium content during an outage period of duration ω , $\text{STP cm}^3 \text{T}_2/\text{cm}^2$

ϵ	Duration of a tritium exposure period, sec
ϵ_1	Duration of the first tritium exposure period, sec
ϵ_2	Duration of the second tritium exposure period, sec
ϵ_i	Duration of the i th tritium exposure period, sec
θ	Variable time, sec
ω	Duration of an outage period, sec
ω_1	Duration of the first outage period, sec
ω_2	Duration of the second outage period, sec
ω_i	Duration of the i th outage period, sec

1.0 APPLICABLE TRANSPORT PROPERTIES

Conduct of engineering estimates of tritium transport through the TFTR equipment and normal tritium releases to the environment requires information on the diffusivity and permeability of the vacuum vessel materials to tritium. For this reason, an effort was made early in the program to seek such information in the open literature. This introductory section summarizes the results of this search.

During the past 40 years, a large number of published papers have dealt with the transport of hydrogenous species in varieties of steels. However, the papers and reports dealing with the movement of tritium through austenitic stainless steels have been relatively few in number. Fortunately, the agreement among these has been fairly good with regard to diffusivity and permeability. The variance in the case of solubility is greater, but nevertheless the agreement is reasonably satisfactory. The austenitic stainless steels investigated include AISI types 304, 304L, 316, and 347, but not 305, the reference material for the TFTR vacuum vessel.

In consideration of the bracketing of SS 305 by the others with regard to concentration of the principal alloying elements and the fact that there is essentially no observed difference in the transport properties of the austenitic stainless steels studied, it is reasonable to take the transport properties for the system tritium SS 305 as those resulting from a least-squares treatment of the published data for austenitic stainless steels. The AISI alloying concentration limits, as listed in Table 1-1, support this assertion.

Measurement of the tritium-stainless steel transport properties have been made by teams of investigators at Knolls Atomic Power Laboratory ^(1,2), Mound Laboratory ^(3,4), North Carolina State University ^(5,6), and Savannah River Laboratory ⁽⁷⁾. In each instance the investigators correlated the results of their experiments by Arrhenius type plots and developed empirical formulations that summarize their findings in the general form:

$$\text{Property} = A e^{-B/T} \quad (1)$$

Among the investigators, a multiplicity of units were used. When their formulations are re-stated in the same units (cm^2/sec for diffusivity; $\text{STP cm}^3\text{T}_2/\text{cm}^2\text{ torr}^{1/2}$ for permeability; $\text{STP cm}^3\text{T}_2/\text{cm}^3\text{ steel torr}^{1/2}$ for solubility) the values of A and B corresponding to the various references are as shown in Table 1-2.

TABLE 1-1
ALLOY CONCENTRATIONS FOR AISI TYPE 300 STAINLESS STEELS

Item	304	304L	305	316	347
Maximum w/o C	.08	.03	.12	.08	.08
Minimum w/o Mn	2.00	2.00	2.00	2.00	2.00
Maximum w/o P	.045	.045	.045	.045	.045
Maximum w/o S	.030	.030	.030	.030	.030
Maximum w/o Si	1.00	1.00	1.00	1.00	1.00
w/o Cr	18-20	18-20	17-19	16-18	17-19
w/o Ni	8-12	8-12	10-13	10-14	9-13
w/o Mo	-	-	-	2-3	-
w/o Ta	-	-	-	-	10 x C min

1. "Solubility of Hydrogen Isotopes in Nickel and Type 347 Stainless Steel", Norval J. Hawkins, KAPL-868 (April 13, 1953).
2. "Diffusion Studies 1. The Permeability of Type 347 Stainless Steel to Hydrogen and Tritium", D. Randall and O. N. Salmon, KAPL-904 (August 24, 1953).
3. "Solubility and Distribution of Tritium in Annealed and Cold Worked 304 Stainless Steel in the 100 to 300°C Temperature Range", G. W. Powell, J. D. Braun, K. F. Chaney, and G. L. Downs, Corrosion NACE 26: 223-228 (1970).
4. "The Diffusion of Tritium in 304 Stainless Steel in the Temperature Range 100 to 300°C", K. F. Chaney and G. W. Powell, Metallurgical Transactions 1: 2436-2537 (1970).
5. "Tritium Diffusion in 304 and 316 Stainless Steels in the Temperature Range 25 to 222°C", J. H. Austin and T. S. Elleman, Journal of Nuclear Materials 43: 119-125 (1972).
6. "Grain Boundary Diffusion of Tritium in 304 and 316 Stainless Steel", R. D. Calder, T. S. Elleman and K. Verghese, Journal of Nuclear Materials 46: 46-52 (1973).
7. "Tritium Absorption in 304L Stainless Steel", M. R. Louthan, Jr., J. A. Donovan, and G. R. Caskey, Jr., DP-MS-74-25 (October, 1974).

TABLE 1-2

MAGNITUDE OF TRANSPORT PARAMETERS

TRITIUM - AUSTENITIC STAINLESS STEELS

Reference	Diffusivity		Permeability		Solubility	
	A	B	A	B	A	B
1, KAPL					3.258×10^{-2}	921.5
2, KAPL	1.293×10^{-2}	7,081	4.219×10^{-4}	8,004	3.263×10^{-2}	922.8
3, Mound					4.15×10^{-1}	1,830
4, Mound	1.24×10^{-2}	6,844				
5, NC State	1.80×10^{-2}	7,079				
6, NC State (Grain Boundary)	8.70	5,108				
7, Savannah	2.71×10^{-3}	6,492	1.25×10^{-4}	7,196	4.64×10^{-2}	704.5

1.1 DERIVED BULK TRANSPORT PROPERTIES

A "least squares" treatment of the findings of the aforementioned investigators (excluding the grain boundary values of reference 6) leads to the following expressions⁽⁸⁾ for the temperature dependence of the bulk transport properties for tritium-austenitic stainless steels in the range 100-1400°C.

$$\text{Diffusivity: } D = 9.400 \times 10^{-3} e^{-6873.8/T} \text{ cm}^2/\text{sec} \quad (2)$$

$$\text{Permeability: } \Phi = 6.325 \times 10^{-4} e^{-7968.5/T} \text{ STP cm}^3 \text{ cm/cm}^2 \text{ sec torr}^{1/2} \quad (3)$$

$$\text{Solubility: } S = 6.782 \times 10^{-2} e^{-1094.7/T} \text{ STP cm}^3 \text{ T}_2/\text{cm}^3 \text{ steel torr}^{1/2} \quad (4)$$

Comparisons of values of the transport properties as calculated by equations 2, 3 and 4 with those predicted by the formulations of the various investigators for selected temperatures are shown in Tables 1-3, 1-4 and 1-5.

8. "Tritium Properties and Related Quantities Used in the TFTR Conceptual Design", Harold J. Garbor, WFPS-TME-004 (September, 1975).

TABLE 1-3
INTERCOMPARISON OF DIFFUSIVITIES
 cm^2/sec

Temp., °C	KAPL ⁽²⁾	Mound ⁽⁴⁾	NC State ⁽⁵⁾	Savannah ⁽⁷⁾	Equation 2
0	7.14×10^{-14}	1.63×10^{-13}	1.00×10^{-13}	1.29×10^{-13}	1.11×10^{-13}
20	4.18×10^{-13}	9.01×10^{-13}	5.86×10^{-13}	6.54×10^{-13}	6.17×10^{-13}
50	3.94×10^{-12}	7.87×10^{-12}	5.52×10^{-12}	5.11×10^{-12}	5.44×10^{-12}
100	7.42×10^{-11}	1.34×10^{-10}	1.04×10^{-10}	7.54×10^{-11}	9.40×10^{-11}
150	6.99×10^{-10}	1.17×10^{-9}	9.77×10^{-10}	5.89×10^{-10}	8.29×10^{-10}
200	4.09×10^{-9}	6.48×10^{-9}	5.72×10^{-9}	2.98×10^{-9}	4.61×10^{-9}
250	1.71×10^{-8}	2.58×10^{-8}	2.39×10^{-8}	1.11×10^{-8}	1.85×10^{-8}
300	5.57×10^{-8}	8.08×10^{-8}	7.79×10^{-8}	3.26×10^{-8}	5.82×10^{-8}
350	1.50×10^{-7}	2.11×10^{-7}	2.10×10^{-7}	8.10×10^{-8}	1.52×10^{-7}
400	3.49×10^{-7}	4.76×10^{-7}	4.88×10^{-7}	1.75×10^{-7}	3.46×10^{-7}

TABLE 1-4
INTERCOMPARISON OF PERMEABILITIES
 $\text{STP cm}^3\text{T}_2\text{cm}/\text{sec cm}^2 \text{ torr}^{1/2}$

Temp., °C	KAPL ⁽²⁾	Savannah ⁽⁷⁾	Equation 3
0	7.94×10^{-17}	4.54×10^{-16}	1.36×10^{-16}
20	5.86×10^{-16}	2.74×10^{-15}	9.92×10^{-16}
50	7.39×10^{-15}	2.67×10^{-14}	1.24×10^{-14}
100	2.04×10^{-13}	5.28×10^{-13}	3.37×10^{-13}
150	2.57×10^{-12}	5.16×10^{-12}	4.20×10^{-12}
200	1.90×10^{-11}	3.11×10^{-11}	3.07×10^{-11}
250	9.57×10^{-11}	1.33×10^{-10}	1.54×10^{-10}
300	3.63×10^{-10}	4.42×10^{-10}	5.80×10^{-10}
350	1.11×10^{-9}	1.21×10^{-9}	1.77×10^{-9}
400	2.89×10^{-9}	2.85×10^{-9}	4.57×10^{-9}

TABLE 1-5
INTERCOMPARISON OF SOLUBILITIES
STP $\text{cm}^3\text{T}_2/\text{cm}^3$ steel $\text{torr}^{1/2}$

Temp., °C	KAPL(1)	KAPL(2)	Mound(3)	Savannah(7)	Equation 4
0	1.12×10^{-3}	1.11×10^{-3}	5.11×10^{-4}	3.52×10^{-4}	1.23×10^{-3}
20	1.41×10^{-3}	1.40×10^{-3}	8.08×10^{-4}	4.20×10^{-3}	1.62×10^{-3}
50	1.88×10^{-3}	1.88×10^{-3}	1.44×10^{-3}	5.25×10^{-3}	2.29×10^{-3}
100	2.76×10^{-3}	2.75×10^{-3}	3.08×10^{-3}	7.03×10^{-3}	3.61×10^{-3}
150	3.69×10^{-3}	3.69×10^{-3}	5.50×10^{-3}	8.79×10^{-3}	5.10×10^{-3}
200	4.65×10^{-3}	4.64×10^{-3}	8.68×10^{-3}	1.05×10^{-2}	6.71×10^{-3}
250	5.60×10^{-3}	5.59×10^{-3}	1.26×10^{-2}	1.21×10^{-2}	8.37×10^{-3}
300	6.53×10^{-3}	6.52×10^{-3}	1.70×10^{-2}	1.36×10^{-2}	1.00×10^{-2}
350	7.43×10^{-3}	7.42×10^{-3}	2.20×10^{-2}	1.50×10^{-2}	1.17×10^{-2}
400	8.29×10^{-3}	8.28×10^{-3}	2.74×10^{-2}	1.63×10^{-2}	1.33×10^{-2}

In connection with equations 2, 3, and 4, it is to be noticed that they conform to the relationship

$$\Phi = SD \quad (5)$$

a condition that applied to the KAPL and Savannah River Lab findings and accordingly was also "force-fitted" into the least-squares correlations of all of the aforementioned transport information.

1.2 GRAIN BOUNDARY TRANSPORT

The foregoing correlations are for experiments conducted in the range 100 to 1400°C. Extrapolation to lower temperatures probably is not valid. The basis for this statement is summarized and borne out by the recent results reported by the North Carolina State University investigators⁽⁶⁾.

Studies have shown that at elevated temperatures the measured diffusivities for single crystals and polycrystalline samples of a given material are essentially identical. At lower temperatures, the polycrystalline material exhibits higher diffusivities, due presumably to the higher mobility in the grain boundaries, and at still lower temperature, the grain boundary diffusivity may dominate ⁽⁹⁾. The implication of this is that it may be risky to extrapolate higher temperature diffusivities to lower temperatures. In this connection, the following issues are relevant:

1. The jump frequency for grain boundary atoms is enormous, compared to lattice atoms, the effect increasing at lower temperatures. But this effect is greatly offset because of the relatively small number of grain boundary atoms on hand compared to the overall population.
2. For temperatures of interest for TFTR, essentially ambient, the grain boundary diffusivity can be grossly larger than the lattice diffusivity by many orders of magnitude, but still not dominate the overall transport.
3. Presently, there is no acceptable method for treating grain boundary diffusion contributions. The practical approach would involve summing up the individual contributions, applying the diffusivities over their operative areas. Considering the small areas involved (typical grain size of ~ 50 micron, with grain boundary width of ~ 1 Angstrom) the grain boundary contribution really cannot be substantial.

9. "Diffusion in Solids", P. G. Shewmon, McGraw Hill Book Co., (1963), pages 164-187.

The most recent report⁽⁶⁾ on tritium diffusion in austenitic stainless steel grain boundaries extricated, on somewhat questionable grounds, a grain boundary diffusivity of

$$D_g = 8.701 e^{-5,108/T} \text{ cm}^2/\text{sec} \quad (6)$$

which at 20°C corresponds to a value of $2.36 \times 10^{-7} \text{ cm}^2/\text{sec}$, about 4×10^5 times larger than the lattice diffusion coefficient listed previously in Table 1-3. In treating the TFTR tritium transport question, a contribution is included for the grain boundary effect in terms of an "effective" diffusivity or permeability as described below.

The contribution due to grain boundary transport is based on the indication that the average grain size for type 305 SS for the TFTR vacuum vessel will be in the range No. 10-11 ASTM (ASTM E 112), corresponding to about $8 \times 10^5 \text{ grains/cm}^2$, for a mean grain dimension of $\sim 1.2 \times 10^{-3} \text{ cm}$ and a grain boundary cross sectional area of $4.47 \times 10^{-11} \text{ cm}^2$ for the associated ~ 1 Angstrom wide grain boundary. The ratio of boundary area to grain area is $\sim 3.56 \times 10^{-5}$.

1.3 EFFECTIVE DIFFUSIVITY AND PERMEABILITY

The "effective" diffusivity, D_e , used in the tritium transport estimates is taken to be

$$D_e = \frac{D + 3.56 \times 10^{-5} D_g}{1 + 3.56 \times 10^{-5}} \quad (7)$$

and correspondingly, the "effective" permeability, Φ_e , is taken as

$$\Phi_e = \Phi \frac{D + 3.56 \times 10^{-5} D_g}{D(1 + 3.56 \times 10^{-5})}$$

The variations of the magnitudes of D_e and Φ_e with temperature are shown in Table 1-6.

TABLE 1-6
EFFECTIVE DIFFUSIVITIES AND PERMEABILITIES

Temperature, °C	D_e , cm ² /sec	Φ_e , STP cm ³ T ₂ cm/sec cm ² torr ^{1/2}
0	2.45×10^{-12}	3.00×10^{-15}
20	9.01×10^{-12}	1.45×10^{-14}
40	2.83×10^{-11}	5.77×10^{-14}
60	7.83×10^{-11}	1.97×10^{-13}
80	1.95×10^{-10}	5.92×10^{-13}
100	4.46×10^{-10}	1.60×10^{-12}
120	9.46×10^{-10}	3.93×10^{-12}
140	1.88×10^{-9}	8.95×10^{-12}
160	3.55×10^{-9}	1.91×10^{-11}
180	6.37×10^{-9}	3.83×10^{-11}
200	1.10×10^{-8}	7.29×10^{-11}
220	1.82×10^{-8}	1.33×10^{-10}
240	2.90×10^{-8}	2.32×10^{-10}
260	4.51×10^{-8}	3.89×10^{-10}
280	6.80×10^{-8}	6.32×10^{-10}
300	9.99×10^{-8}	9.96×10^{-10}
320	1.44×10^{-7}	1.53×10^{-9}
340	2.02×10^{-7}	2.28×10^{-9}
360	2.78×10^{-7}	3.32×10^{-8}
380	3.77×10^{-7}	4.75×10^{-9}
400	5.02×10^{-7}	6.65×10^{-9}

As can be seen by comparing the entries of Table 1-6 with those of Tables 1-3 and 1-4, the grain boundary contribution drops off strongly with increasing temperature.

2.0 VACUUM VESSEL DIMENSIONAL CHARACTERISTICS

The key dimensional characteristics of the torus and vacuum system that are relevant to the expected chronic tritium releases during TFTR operations and stand-by at base pressure during non-operating periods are listed in Table 2-1.

TABLE 2-1

TFTR TORUS AND VACUUM SYSTEM DIMENSIONAL PARAMETERS *

Item	Internal Surface cm ²	Thickness cm	Surface to Thickness Ratio cm	Internal Volume cm ³
Torus				
Bellows (1)	6.047×10^6	0.102	6.306×10^7	
Body (Shell)	8.276×10^5	0.675	1.226×10^6	
Reinforcing Rings	1.101×10^5	7.62	1.445×10^4	
Sub-Total	7.345×10^6		6.430×10^7	7.170×10^7
Diagnostics(2)	1.350×10^6	0.388	3.479×10^6	6.750×10^6
Margin for Ducts, Ports, Etc.(3)	1.739×10^6	0.388	4.482×10^6	1.044×10^7
Totals	1.043×10^7		7.226×10^7	8.889×10^7
<p>(1) On basis of added conservatism, deletes permeation impedance of bellows cover plates and vacuum pumping on bellows exterior volume.</p> <p>(2) Based on diagnostics surface estimates of early September, 1975, which show a volume to surface ratio of 5.</p> <p>(3) Based on a 20% additional surface allowance for ducts, valves, etc., and a volume to surface ratio of 6.</p> <p>* Subsequent to preparation of this report, the vacuum vessel design was altered, resulting in an internal volume increase of ~12% and an internal surface increase of ~1%. The effect of this "last-minute change" is not incorporated in the results reported herein.</p>				

Figures 2-1 and 2-2 show some of the features of the TFTR vacuum vessel and a bellows assembly for the design status as of early September, 1975.

Figure 2-1. Vacuum Vessel

Figure 2-2. Bellows Assembly

3.0 PLASMA SCENARIOS AND GAS INJECTION QUANTITIES

The quantities of tritium and neutral beam deuterium injected into the torus determine the pressures seen by the vacuum vessel and this in turn influences the tritium transport through the vessel walls. The tritium injection required for a pulse depends on a number of factors, primarily on the specific plasma experiment scenario and the quantity of gas held up in "dead zones" within the vacuum chamber that does not get drawn into the plasma. The required neutral beam deuterium injection derives directly from energetics considerations and includes both the preheat and fusion promoting energy requirements.

3.1 TRITIUM INJECTIONS

Estimation of the tritium content in the plasma so as to include the neutrals is based on scaling up the results of some limited plasma population measurements made at Princeton Plasma Physics Laboratory ⁽¹⁰⁾. These measurements showed: (a) a maximum cold neutrals content of $3.55 \times 10^{10}/\text{cm}^3$ at $r/a = 1$, with negligible content at $r/a = 0.5$; (b) a maximum electron (or ion) content of $2.60 \times 10^{13}/\text{cm}^3$ at $r/a = 0$, dropping off to $\sim 7.8 \times 10^{12}$ at $r/a = 1$. In making the estimates for TFTR, the following assumptions and normalizations are made:

1. In order to achieve a mean 5×10^{13} particles/ cm^3 population, the scale-up factor is $5 \times 10^{13}/2.60 \times 10^{13} = 1.923$. This corresponds to a maximum T+ population density of $9.6 \times 10^{13}/\text{cm}^3$.
 2. At $r/a = 1$, the T+ population density is $7.8 \times 10^{12} \times 1.923 = 1.50 \times 10^{13}/\text{cm}^3$.
 3. Outside of the plasma ($r/a = 1$) up to the wall the T+ drops off linearly, giving a mean population for this region of $1.50 \times 10^{13} \times 0.5 = 7.50 \times 10^{12}/\text{cm}^3$.
 4. Outside of the plasma ($r/a = 1$), the cold neutral particle content is constant at $3.55 \times 10^{10} \times 1.923 = 6.83 \times 10^{10}/\text{cm}^3$.
-
10. "High Speed Photographic Studies of the Equilibrium and Stability of the ATC Tokamak", R. A. Jacobsen, Matt-1038 (April, 1974).

5. The cold neutrals content within the plasma varies linearly according to $n(r) = 1.37 \times 10^{11} r/a - 6.83 \times 10^{10}$, whereupon the cold neutrals within the plasma via integration is $5.62 \times 10^{11} R_p r_p^2$ particles, where R_p = plasma major radius and r_p = plasma minor radius, both in cm.

Calling V_t the vacuum vessel volume (cm^3) available to gas, and invoking the above assumptions, the tritium loading components are:

$$T^+ \text{ within the plasma} = 5.0 \times 10^{13} \times 2\pi^2 R_p r_p^2$$

$$T^+ \text{ outside the plasma} = 7.5 \times 10^{12} (V_t - 2\pi^2 R_p r_p^2)$$

$$\text{Cold neutrals within the plasma} = 5.62 \times 10^{11} R_p r_p^2 \text{ atoms T}$$

$$\text{Cold neutrals outside the plasma} = 6.83 \times 10^{10} (V_t - 2\pi^2 R_p r_p^2) \text{ atoms T}$$

Accordingly, the estimated total amount of tritium required in the plasma precursor gas, N_t (atoms T) is given by:

$$N_t = 7.57 \times 10^{12} V_t + 8.38 \times 10^{14} R_p r_p^2 \text{ tritium atoms} \quad (9)$$

It is to be observed that V_t consists of two components, the gas space within the torus ($7.170 \times 10^7 \text{ cm}^3$) and the volume available to the gas in the diagnostics lines ($6.750 \times 10^6 \text{ cm}^3$), i.e. $V_t = 7.845 \times 10^7 \text{ cm}^3$. The margin volume ($1.043 \times 10^7 \text{ cm}^3$) indicated in Table 2-1 is excluded as a consequence of the closed mode of operation envisioned for the pulsing experiments. For this mode, after the torus is pumped down to the base pressure [$\sim 5.7 \times 10^{-6} \text{ Pa}$ ($4.3 \times 10^{-8} \text{ torr}$)], the torus is isolated from the diffusion pumps and ducting, whereupon the tritium is injected, filling only the torus and diagnostics spaces.

The TFTR has been designed to accommodate a great deal of experimental flexibility, hence a limitless number of possible experimental scenarios can be envisioned involving various mixtures of hydrogen and helium isotopes, strong and weak magnetic compression, neutral beam injection, and pulse duration. In order to bound the range of operating parameters, four reference scenarios have been defined (September, 1975), three of which involve plasma discharge currents of one MA and one involving a current of 2.5 MA. The expectation is that the mix of the 1000 D-T full power pulses conducted per year will run 90% 1 MA scenarios and 10% 2.5 MA scenarios. In this connection, Table 3-1 summarizes the plasma characteristics under

consideration for TFTR D-T experiments and the corresponding tritium required for these scenarios.

TABLE 3-1
PLASMA CHARACTERISTICS RELATED TO TRITIUM REQUIREMENTS

Item	Transient Regimes		Quasi-Static Regimes	
	Strong Compression	Weak Compression	Weak Compression	High Current
Plasma Designation	A	B	C	D
I, Compression, MA	1	1	1	2.5
R _p , Precompression, cm	314	310	310	248
R _p , Compression, cm	(209)	(248)	(248)	-
r _p , Precompression, cm	56	60	60	85
r _p , Compression, cm	(46)	(85)	(85)	-
n _e , Max (Compression), Particles/cm ³	1.1×10^{14}	9.9×10^{13}	1.1×10^{14}	6×10^{13}
Tritium Particles in Torus	1.37×10^{21}	1.48×10^{21}	1.48×10^{21}	2.04×10^{21}
Ci/Pulse *				
In Torus	65.7	71.0	71.0	98.2
In Diagnostic Spaces	6.2	6.7	6.7	9.2
Total	71.9	77.7	77.7	107.4

Item	Torus	Torus and Diagnostics
Mean Tritium Injection, Ci/Pulse		
1 MA Plasmas	69.2	75.7
90% 1 MA and 10% 2.5 MA Plas-	72.1	78.9
mas		
Molecules T ₂ Injection/Pulse	7.506×10^{20}	8.214×10^{20}
Deuterium Injection, g mole/pulse		
90% 1 MA and 10% 2.5 MA plas-	0.00582	
mas for T:D = 1:0.2143		

* 1 g Tritium = 9589.4 Ci

As shown in Table 3-1, tritium injections of ~ 76 Ci (~ 7.9 mg) are required for an average 1 MA plasma and ~ 107 Ci (~ 11.2 mg) for 2.5 MA plasmas, for an overall required mean tritium injection per pulse of ~ 79 Ci (~ 8.2 mg).

The bottom insert in Table 3-1 shows the mean tritium injection per pulse to be 72.1 Ci in the torus, 6.8 Ci in the "dead zones", and 78.9 in the combined torus and diagnostics volumes. These mean values will be utilized in a subsequent section in connection with treating the tritium permeation and release issue on an overall basis instead of dealing with each plasma scenario on a separate basis. The last entry in the insert in Table 3-1 indicates the required neutral beam deuterium injection for a mean full power pulse. The basis for this quantity is summarized in the following exposition.

3.2 NEUTRAL BEAM DEUTERIUM INJECTION

The neutral beam deuterium injection required per pulse depends on the pulse scenario and the operating mode as they relate to energy input considerations. Details concerning this issue are listed in Table 3-2.

As indicated by the last entry of Tables 3-1 and 3-2, for an average D-T full power pulse, the spent plasma gas, barring complications, will have a $D_2:T_2$ (molecule) ratio of 0.2143:1.

3.3 OPERATING SCENARIOS AND EVENTS FOR A TYPICAL PULSING EXPERIMENT

Prior to the onset of a sequence of full power D-T pulsing experiments, the torus will have been "conditioned" to bring the composition of the vessel contents to the appropriate composition via a series of tritium build-up operations. For the mean D-T pulse, as indicated previously this composition corresponds to a tritium mole fraction of 0.8235 ($D_2:T_2 = .2143:1$), both for the residual gas in the torus and the adsorbed monomolecular layer on the equipment walls. The adsorbed layer population density is estimated⁽¹¹⁾ to be 8.5×10^{14} molecules/cm².

Prior to injecting the tritium charge into the torus, the vacuum vessel will have been evacuated down to the system base pressure of $\sim 5.68 \times 10^{-6}$ Pa (4.258×10^{-8} torr), whereupon

11. Personal communication, W. Lange, Westinghouse R&D Center

TABLE 3-2
SUMMARY OF NEUTRAL BEAM INJECTION KEY QUANTITIES

<u>ITEM</u>	<u>Mode 1-A</u>	<u>Mode 1-B</u>	<u>Mode 2</u>
Function	Preheating	Fuse	Combination
W_0 , keV	83	125	154
I injection as D^0 , amp	725 (all)	156 (125 keV)	78 (154 keV)
τ Injection, msec	43	32	500
Ions/pulse	1.95×10^{20}	3.12×10^{19}	2.43×10^{20}
All D^+ s/highest energy D^+ s	1	2.62	3
D^+ /pulse	1.95×10^{20}	8.16×10^{19}	7.30×10^{20}
Total D^+ /pulse	2.77×10^{20}		7.30×10^{20}
D_2 /pulse	1.38×10^{20}		3.65×10^{20}
T_2 /pulse (in torus)	7.20×10^{20}		1.02×10^{21}
D_2/T_2	1.917×10^{-1}		3.573×10^{-1}
For 90% 1 MA & 10% 2.5 MA plasmas			
Ci Tritium/pulse		72.1	
T_2 molecules (torus + diagnostics)/pulse		7.505×10^{20}	
D_2 molecules/pulse		1.609×10^{20}	
D_2/T_2 ratio in spent plasma gas		2.143×10^{-1}	

the vessel would be isolated and held in the closed state by appropriate valving. At this state, the pertinent quantities regarding the system state are:

Total pressure = 4.258×10^{-8} torr (based on an outgassing rate of 10^{-10} torr liter/cm² sec and a diffusion pump capability of 2.449×10^4 liters/sec for D₂:T₂ = 0.2143:1.

Tritium partial pressure = $4.258 \times 10^{-8} \times 0.8235 = 3.506 \times 10^{-8}$ torr

Gas volume (torus + diagnostics) = 7.845×10^7 cm³

Operating temperature = 70°F, corresponding to 294.3°K

Gas space content = $4.258 \times 10^{-8} \times 7.845 \times 10^7 / (760 \times 82.056 \times 294.3) = 1.820 \times 10^{-7}$ g mole

Surface exposed (torus + diagnostics) = 8.70×10^6 cm²

Adsorbed gas population = $8.70 \times 10^6 \times 8.5 \times 10^{14} / 6.0222 \times 10^{23} = 1.228 \times 10^{-2}$ g mole

The tritium injection of 78.9 Ci/pulse (72.1 Ci to the torus and 6.8 Ci to the diagnostics) corresponds to 1.364×10^{-3} g mole [$78.9 / (9589.4 \times 6.032)$], resulting in a pressure elevation to 3.191×10^{-4} torr.

During the pulsing operation 1.609×10^{20} molecules of neutral beam D₂ is injected, corresponding to 2.672×10^{-4} g mole. After the plasma discharges the gas space content is 1.631×10^{-3} g mole, giving rise to a pressure of 3.816×10^{-4} torr. For purposes of making tritium permeation estimates, the pulsing operation is assumed to last one second, and the post-pulse period is taken as five seconds prior to initiation of the pump-down, in preparation for conducting the next pulse experiment.

When the pump-down is started, the gas space volume is augmented by an additional 1.043×10^7 cm³ margin for ducts, ports, etc. of the vacuum system which contains 2.42×10^{-8} g mole, resulting in a system pressure drop to 3.369×10^{-4} torr.

During the six seconds involved for these operations, the outgassing from the walls amounts to 3.410×10^{-7} g mole, which quantity can be neglected.

The temporal variation of the system pressure (P) during the pump-down operation can be generated through a differential material balance for the system, based on the pumping capacity of $T_2:D_2 = 1:0.2143$ (2.449×10^4 liter/sec) and the outgassing rate (5.683×10^{-8} g_mole/sec). The relationship is:

$$P = 4.258 \times 10^{-8} + (P_0 - 4.258 \times 10^{-8}) e^{-0.2756 \Theta} \quad (10)$$

where:

P = variable pressure at time Θ , torr (multiply torr by 1.333×10^2 to convert to Pa)

P_0 = initial pressure at start of pump-down, torr

Θ = pump-down time, sec

Figure 3-1 shows the torus pressure variation during a typical pulse experiment. This pressure variation has relevance with regard to the estimation of tritium transport through the system walls in that it partially determines the driving force for the transport as will be shown in a subsequent section of this document.

3.4 TRITIUM HOLDUP, BUILDUP, FLUSHOUT AND CONSUMPTION

The opening paragraph of the preceding subsection referred to the necessity for "conditioning" the torus prior to commencing full power D-T pulsing experiments. The number and frequency of these conditionings, which are essential in order to attain the required plasma precursor gas composition, depends strongly on the manner in which one component (D, H, He-3, natural He) plasma experiments are interspersed with the D-T pulse experiments.

The surface conditioning requirement stems from the fact that the internal surfaces of the torus and the associated vacuum system components under the best of circumstances are covered with adsorbed gases ($\sim 8.5 \times 10^{14}$ molecules/cm²) so that the inter-transport of gaseous species between the adsorbed material and the contiguous gas within the torus lead to substantial "memory effects". These memory effects can be long-enduring, particularly when the required plasma precursor gas composition for a new set of experiments differs significantly from the compositions involved for immediately previous experiments. This is

Figure 3-1. Torus Pressure Variation During a Typical Pulse Experiment

readily understood in consideration of the following circumstances: (a) for an estimated adsorbed population density of 8.5×10^{14} molecules/cm², the adsorbed layer population within the TFTR vessel seen by the plasma precursor gas is $\sim 7 \times 10^{21}$ molecules; (b) the gas within the torus gas phase at the vacuum system base pressure of $\sim 5.7 \times 10^{-6}$ Pa ($\sim 4.3 \times 10^{-8}$ torr) prior to plasma precursor gas injection consists of $\sim 10^{17}$ molecules; (c) the gases injected for a typical pulse experiment consists of $\sim 7 \times 10^{20}$ molecules.

The circumstance that the quantity of adsorbed gas is on the order of 8-20 times greater than the amount of gas injected for the conduct of a pulse experiment, coupled with the ready interactions between the adsorbed and injected gases has far-reaching ramifications that can complicate the execution of the experimental program. The greater of these complications include the following:

1. Requirements of substantial quantities of "build-up" tritium when changing over from non-tritium to tritium based plasma experiments, and vice versa, requirement of many "flush-outs" when changing back to non-tritium experiments.
2. Relatively slow change in gas phase composition effected by each build-up or flush-out increment for these operations.
3. Imposition of a high loading on both tritium and non-tritium hydrogenous material on the getter cartridges used to trap the spent plasma gases.
4. Need for increased frequency of shipment of tritium generators for replenishment off-site.
5. Need for increased frequency of removal of spent getters canisters and shipping them off-site for regeneration or disposal.
6. Complicating the matter of recovering the gettered tritium (e.g. by cryogenic distillation) at the ERDA regeneration facility due to the lower concentration of tritium.

The number of tritium build-ups required (n) to achieve a tritium mole fraction F_t in the plasma precursor gas, starting with tritium-free gas in the torus (e.g., pure deuterium) is related to the adsorbed molecule population and the molecules of tritium added per build-up (or pulse) by

$$F_t = 1 - [A/(t + A)]^n \quad (11)$$

where:

- A = number of surface adsorbed molecules (assumed constant)
- F_t = desired tritium mole fraction in the plasma precursor gas
- n = number of tritium build-ups required
- t = molecules of tritium added per build-up (or pulse)

The number of tritium flush-outs (using deuterium) required (n) to achieve a deuterium mole fraction F_D in the plasma precursor gas, starting with mixtures in the torus having a deuterium to tritium mole ratio of $d:1$ is given by:

$$F_D = 1 - [1/(1 + d)] \left\{ A/[A + t(1 + d)] \right\}^n \quad (12)$$

where:

- A = number of surface adsorbed molecules (assumed constant)
- d = initial deuterium to tritium mole ratio for torus population
- F_D = desired final deuterium mole fraction in the torus residual gas
- t = number of tritium molecules previously added per pulse, with the further assumption that the number of deuterium molecules added per flush-out is $t(1 + d)$

The nature of the tritium build-up and flush-out problem is illustrated graphically in Figures 3-2 and 3-3. Figure 3-2, for example, shows the progress of tritium concentration build-up with number of tritium build-up injections conducted, indicating that 22 such injections are needed to attain the 0.8235 tritium mole fraction required for a mean D-T full power pulse experiment. Figure 3-3, in contrast, shows the progress of tritium concentration drop-off during a tritium flush-out campaign, starting out with a 0.8235 tritium mole fraction.

Figure 3-2. Build-Up of Tritium Concentration with Number of Tritium Injections

Figure 3-3. Tritium Concentration Drop-Off with Number of Deuterium Flushings

This plot shows that 140 flush-outs are required to reduce the final tritium mole fraction to 10^{-6} , in preparation for conducting "pure" deuterium plasma experiments.

The quantities cited above are based on the assumption of rapid interchanges between the gas phase and adsorbed monolayer species, with ultimate identical composition attainment in these phases. This may not be entirely valid. Another complication is the memory effect due to embedment of plasma gases (hydrogen, deuterium, tritium, etc.) into the vacuum vessel limiters, liners and beam catchers. Gases that leave the plasma will probably penetrate into the metal a few Angstroms. Previously embedded material may also be knocked back out and can also diffuse out. Although the precise course of the associated gas recycling is difficult to define, it is clear that its path will depend on the previous events within the device. Past experience at Princeton Plasma Physics Laboratory has been that many pulses in a single working gas can be required to obliterate the memory effects from earlier discharges. (12)

Both the number of tritium build-ups and tritium flush-outs with deuterium (or H, He-3, natural He) per year and the frequency of these operations have a substantial effect on the quantity of tritium permeated through the equipment and into the environment, as well as on the annual tritium consumption. The former issue is treated in a subsequent section of this document. The following exposition deals briefly with the tritium consumption question.

For TFTR experimentation the expected or reference operating basis is 40 two-component D-T full power pulses per operating day, with the time interval between pulses equal to or greater than five minutes, as restricted by the design of the field coil cooling water system. Extremes may be encountered. For example, situations are anticipated where there might be as low as one full power D-T pulse per day. On the other hand, because there is a significant advantage

12. "Vacuum and Wall Problems in Precursor Reactor Tokamaks", S. A. Cohen (Princeton Plasma Physics Laboratory), Paper Prepared for 22nd National Vacuum Symposium, (Philadelphia, Pa. - October 30, 1975) and Submitted to Journal of Vacuum Science and Technology.

operations-wise to pulse at the maximum repetition rate when all of the equipment is working properly, a maximum of 96 pulses is anticipated over any eight hour shift. If the D-T pulsing campaigns are carried out with different numbers of pulses per sequence, and these are immediately followed by return to non-tritium operations, the gross tritium consumption per mean D-T full power pulse will vary widely as shown by the following tabulation:

<u>D-T Pulses/Sequence</u>	<u>Ci Consumed/Full Power D-T Pulse</u>
1	1,665
40	119
96	95

These numbers do not include credit for the fact the build-ups and flush-outs may indeed be partial power pulse experiments which generate relevant plasma physics and device characteristics data.

For the 40 full-power pulse per sequence expected operational mode, the annual tritium consumption amounts to 118,560 Ci, of which 39,660 Ci is for tritium build-up operations.

As indicated previously, gross variation in the annual tritium consumption can arise as a consequence of interspersed modes of operation. As a means for quantifying the consequences of interspersing, the expected operation mode is taken as the reference estimation base.

Whether realistic or not, this presumes that: (a) 40 mean D-T, full power pulses are conducted in each sequence at five minute intervals during an operating day, whereupon the device is kept at the vacuum base pressure during the rest of the day; (b) on the day immediately prior to this D-T pulsing sequence, the device is prepared for this pulsing by building up the tritium mole fraction in the adsorbed layer and residual gas to 0.8235 by conducting 22 build-ups, whereupon the device is maintained at the vacuum base pressure during the rest of this day; (c) on the day immediately following the D-T pulsing sequence, the device is prepared for return to deuterium plasma parameter testing via conduct of 140 flush-outs with deuterium. For operations involving less than 40 pulses per sequence the same schedules for tritium build-ups and flush-outs with deuterium are presumed to apply.

Table 3-3 exemplifies the kind of spread in annual tritium consumption that can be encountered for various modes of interspersing one and two component plasma sequences. In all cases the total full power D-T pulses per year is 1000, but these are conducted in clusters of 10, 20, and 40 pulses per sequence, for various numbers of consecutive D-T operating days ranging from one to 25. For the examples shown in Table 3-3, the annual tritium consumption spread is 80,490 to 237,540 Ci, for which the tritium consumption for the build-up operations varies from 1590 to 158,640 Ci. As will be shown in a subsequent section interspersing of one and two component plasma experiments also invokes a parallel penalty of substantial increases in tritium releases to the environment, the magnitudes of which depend on the details of the operations schedule. The significance of this is quite clear-judicious schedule planning of TFTR operations is required in order to hold down the tritium consumption and for attainment of minimal environmental impact, as regards tritium releases.

TABLE 3-3
ANNUAL TRITIUM CONSUMPTION FOR SELECTED OPERATING MODES

ITEM	OPERATING MODE								
	A	B	C	D	E	F	G	H	I
Number of D-T Pulses/Sequence	10	10	10	20	20	20	40	40	40
Number of Consecutive D-T Pulsing Days	1	2	4	1	2	5	1	5	25
Number of D-T Pulsing Days	100	100	100	50	50	50	25	25	25
Number of Tritium Buildup Days	100	50	25	50	25	10	25	5	1
Number of Tritium Flush-out Days	100	50	25	50	25	10	25	5	1
Number of Outage or D Pulsing Days	65	165	215	215	265	295	290	330	338
Tritium Consumption, Ci									
For D-T Pulsing	78,900	78,900	78,900	78,900	78,900	78,900	78,900	78,900	78,900
For Tritium Build-Up	158,640	79,320	39,660	79,320	39,660	15,860	39,660	7,930	1,590
Total	237,540	158,220	118,560	158,220	118,560	94,760	118,560	86,830	80,490

4.0 ESTIMATION OF TRITIUM PERMEATION FOR TFTR OPERATIONS

This section attempts to quantify the estimated tritium releases expected for normal TFTR operations. These estimates are made on the basis of permeation calculations.

The major chronic gaseous tritium release to be encountered will be the continual permeation-diffusion through the torus walls to the cell air on an around-the-clock basis, once the tritium plasma tests commence. During outage periods, the torus and its associated auxiliaries will be maintained at an internal pressure of $\sim 5.7 \times 10^{-6}$ Pa (4.3×10^{-8} torr) with the contained gas residue having a tritium partial pressure ranging downward from $\sim 4 \times 10^{-6}$ Pa ($\sim 3 \times 10^{-8}$ torr), the exact value depending on the nature of the campaign conducted immediately prior to the outage. The very low baseline tritium contents within the equipment will give rise to "background tritium levels" in the cell air and the air discharged from the facility exhaust duct. The estimated background levels associated with the three relevant outage situations, based on the two air changes per hour ventilation rate for the test cell can be shown to be:

$\sim 1 \times 10^{-8} \mu\text{Ci}/\text{cm}^3$ for outages immediately following D-T pulsing
or following T buildups,

$\sim 1 \times 10^{-11} \mu\text{Ci}/\text{cm}^3$ for outages immediately following T flushouts.

Both of these levels are substantially below the $5 \times 10^{-6} \mu\text{Ci}/\text{cm}^3$ and $2 \times 10^{-7} \mu\text{Ci}/\text{cm}^3$ mpc values for controlled and uncontrolled areas as specified in ERDAM-0524, Tables 1 and 2 therein.

The foregoing estimates do not account for the additional permeation that may occur during the experiments due to the higher tritium pressures that exist within the equipment during these operations where these pressures may peak to $\sim 4 \times 10^{-2}$ Pa ($\sim 3 \times 10^{-4}$ torr), as shown

in Figure 3-1. The additional permeations associated with these conditions are relatively small compared to the background permeations, primarily because of the short time periods during which these higher tritium pressures prevail.

Precise calculation of the tritium releases expected is exceedingly complex, and was not attempted. Instead, a simpler approach was used, both highly conservative and adequate for conceptual design purposes. Although all of the permeations involved are transient in character, calculation of them has been as though they were a steady-state nature, instantly responsive to changes in transport driving forces. In order to introduce additional conservatism in the estimates, an equivalent additional tritium partial pressure contribution from the adsorbed monolayer tritium was incorporated into the calculation routine.

Table 4-1 lists the assumptions made regarding plasma scenario, operations sequence and schedule, and rudiments of the model used in making the tritium permeation and release estimates. As indicated in Table 4-1, the expected operation mode (40 full power D-T pulses per sequence) is taken as the estimation base, with one day each devoted to the tritium build-up and deuterium flush-out operations prior and subsequent to conducting a 40 full power D-T pulse sequence.

4.1 ESTIMATION DETAILS FOR THE D-T PULSING OPERATIONS

The estimates utilize the surface and volume characteristics of the torus and vacuum system listed in Table 2-1, an outgassing rate of 10^{-10} torr liter/sec cm^2 for all surfaces (independent of pressure or material) and a pumping capability of 2.449×10^4 liters/sec (based on $D_2:T_2 = 0.2143:1$, but taken constant, independent of gas composition in order to avoid excessive calculation complications. The internal surface exposed is $1.043 \times 10^7 \text{ cm}^2$. Accordingly, the vacuum system base pressure is 4.258×10^{-8} torr ($1.043 \times 10^7 \times 10^{-10} / 2.449 \times 10^4$).

TABLE 4-1

TRITIUM PERMEATION AND RELEASE ASSUMPTIONS AND ESTIMATION MODEL

- 1000 D-T Full Power Pulses Per Year, 90% 1 MA, 10% 2.5 MA
- 40 D-T Pulses in a Typical Sequence, Conducted in One Day
- 5 Minute Interval Between Pulses
- Tritium Hold Times - 1 Second for Pre-Plasma, Formation and Burn; 5 Seconds for Post-Pulse to Initiation of Pump-Down
- Base Pressure of $\sim 5.7 \times 10^{-6}$ Pa ($\sim 4.3 \times 10^{-8}$ torr)
- Tritium Injection - 78.9 Ci/Pulse; 72.1 Ci to Torus, 6.8 Ci into Diagnostics
- Tritium Build-up and Flush-out Campaigns Each Conducted in One Day
 - 22 Build-ups - Each 72.1 Ci to Yield 0.8235 Mole Fraction Tritium
 - 140 Flush-outs with Deuterium - Each 0.000151 g Mole to Yield 1×10^{-6} Final Tritium Mole Fraction
- Specific Outgassing Rate - 5.9×10^{-15} g mole/sec cm^2 (10^{-10} torr liter/sec cm^2)
- Adsorbed Layer Population - 8.5×10^{14} molecules / cm^2
- Rapid, Essentially Instantaneous Equilibration Between Hydrogenous Species in Torus Gas Phase and Adsorbed Material
 - Species Mole Fraction Corresponding to Species Total Population
 - Neglect Chemical Interactions Among Hydrogen Isotopes
- Operation Temperature Essentially at Ambient - 21°C
- Neutral Beam Deuterium Injection - 0.000267 g mole/pulse
- Emergency Basis Removable Tritium Gas in Release - 2000 Ci
- Quasi-Steady State Treatment of Tritium Permeation
 - Essentially Instantaneous Response to Changes in Partial Pressure
 - Sievert's Half-Power Pressure Law Applicable Over Entire Partial Pressure Range
 - Effective Partial Pressure for Driving Permeation Includes Contribution from Adsorbed Layer
 - Effective Permeability Includes Grain Boundary Contribution, 1.4×10^{-15} STP cm^3 cm/sec cm^2 Pa $^{1/2}$
(1.6×10^{-14} STP cm^3 cm/sec cm^2 torr $^{1/2}$)
 - Discount Permeation Impedance of Bellows Assembly Cover Plates
- TFTR Cell Ventilation According to:
 - 2 Air Changes Per Hour Only after Cessation of Tests
 - Inleakage and Equivalent Continuous Exhaust for Maintenance of 2.5 cm Water (1 inch) Sub-Atmospheric Pressure -
3.4 m^3 /min (120 cfm)

The key quantities are the system pressure and tritium partial pressure at the various stages of the operations. These quantities are obtained through determination of the amounts (g moles) of materials present in the system and application of the ideal gas law.

Immediately after pump-down of the torus and diagnostics (volume = $7.845 \times 10^7 \text{ cm}^3$) to the vacuum system base pressure of 4.258×10^{-8} torr the amount of contained gas mixture is 1.820×10^{-7} g moles ($4.258 \times 10^{-8} \times 7.845 \times 10^7 / 760 \times 82.056 \times 294.3$). The tritium to deuterium mole ratio in this gas as well as the adsorbed layer is 1:0.2143 during the conduct of mean full power D-T pulses, corresponding to a tritium mole fraction of 0.8235.

The 78.9 Ci injection of tritium corresponds to 1.364×10^{-3} g mole T_2 ($78.9/9589.4 \times 6.032$), so that after this injection the total gas quantity is $1.820 \times 10^{-7} + 1.364 \times 10^{-3}$ g mole, corresponding to a system gas pressure of 3.191×10^{-4} torr. The quantity of neutral beam deuterium injected corresponds to 2.923×10^{-4} g mole ($1.364 \times 10^{-3} \times 0.2143$), and this causes the system pressure to rise to 3.816×10^{-4} torr at the conclusion of the pulse, neglecting fusions, outgassing, and side reactions.

As indicated in Table 4-1, the duration of the pre-plasma, plasma formation, and burn period is assumed to aggregate one second, with a five-second hold time between post-pulse to initiation of pump-down to clear the torus in preparation for the next pulse.

When the system is reconnected to the vacuum system at the start of pump-down, the system volume is augmented by a volume of $1.043 \times 10^7 \text{ cm}^3$ containing gas at a pressure of 4.258×10^{-8} torr. Neglecting the outgassing, this causes the system pressure to drop to 3.369×10^{-4} torr. Over the six second period this outgassing corresponds to 3.410×10^{-7} g mole ($1.043 \times 10^7 \times 10^{-10} \times 6 \times 10^3 / 760 \times 82.056 \times 294.3$), which is justifiably negligible.

The pressure variation during the pump-down, as indicated previously, can be generated

by making a differential material balance for the system for a pumping time increment, $d\theta$ (sec) utilizing the following factors: (a) the pumping rate of 2.449×10^4 liter/sec corresponds to a mass flow rate of $1.335 P$ ($2.449 \times 10^4 \times 10^3 \times P/760 \times 82.056 \times 294.3$) g mole/sec, where P is the variable pressure in torr; (b) the variable amount of gas in the system is $4.844 P$ ($8.889 \times 10^7 \times P/760 \times 82.056 \times 294.3$) g mole; (c) entry of gas into the system via outgassing amounts to 5.683×10^{-8} ($1.043 \times 10^7 \times 10^{-10} \times 10^3/760 \times 82.056 \times 294.3$) g mole/sec. The differential material balance is

$$4.844 dP = -1.335 P d\theta + 5.683 \times 10^{-8} d\theta$$

which leads to the pump-down expression listed previously as equation 10

$$P = 4.258 \times 10^{-8} + (P_0 - 4.258 \times 10^{-8}) e^{-0.2756\theta}$$

where P_0 is the initial system pressure in torr.

As shown in Figure 3-1, the pump-down occurs quite rapidly, attaining very close to the system calculated base pressure of 4.258×10^{-8} torr in a matter of ~ 77 seconds, whereupon the pressure remains essentially constant for an additional 217 seconds until the next pulse is initiated. This same kind of behavior applies for the tritium build-up and flush-out operations.

Estimation of tritium permeations on the basis of a quasi-steady state model, with application of Sievert's half-power pressure law, involves the square-root of the tritium partial pressure for the several portions of the experimental scenario. The partial pressures are obtained as the product of the total system pressure and the tritium mole fraction. As indicated previously, the composition of the gas phase is essentially constant during most of the 300 second period, with a tritium mole fraction of 0.8235. During about one second of this period the gas phase is 100 percent tritium, if the effect of the adsorbed layer-gas phase interchanges are overlooked for the moment. Accordingly, the relevant quantities regarding

tritium partial pressures are:

Time Period sec	Total Pressure torr	T ₂ Mole Fraction	T ₂ Partial Pressure torr
0-1	3.191×10^{-4}	~ 1.0000	3.191×10^{-4}
1-6	3.816×10^{-4}	0.8235	3.142×10^{-4}
0	3.369×10^{-4}	0.8235	2.774×10^{-4}
6-83	$4.258 \times 10^{-8} +$ $3.369 \times 10^{-4} e^{-0.2756\theta}$	0.8235	$3.507 \times 10^{-8} +$ $2.774 \times 10^{-4} e^{-0.2756\theta}$
83-300	4.258×10^{-8}	0.8235	3.507×10^{-8}

The foregoing tritium partial pressures, however, are based strictly on the total gas pressure in the torus gas phase, and do not account for the impingement effects at the surface by the adsorbed molecules, which contribute additionally to the driving forces causing permeation. In order to account for this effect and introduce additional conservatism for the permeation estimates in the direction of overstating releases, as indicated in Table 4-1, a tritium partial pressure contribution originating from the surface adsorbed molecules is incorporated. This is done by distributing the adsorbed tritium, 1.212×10^{-2} ($1.043 \times 10^7 \times 8.5 \times 10^{14} \times 0.8235 / 6.022 \times 10^{23}$) g mole over the system volume of $8.889 \times 10^7 \text{ cm}^3$ to obtain an effective tritium incremental partial pressure of 2.503×10^{-3} ($1.212 \times 10^{-2} \times 82.056 \times 294.3 \times 760 / 8.889 \times 10^7$) torr, which is added to the previous gas phase tritium partial pressures. This procedure revises the tritium partial pressure schedule as shown:

Time Period sec	T ₂ Partial Pressure torr	Mean Value of Square Root of T ₂ Partial Pressure torr ^{1/2}
0-1	2.822×10^{-3}	5.313×10^{-2}
1-6	2.817×10^{-3}	5.308×10^{-2}

<u>Time Period</u> <u>sec</u>	<u>T₂ Partial Pressure</u> <u>torr</u>	<u>Mean Value of</u> <u>Square Root of T₂ Partial Pressure</u> <u>torr^{1/2}</u>
~ 0	2.781×10^{-3}	5.273×10^{-2}
6-83	$2.503 \times 10^{-3} + 3.369 \times 10^{-4} e^{-0.2756\theta}$	5.169×10^{-2}
83-300	2.503×10^{-3}	5.003×10^{-2}
Outages	2.503×10^{-3}	5.003×10^{-2}
Mean Values For		
300 second, 1 pulse operation		5.052×10^{-2}
40 pulses/sequence over a 24 hr day		5.010×10^{-2}
24 hour outage day		5.003×10^{-2}

In the above tabulation the "outages" entry refers to periods when the system is maintained at the system base pressure subsequent to performing a sequence of D-T pulses without conducting a deuterium flush-out campaign. The last three entries indicate that: (a) the tritium permeation rate is essentially constant throughout a D-T pulsing sequence and outages following the sequence up to the point where deuterium (or other non-tritium) flush-outs are initiated; (b) in order to minimize tritium permeation it is essential that flush-out campaigns be conducted immediately after completing a D-T pulsing sequence.

Based on the surface-to-thickness ratios shown in Table 2-1, the major contributor, with regard to tritium permeation, is the array of bellows assemblies. The percentages of the total permeation assignable to the various components are:

<u>Item</u>	<u>% of Total Permeation</u>
Bellows Assemblies	87.27
Ducts, Ports, etc.	6.20

<u>Item</u>	<u>% of Total Permeation</u>
Diagnostics	4.81
Shell Sections	1.70
Reinforcing Rings	0.02

It is to be noticed in this connection that no credit is taken for the permeation impedance of the bellows assembly cover plates (see Figure 2-2) and the fact that the spaces between the bellows and cover plates are connected to the vacuum system. This introduces added conservatism in the tritium permeation estimates.

The amount of tritium permeated Q through the device walls during the time interval θ is given by Sievert's law as:

$$Q = \Phi_e \bar{P}_T^{1/2} \theta \sum_{i=1}^n (Si/Li) \quad (13)$$

where:

L = device component thickness, cm

$\bar{P}_T^{1/2}$ = integral mean square root of the tritium partial pressure over the time interval, $\text{torr}^{1/2}$

Q = total tritium permeated during the time interval, μCi

S = device component surface exposed to the vacuum side, cm^2

θ = duration of permeation period, sec

Φ_e = effective tritium permeability, as defined in equation 8, in units of $\mu\text{Ci cm/sec cm}^2 \text{ torr}^{1/2}$

For the assumed device operating temperature of 21.1°C (70°F), application of equations 2, 3, 6, and 8 leads to a Φ_e value of

$$\begin{aligned}\Phi_e &= 1.571 \times 10^{-14} \text{ STP cm}^3 \text{ T}_2 \text{ cm/sec cm}^2 \text{ torr}^{1/2} \\ &= 4.054 \times 10^{-8} \mu\text{Ci cm/sec cm}^2 \text{ torr}^{1/2}\end{aligned}$$

Based on the foregoing value for Φ_e and the relevant values of $\bar{P}_T^{1/2}$ listed previously, the following estimated tritium permeations are generated for D-T pulsing operations:

<u>Operation</u>	<u>Tritium Permeated μCi</u>	<u>Rate, $\mu\text{Ci/sec}$</u>
300 second, 1 pulse operation	44.4	1.480×10^{-1}
40 D-T pulses over a 3.33 hr period	1,776	1.480×10^{-1}
Stand-by of 20.67 hr after 40 D-T pulses	10,904	1.466×10^{-1}
40 D-T pulses over a 24 hr day	12,680	1.468×10^{-1}
24 hour outage day following a 40 D-T pulse day	12,664	1.466×10^{-1}

As indicated by the above numbers, there is very little difference in the tritium permeations associated with a 40 full power D-T pulse/sequence operating day and that for a subsequent outage day. The corresponding situation is somewhat different for tritium build-up operations and considerably different for tritium flush-out operations as will be shown in the subsequent two subsections.

4.2 ESTIMATION DETAILS FOR THE TRITIUM BUILD-UP OPERATIONS

The manner in which the tritium concentration within the system varies during a tritium build-up campaign is complex, occurring as it does in a multiple stepwise fashion. As can be seen from equation 11, for each build-up step the non-tritium decrease factor is $[A/(t + A)]$ which for the A and t values specified is 0.92192. Figure 3-2 shows how the incremental tritium concentration per build-up step drops off with each successive build-up injection (drawn as a smooth curve without indicating the step-wise concentration details).

On the basis that the tritium build-up schedule is identical to that for D-T full power pulses, i.e. build-ups at five minute intervals, the temporal variation of the tritium mole fraction is mapped by:

$$F_T = 1 - (0.92192)^{3.3333 \times 10^{-3} \theta} = 1 - e^{-2.7098 \times 10^{-4} \theta} \quad (14)$$

As indicated previously, the goal of the build-up operation is a F_T value of 0.8235 starting with $F_T = 0$, which requires 22 build-up injections. In connection with determining the applicable tritium permeations associated with a tritium build-up campaign and subsequent outage, the previous calculation steps conducted for D-T pulsing are imitated, to the extent possible. The key quantities involved are: (a) the surface adsorbed molecule population, amounting to 1.472×10^{-2} g mole; (b) the initial gas phase content (non-tritium) of the system at the vacuum base pressure, amounting to 2.062×10^{-7} g mole, of which 1.820×10^{-7} g mole is in the torus and diagnostics; (c) the tritium added per build-up injection which in this case is taken as 72.1 Ci, corresponding to 1.247×10^{-3} g mole; (d) the total system pressure in torr is $2.065 \times 10^{-1} N$ where N is the total g mole of materials in the system.

Manipulations with the foregoing numbers leads to the following quantities for a single build-up injection:

Time Period sec	Total System Material g mole	Total System Pressure torr	Mean Value of Square Root of System Effective Pressure torr ^{1/2}
0-6	1.597×10^{-2}	3.297×10^{-3}	5.742×10^{-2}
83	1.472×10^{-2}	3.040×10^{-3}	
6-83			5.629×10^{-2}
83-300	1.472×10^{-2}	3.040×10^{-3}	5.513×10^{-2}
0-300			5.548×10^{-2}

The instantaneous value of the permeation driving force during the tritium build-up operations

is then given by:

$$\bar{P}_T^{1/2} = 5.548 \times 10^{-2} \left[1 - e^{-2.7098 \times 10^{-4} \theta} \right]^{1/2} \text{ torr}^{1/2} \quad (15)$$

for $\theta \leq 6.60 \times 10^3 \text{ sec}$

leading to the following value for the instantaneous permeation rate (r , $\mu\text{Ci/sec}$) for the tritium buildup campaign

$$r = 1.625 \times 10^{-1} \left[1 - e^{-2.7098 \times 10^{-4} \theta} \right]^{1/2} \mu\text{Ci/sec} \quad (16)$$

for $\theta \leq 6.60 \times 10^3 \text{ sec}$

where it is to be noted that the quantity within the brackets is the instantaneous tritium mole fraction in the torus gas.

Figure 4-1 shows the temporal variation of the tritium permeation rate and tritium mole fraction in the torus gas during a typical tritium build-up campaign. The time of operation corresponding to completion of 22 tritium injections to complete the build-up for conducting reference full power D-T pulses is 1.83 hours. During the build-up the tritium permeation rate rises to $1.466 \times 10^{-1} \mu\text{Ci/sec}$, and thereafter remains at this level during stand-by conditions.

Numerical integration of the permeation rate over various times of interest by means of the three point approximate Simpson rule and direct integration leads to the following estimated tritium permeations for relevant tritium build-up related operations:

<u>Operation</u>	<u>Tritium Permeated, μCi</u>	<u>Rate, $\mu\text{Ci/sec}$</u>
22 build-up injections over 1.83 hr period	743	1.126×10^{-1}
stand-by of 22.17 hr after a build-up campaign	11,699	1.466×10^{-1}
22 build-up injections over a 24 hr day	12,449	1.441×10^{-1}
24 hour outage day following a build-up campaign	12,664	1.466×10^{-1}

Figure 4-1. Variation of Torus Gas Makeup and Tritium Release During Tritium Build-up Operations

4.3 ESTIMATION DETAILS FOR THE TRITIUM FLUSH-OUT OPERATIONS

The objective of a flush-out campaign is to reduce the mole fraction of the tritium in the gas phase and adsorbed monolayer from 0.8235 (for the reference mean full power pulse composition) to a very low value (taken as 10^{-6}) so as to set the stage for non-tritium experiments. The flush-out gas could be any of the non-tritium gases (H, D, He-3, natural He). Deuterium is specified in these considerations in that it is anticipated that the testing program will involve many thousands of deuterium pulses annually.

Associated with each tritium flush-out, assumed here to be conducted by adding 9.117×10^{20} ($72.1 \times 6.022 \times 10^{23} \times 1.2143/9589.4 \times 6.032$) molecules of D_2 (corresponding to 1.514×10^{-3} g mole) the tritium content of the material in the torus drops off in a stepwise fashion as indicated by equation 12. Successive flush-outs cause the tritium mole fraction to follow the course shown in Figure 3-3. Each additional flush-out effects a fractional decrease of (0.90675) in the residual tritium mole fraction. As indicated previously a total of 140 reference tritium flush-outs is required to reduce the tritium mole fraction from 0.8235 to 10^{-6} . On the basis that the flush-outs are conducted at five minute intervals as data gathering plasma physics experiments, if desired, a reference flush-out campaign will consume 4.2×10^4 seconds (~ 11.7 hr).

The temporal variation of the tritium mole fraction in the system is mapped by:

$$F_T = 0.8235 (0.90675)^{3.3333 \times 10^{-3} \theta} \quad \theta \leq 4.2 \times 10^4 \text{ sec} \quad (17)$$

The main quantities relevant to the flush-out operations are: (a) the surface adsorbed molecule population of 1.472×10^{-2} g mole; (b) the initial gas phase content of the system at the vacuum base pressure, amounting to 2.062×10^{-7} g mole, of which 1.820×10^{-7} g mole is in the torus and diagnostics, all with an initial tritium mole fraction of 0.8235; (c) the deuterium added per flush-out injection is 1.514×10^{-3} g mole; (d) the total system

pressure in torr is $2.065 \times 10^{-1} N$ where N is the total g mole of materials in the system;
 (e) the instantaneous tritium mole fraction in the system gas during the flush-out operations is as given by equation 17.

Analysis based on the aforementioned quantities generates the following numbers for a single flush-out injection:

Time Period sec	Total System Material g mole	Total System Pressure torr	Mean Value of Square Root Of System Effective Pressure torr ^{1/2}
0-6	1.623×10^{-2}	3.350×10^{-3}	5.788×10^{-2}
83	1.472×10^{-2}	3.040×10^{-3}	
6-83			5.652×10^{-2}
83-300	1.472×10^{-2}	3.040×10^{-3}	5.513×10^{-2}
0-300			5.553×10^{-2}

For the duration of the flush-out campaign the instantaneous value of the tritium permeation driving force is given by:

$$\begin{aligned} \bar{P}_T^{1/2} &= 5.553 \times 10^{-2} \left[0.8235 (0.90675)^{3.3333 \times 10^{-3} \theta} \right]^{1/2} \\ &= 5.039 \times 10^{-2} (0.90675)^{1.6667 \times 10^{-3} \theta} \text{ torr}^{1/2} \quad \theta \leq 4.2 \times 10^4 \text{ sec} \end{aligned} \quad (18)$$

leading to an instantaneous tritium permeation rate (r , $\mu\text{Ci/sec}$) of

$$r = 0.1476 (0.90675)^{1.6667 \times 10^{-3} \theta} \mu\text{Ci/sec} \quad \theta \leq 4.2 \times 10^4 \text{ sec} \quad (19)$$

Figure 4-2 displays the instantaneous variations of the rate of tritium permeation and tritium mole fraction in the torus gas during typical tritium flush-out operations. During the 140 flush-outs the permeation rate drops to the very low value of $1.560 \times 10^{-4} \mu\text{Ci/sec}$, and thereafter remains at this level during stand-by conditions.

Direct integration of the permeation rate over the relevant times of concern yields the

following estimated tritium permeations for the flush-out related operations:

<u>Operation</u>	<u>Tritium Permeated, μCi</u>	<u>Rate, $\mu\text{Ci}/\text{sec}$</u>
140 flush-out injections over 11.7 hr period	1,166	2.78×10^{-2}
Stand-by of 12.3 hr after a flush-out campaign	7	1.27×10^{-4}
140 flush-out operations and stand-by over a 24 hr day	1,173	1.36×10^{-2}
24 hour outage following a flush-out campaign	13	1.27×10^{-4}

These numbers highlight a statement made previously - the total tritium permeation associated with a flush-out operating day is considerably higher than that for the subsequent outage days, by a factor of ~ 90 .

4.4 ESTIMATED ANNUAL TRITIUM PERMEATION

Just as the annual tritium consumption can vary widely, depending on the operational schedule followed, the annual tritium permeation (and release to the environment) also is subject to substantial variations. From the previous examination of permeation quantities, it is apparent that holding down the annual tritium permeation is keyed to limiting the outage days allowed without prior flush-out tritium. This matter is made more evident by referring to the summary of the estimates of 24 hour cumulative tritium permeations shown in Table 4-2.

TABLE 4-2
SUMMARY OF ESTIMATED 24 HOUR TRITIUM PERMEATIONS

<u>Operation</u>	<u>Tritium Permeation $\mu\text{Ci}/\text{day}$</u>
Tritium Build-up (22 build-ups, then stand-by)	12,449
Outage After Tritium Build-up	12,664
D-T Pulsing (40 Pulses, then stand-by)	12,680
Outage After D-T Pulsing	12,664
Tritium Flush-out (140 flushes, then stand-by)	1,173
Outage After Tritium Flushout	13

Figure 4-2. Variation of Torus Gas Make-Up and Tritium Release During Tritium Flush-out Operations.

Table 4-3, which is a companion to the previously presented Table 3-3 shows how the annual tritium permeation (and release to the environment) can vary grossly as a consequence of interspersed modes of operation. For the nine example modes of operation listed in Table 4-3 the spread in annual tritium release amounts to 0.33 to 2.6 Ci, for a 1:7.85 ratio. Operating mode G in Table 4-3 (which involves conduct of D-T full power pulses in 40 pulses/sequence for an operating day repeated 25 times a year, with interspersing of non-tritium pulsing experiments) corresponds to the reference operating mode. This mode of operation is accomplished with an estimated annual tritium release of 0.66 Ci. The thrust of the numbers displayed in Table 4-3 is evident - careful schedule planning of TFTR operations is required in order to ensure minimal environmental impact with respect to "chronic" type tritium releases.

TABLE 4-3
ANNUAL TRITIUM PERMEATION RELEASE FOR SELECTED OPERATING MODES
No Outage Days Without Prior Tritium Flush-Out

ITEM	OPERATING MODE								
	A	B	C	D	E	F	G	H	I
Number of D-T Pulses/Sequence	10	10	10	20	20	20	40	40	40
Number of Consecutive D-T Pulsing Days	1	2	4	1	2	5	1	5	25
Number of D-T Pulsing Days	100	100	100	50	50	50	25	25	25
Number of Tritium Build-Up Days	100	50	25	50	25	10	25	5	1
Number of Tritium Flush-Out Days	100	50	25	50	25	10	25	5	1
Number of Outage or D Pulsing Days	65	165	215	215	265	295	290	330	338
Tritium Permeations, $\mu\text{Ci}/\text{Day}$									
Per D-T Pulsing Day	12,668	12,668	12,668	12,672	12,672	12,672	12,680	12,680	12,680
Per T Build-Up Day	12,449	12,449	12,449	12,449	12,449	12,449	12,449	12,449	12,449
Per T Flush-Out Day	1,173	1,173	1,173	1,173	1,173	1,173	1,173	1,173	1,173
Per Outage or D Pulsing Day	13	13	13	13	13	13	13	13	13
Annual Tritium Permeations, mCi/Year									
For D-T Pulsing Days	1,266.8	1,266.8	1,266.8	633.6	633.6	633.6	317.0	317.0	317.0
For T Build-Up Days	1,244.9	622.5	311.2	622.5	311.2	124.5	311.2	62.2	12.4
For T Flush-Out Days	117.3	58.6	29.3	58.6	29.3	11.7	29.3	5.9	1.2
For Outage or D Pulsing Days	0.8	2.1	2.8	2.8	3.4	3.8	3.8	4.3	4.4
Total	2,629.8	1,950.0	1,610.1	1,317.5	977.5	773.6	661.3	389.4	335.0

5.0 TRITIUM LEVEL VARIATIONS IN THE TEST CELL ATMOSPHERE

Because the tritium release rates and onset of once-through ventilation of the test cell are different for the tritium build-up, D-T pulsing, and tritium flush-out operations there are corresponding differences in the temporal variation of the tritium level in the test cell during these operations.

As indicated in Table 4-1, the common features of the ventilation schedules for these operations are: (a) throughout the operations involving gas injections - pulsing the test cell is maintained as a sealed closed system at a subatmospheric pressure of ~ 2.5 cm (1 in) of water; (b) in order to maintain this negative pressure and to promote inleakage rather than outleakage, an amount of air corresponding to the estimated inleakage is purged out of the cell into the exhaust system at a rate of $5.663 \times 10^4 \text{ cm}^3/\text{sec}$ (120 cfm); (c) immediately after cessation of the gas injection-pulsing operations, once-through ventilation of air is initiated, corresponding to two air changes per hour, which for the test cell volume of $1.944 \times 10^{10} \text{ cm}^3$ (686,400 ft^3) corresponds to a ventilation rate of $1.080 \times 10^7 \text{ cm}^3/\text{sec}$ (22,880 cfm).

In connection with conducting analyses of the ventilation events the following symbols are used for the relevant variables and parameters:

- c = instantaneous tritium concentration in the cell air, $\mu\text{Ci}/\text{cm}^3$
- L = air inleakage rate, cm^3/sec
- r = tritium transport rate into the cell air via permeation, $\mu\text{Ci}/\text{sec}$
- R = amount of tritium released to the environment, μCi
- V = test cell volume, cm^3
- v = test cell ventilation rate, cm^3/sec
- θ = time elapsed, sec

The basic relationships describing the temporal variation of tritium level in the test cell

atmosphere and cumulative tritium release to the environment are based on material balances in the following forms:

Sealed Test Cell Operating Period:

$$r d\theta = Vdc + Lcd\theta \quad (20)$$

$$R = \int_0^{\theta} Lcd\theta \quad (21)$$

where θ = duration of closed cell operation period in seconds, having a magnitude for the tritium build-up, D-T pulsing, and tritium flush-out periods for reference mode operations of 6.6×10^3 , 1.2×10^4 and 4.2×10^4 respectively.

Test Cell Ventilation Period:

$$r d\theta = Vdc + (L + v)cd\theta \quad (22)$$

$$R = \int_0^{\theta} (L + v)cd\theta \quad (23)$$

where θ = duration of cell ventilation once-through operation period in seconds, having a magnitude for the tritium build-up, D-T pulsing, and tritium flush-out periods for reference mode operation of 7.98×10^4 , 7.44×10^4 , and 4.44×10^4 respectively for a day.

As indicated in the preceding subsections the tritium release rates, r vary for each of the operating modes in the following manner:

Tritium Build-Up: $r_b = 1.625 \times 10^{-1} \left[1 - e^{-2.7098 \times 10^{-4} \theta} \right]^{1/2} \quad \theta \leq 6.60 \times 10^3$

$$\begin{aligned}
& r_B = 1.466 \times 10^{-1} \quad 6.60 \times 10^3 \leq \theta \leq 8.64 \times 10^4 \\
\text{D-T Pulsing:} \quad & r_p = 1.468 \times 10^{-1} \quad \theta \leq 1.20 \times 10^4 \\
& r_p = 1.466 \times 10^{-1} \quad 1.20 \times 10^4 \leq \theta \leq 8.64 \times 10^4 \\
\text{Tritium Flush-Out} \quad & r_f = 1.476 \times 10^{-1} (0.90675)^{1.6667 \times 10^{-3} \theta} \\
& = 1.476 \times 10^{-1} e^{-1.6315 \times 10^{-4} \theta} \quad \theta \leq 4.20 \times 10^4 \\
& r_F = 1.273 \times 10^{-4} \quad 4.20 \times 10^4 \leq \theta \leq 8.64 \times 10^4
\end{aligned}$$

The explicit formulations for the temporal variation of c and R are indicated in the following subsections.

5.1 RELATIONSHIPS FOR THE TRITIUM BUILD-UP OPERATIONS

For the period $\theta \leq 6.60 \times 10^3$ seconds it is convenient to state the tritium permeation rate as

$$r_b = a(1 - e^{-b\theta})^{1/2} \quad (24)$$

where

$$\begin{aligned}
a &= 1.625 \times 10^{-1} \text{ } \mu\text{Ci/sec} \\
b &= 2.7098 \times 10^{-4} \text{ sec}^{-1}
\end{aligned}$$

Insertion of r_b as given by equation 24 into equations 20 and 21 with subsequent manipulations leads to the following expressions for c and R :

$$dc/d\theta = (a/V)(1 - e^{-b\theta})^{1/2} - (L/V)c \quad (25)$$

$$c = c_o e^{-L\theta/V} + (a/V) e^{-L\theta/V} \int_0^\theta (1 - e^{-b\theta})^{1/2} e^{L\theta/V} d\theta \quad (26)$$

$$R = L \int_0^\theta \left\{ c_o e^{-L\theta/V} + (a/V) e^{-L\theta/V} \int_0^\theta (1 - e^{-b\theta})^{1/2} e^{L\theta/V} d\theta \right\} d\theta \quad (27)$$

$c_o = 0$ for the very first TFTR tritium build-up campaign

$c_o = 1.17 \times 10^{-11} \mu\text{Ci}/\text{cm}^3$ once TFTR has been committed to tritium operations,

based on the reference operating modes

$a/V = 8.360 \times 10^{-12} \mu\text{Ci}/\text{sec cm}^3$

$L/V = 2.914 \times 10^{-6} \text{sec}^{-1}$

During the tritium build-up operation the tritium level in the test cell air increases to $c_b = 3.71 \times 10^{-8} \mu\text{Ci}/\text{cm}^3$ and this is accompanied by a release of $\sim 7 \mu\text{Ci}$ to the environment via the $3.78 \times 10^8 \text{cm}^3$ ($13,200 \text{ft}^3$) of air purged out of the cell over this 110 minute period.

For the period $6.60 \times 10^3 \leq \theta \leq 8.64 \times 10^4$ the tritium permeation rate r_B is constant. Insertion of this r_B value into equations 22 and 23 leads to the following formulations for c and R applicable for the stand-by 7.98×10^4 second (22.17 hr) portion of the tritium build-up day:

$$c = r_B/(v + L) + \left[c_b - r_B/(v + L) \right] e^{-(v + L) \theta/V} \quad (29)$$

$$R = r_B \theta + \left[r_B V/(v + L) + c_b V \right] \left[1 - e^{-(v + L) \theta/V} \right] \quad (30)$$

where in the use of equations 29 and 30 θ refers to the time elapsed subsequent to initiating once-through ventilation of the test cell. The magnitudes of the quantities of interest in this case are:

$$r_B/(v + L) = 1.350 \times 10^{-8} \mu\text{Ci}/\text{cm}^3$$

$$c_b - r_B/(v + L) = 2.440 \times 10^{-8} \text{ } \mu\text{Ci/cm}^3$$

$$(v + L)/V = 5.585 \times 10^{-4} \text{ sec}^{-1}$$

$$r_B V/(v + L) + c_b V = 9.992 \times 10^2 \text{ } \mu\text{Ci}$$

During this tritium post build-up period the test cell air tritium level drops off to $C_B = 1.35 \times 10^{-8} \text{ } \mu\text{Ci/cm}^3$, and the associated cumulative tritium release to the environment amounts to $\sim 12,440 \text{ } \mu\text{Ci}$ for a total of $\sim 12,500 \text{ } \mu\text{Ci}$ for a reference tritium build-up day.

5.2 RELATIONSHIPS FOR THE D-T PULSING OPERATIONS

For the period $\theta \leq 1.20 \times 10^4$ seconds when the 40 D-T pulses are conducted and the test cell is sealed the tritium permeation rate is constant at $r_p = 1.468 \times 10^{-1} \text{ } \mu\text{Ci/sec}$, whereupon insertion of the constant r_p into equations 20 and 21 lead to:

$$c = r_p/L + (c_B - r_p/L) e^{-L\theta/V} \quad (31)$$

$$R = r_p \theta + V [c_B - r_p/L] [1 - e^{-L\theta/V}] \quad (32)$$

where

$$r_p/L = 2.592 \times 10^{-6} \text{ } \mu\text{Ci/cm}^3$$

$$c_B - r_p/L = -2.579 \times 10^{-6} \text{ } \mu\text{Ci/cm}^3$$

$$L/V = 2.914 \times 10^{-6} \text{ sec}^{-1}$$

$$V [c_B - r_p/L] = -5.013 \times 10^4 \text{ } \mu\text{Ci}$$

During this 200 minute D-T pulsing period the tritium level in the test cell air builds up to $c_p = 1.007 \times 10^{-7} \text{ } \mu\text{Ci/cm}^3$ and the accompanying tritium release to the environment by

the $6.80 \times 10^8 \text{ cm}^3$ ($24,000 \text{ ft}^3$) amounts to $\sim 39 \text{ } \mu\text{Ci}$.

During the remaining stand-by period of $1.20 \times 10^4 \leq \theta \leq 8.64 \times 10^4$ seconds while the test cell is once-through ventilated, the tritium permeation rate is constant at $r_p = 1.466 \times 10^{-1} \text{ } \mu\text{Ci/sec}$. The equations describing the temporal variation of the tritium level in the test cell air and the cumulative tritium release to the environment during this period are similar to equations 29 and 30 and have the makeup:

$$c = r_p/(v + L) + \left[c_p - r_p/(v + L) \right] e^{-(v + L) \theta/V} \quad (33)$$

$$R = r_p \theta + \left[r_p V (v + L) + c_p V \right] e^{-(v + L) \theta/V} \quad (34)$$

where in manipulations with these equations θ refers to the time elapsed after starting the once-through cell ventilation. In this case the magnitudes of the quantities involved are:

$$r_p/(v + L) = 1.350 \times 10^{-8} \text{ } \mu\text{Ci/cm}^3$$

$$c_p - r_p/(v + L) = 8.719 \times 10^{-8} \text{ } \mu\text{Ci/cm}^3$$

$$(v + L)/V = 5.585 \times 10^{-4} \text{ sec}^{-1}$$

$$r_p V (v + L) + c_p V = 2.219 \times 10^3 \text{ } \mu\text{Ci}$$

During the post D-T pulsing period the test cell air tritium level drops off to $c_p = 1.35 \times 10^{-8} \text{ } \mu\text{Ci/cm}^3$ and the associated cumulative tritium release amounts to $\sim 12,640 \text{ } \mu\text{Ci}$; for a total of $\sim 12,680 \text{ } \mu\text{Ci}$ over the pulsing operating day.

5.3 RELATIONSHIPS FOR THE TRITIUM FLUSH-OUT OPERATIONS

At the start of the flush-out operations the initial tritium level in the test cell air is $c = c_p = 1.35 \times 10^{-8} \text{ } \mu\text{Ci/cm}^3$. For the 140 flush-outs for the time interval $0 \leq 4.20 \times$

10^4 seconds the tritium permeation rate can be stated as

$$r_f = a e^{-b\theta} \quad (35)$$

where

$$a = 1.476 \times 10^{-1} \mu\text{Ci/sec}$$

$$b = 1.6315 \times 10^{-4} \text{sec}^{-1}$$

Combining equation 35 into equations 20 and 21 leads to the following formulas for c and R :

$$c = \left[c_p - a/(L - bV) \right] e^{-L\theta/V} + \left[a/(L - bV) \right] e^{-b\theta} \quad (36)$$

$$R = V \left[c_p - a/(L - bV) \right] \left[1 - e^{-L\theta/V} \right] + \left[La/b(L - bV) \right] \left[1 - e^{-b\theta} \right] \quad (37)$$

where:

$$a/(L - bV) = 4.740 \times 10^{-8} \mu\text{Ci/cm}^3$$

$$c_p - a/(L - bV) = 6.090 \times 10^{-8} \mu\text{Ci/cm}^3$$

$$L/V = 2.914 \times 10^{-6} \text{sec}^{-1}$$

$$b = 1.6315 \times 10^{-4} \text{sec}^{-1}$$

$$La/b(L - bV) = 1.645 \times 10^{-1} \mu\text{Ci}$$

$$V \left[c_p - a/(L - bV) \right] = 1.184 \times 10^3 \mu\text{Ci}$$

During the tritium flush-out operation over 140 flushouts the tritium level in the test cell air increases from its initial value of $c_p = 1.35 \times 10^{-8} \mu\text{Ci/cm}^3$ to $c_f = 5.38 \times 10^{-8} \mu\text{Ci/cm}^3$ and this is accompanied by a tritium release of $\sim 120 \mu\text{Ci}$ to the environment via the $2.38 \times 10^9 \text{cm}^3$ ($84,000 \text{ft}^3$) of air purged out of the cell over this 700 minute period.

During the $4.20 \times 10^4 \leq \theta \leq 8.64 \times 10^4$ second stand-by period while the test cell is again once-through ventilated at a rate of two air changes per hour the tritium permeation rate is substantially constant at $r_F = 1.273 \times 10^{-4}$ $\mu\text{Ci/sec}$. The c and R equations in this case are identical in form to equations 29 and 30, having the makeup:

$$c = r_F/(v + L) + [c_f - r_F/(v + L)] e^{-(v + L)\theta/V} \quad (38)$$

$$R = r_F\theta + [r_F V/(v + L) + c_f V] e^{-(v + L)\theta/V} \quad (39)$$

where θ refers to the time elapsed subsequent to initiating the cell ventilation. The applicable values in this case are:

$$r_F/(v + L) = 1.173 \times 10^{-11} \mu\text{Ci/cm}^3$$

$$c_f - r_F/(v + L) = 5.382 \times 10^{-8} \mu\text{Ci/cm}^3$$

$$(v + L)/V = 5.585 \times 10^{-4} \text{sec}^{-1}$$

$$r_F V/(v + L) + c_f V = 1.047 \times 10^3 \mu\text{Ci}$$

During this 740 minute ventilation period of the flush-out operation the tritium concentration in the test cell air drops off and levels off to a constant value of $c_F = 1.17 \times 10^{-11} \mu\text{Ci/cm}^3$. The associated cumulative tritium release to the environment corresponds to $\sim 1050 \mu\text{Ci}$, for a total release of $\sim 1170 \mu\text{Ci}$ during the 24 hour day assigned for the flush-out operation.

5.4 SUMMARY OF ESTIMATES OF TRITIUM LEVELS AND RELEASES TO THE ENVIRONMENT

Figure 5-1 delineates how the estimated tritium level in the test cell will vary throughout the day for one day each for separate phases of tritium build-up, D-T pulsing, and tritium flush-out. The estimates indicate that a peak tritium level of $\sim 1 \times 10^{-7} \mu\text{Ci/cm}^3$ can be anticipated. This level, which is ~ 2 percent of mpc for controlled areas, occurs at the

Figure 5-1. Temporal Variation of TFTR Cell Air Tritium Level During Operations Periods

termination of a 40 D-T reference pulse sequence immediately before actuating ventilation of the test cell and discharge of the exhaust to the environment.

Figure 5-2 indicates how the cumulative release of tritium to the facility exhaust varies with time during the 24 hour period immediately following inception of the three principal operation phases for reference tritium build-ups, D-T pulsings, and tritium flush-outs. The largest release for these operations (D-T pulsing) is estimated to be 12,680 μCi over a reference operating day.

Figure 5-2. Temporal Variation of Cumulative Tritium Releases During Operations Periods

6.0 VACUUM VESSEL OUTGASSING AND BAKEOUT CONSIDERATIONS

Some aspects of the problems associated with in-situ bakeout and related means to reduce outgassing from the TFTR vacuum vessel and vacuum pumping system hardware and otherwise minimize plasma impurities have been considered elsewhere^(13,14) in a more or less qualitative fashion. This section summarizes the more relevant quantitative findings of a limited examination of the outgassing problem derived from diffusion considerations which centered on estimating the expected gas releases at elevated vessel temperatures.

6.1 OUTGASSING ESTIMATION APPROACH

Guidance regarding making the estimates was obtained by prior considerations of metal outgassing available in the vacuum technology literature^(15,16). Because a detailed and general treatment of metal bakeout is a highly complex matter, a rather simple and narrow approach was adopted that could quickly yield quantitative assessment of the expected outgassing improvement afforded by bakeout, either in-situ or by treatment of materials or components immediately prior to device assembly. This approach focusses on hydrogen as the substance to be removed from the device material. Accordingly, the approach ignores the other constituents that may be adsorbed on the metal surfaces or contained within the metals, such as moisture, carbon monoxide, carbon dioxide, ethane, other hydrocarbons, oils, etc. Their removal behavior will parallel that of the hydrogen.

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13. "TFTR Vacuum System Considerations," W. J. Lange, J. G. Gorman, D. Green and D. A. Sink, WFPS-TME-021 (November 1975).
 14. "The Vacuum System for the Tokamak Fusion Test Reactor (TFTR)," W. J. Lange, D. Green and D. A. Sink, Paper Prepared for Sixth IEEE Symposium on Engineering Problems of Fusion Reactors (San Diego, California, November 18-21, 1975).
 15. "Fundamentals of Vacuum Science and Technology," Gerhard Lewin, McGraw Hill Book Co. (1965) p. 24-35, 69-76.
 16. "Reduction of Stainless Steel Outgassing in Ultra-High Vacuum," R. Calder and G. Lewin. British Journal of Applied Physics, 18: 1459-1472 (1967).

The initial concentration of hydrogen in the as-fabricated vacuum vessel steel, C_o , is a key parameter in the analysis. The magnitude of this is taken as the equilibrium concentration corresponding to the final anneal conditions for AISI 305-SS used in the steel industry, 1010-1120°C (1850-2050°F) and in a 10^5 Pa (770 torr) hydrogen atmosphere. Based on the solubility relationship shown by equation 4 for austenitic steels and a mean anneal temperature of 1070°C, a value of $C_o = 0.833 \text{ STP cm}^3 \text{ H}_2/\text{cm}^3 \text{ steel}$ is estimated. This C_o value corresponds to concentrations expressed otherwise of 0.633 torr · liter H_2/cm^3 steel or 9.51 ppm hydrogen (density of SS-305 is 7.879 g/cm³).

The assessment methodology is based on one-dimensional isothermal diffusion of hydrogen at the bakeout temperature T_b (°K) of a slab of steel of thickness L (cm) and unit face surface (1 cm^2) for a bakeout period θ_b (sec), starting with the initial uniform hydrogen concentration C_o . The temperature-time transient during heatup from room conditions to T_b is neglected. The air surrounding the outside of the torus is assumed to be hydrogen-free, and the vacuum exposed side likewise is taken to be essentially hydrogen-free, to keep things simple and make the mathematics easy. This means that the cleanup calculated for the steel is considerably more complete than can be achieved for an actual bakeout for the bakeout time considered. Additionally, the predicted outgassing rates at the lower TFTR operating temperature subsequent to bakeout can be expected to be somewhat lower than will actually be experienced for the device.

For the estimations the diffusivity of SS-305 for hydrogen is calculated from the tritium diffusivity given in equation 2, making an appropriate modification [multiplying by the square-root of the molecular weight ratio, $(6.032/2.016)^{1/2} = 1.730$] and correcting for the grain boundary contribution as set forth in equation 7. This routine leads to the values shown in Table 6-1 for the "effective" diffusivity of SS-305 to hydrogen, D (the previously affixed e subscript is dropped in this case to avoid the use of double subscripts).

TABLE 6-1
EFFECTIVE DIFFUSIVITY OF SS-305 TO HYDROGEN

$^{\circ}\text{C}$	$D, \text{ cm}^2/\text{sec}$
21.1 (70°F)	1.67×10^{-11}
50	8.26×10^{-11}
100	7.71×10^{-10}
150	4.50×10^{-9}
200	1.90×10^{-8}
250	6.28×10^{-8}
300	1.73×10^{-7}
350	4.11×10^{-7}
400	8.69×10^{-7}
450	1.67×10^{-6}
500	2.96×10^{-6}

As shown previously in Figure 2-1 and Table 2-1 the vacuum vessel is made up of sections having different thicknesses ranging from 0.102 cm for the bellows plates to 7.62 cm for the reinforcing rings. Because of this thickness disparity, each of these parts will be cleaned to a different degree by a high temperature bakeout. Additionally, the residual hydrogen concentration gradients at the interior surface $[(\partial C / \partial x)_{x=0}]$ generated by the bakeout will be substantially different for each of the thicknesses. Accordingly, inasmuch as the surface diffusion current (STP $\text{cm}^3 \text{ H}_2 / \text{sec cm}^2$) is $D (\partial C / \partial x)_{x=0}$, the different thickness sections will exhibit different specific outgassing rates under service conditions.

In presenting the results of the bakeout-outgassing considerations the cleanup performance and subsequent outgassing rates are listed only for the two principal section thicknesses for the vacuum vessel parts - the bellows ($L = 0.102 \text{ cm}$) and the shell pieces ($L = 0.675 \text{ cm}$). The reasons for omitting the reinforcing rings are their low surface (~ 1.5 percent of the total) and non-applicability of one dimensional diffusion for these rings. The items included in the analyses comprise the following:

1. Outgassing rates for room temperature (21.1°C) and 100°C for the as-fabricated vessel sections (without subjecting the pieces to prior high temperature bakeout) at various times after inception of operation. This provides a base for making comparisons of the efficacy of various bakeout temperature-time schedules.
2. Outgassing rate variation encountered during various isothermal bakeouts in the range $200\text{--}500^{\circ}\text{C}$.
3. Initial outgassing rates for device operation at 21.1°C and 100°C , subsequent to isothermal bakeouts in the range $200\text{--}500^{\circ}\text{C}$ for varying bakeout times.
4. Quantities of gas diffused out of the steel during the various bakeout scenarios, expressed in terms of the fraction of the originally contained hydrogen still retained at the end of the bakeout.

The basis for including estimations of outgassing at 100°C is that the contemplated mode of conducting periodic "discharge-cleaning" of the vessel interior surfaces may result in heating the vessel to $\sim 100^{\circ}\text{C}$.

The starting point for conducting the estimates is Fick's equation for one dimensional diffusion for an infinite extent slab of thickness L cm and unit area 1 cm^2 for a time duration θ seconds. The point concentration variation with time at depth x cm is to be extricated from:

$$\partial C / \partial \theta = D \partial^2 C / \partial x^2 \quad (40)$$

subject to the boundary conditions:

$$\begin{array}{lll} \text{at } \theta = 0 & C = C_0 & \text{for } 0 \leq x \leq L \\ \text{at } \theta > 0 & C = 0 & \text{for } x = 0 \text{ and } x = L \end{array}$$

The basis for the second boundary condition is that at the vacuum side ($x = 0$) the vacuum system draws off all the gases and at the air side ($x = L$) the air provides infinite dilution. For the aforementioned boundary conditions the solution of equation 40 for the concentration distribution, which is symmetric with respect to the midplane of the slab, is given by^(17, 18)

$$C(x, \theta) = (2C_0/\pi) \sum_{n=1}^{\infty} \frac{1 - (-1)^n}{n} \sin(n\pi x/L) e^{-(n\pi/L)^2 D \theta} \quad (41)$$

This solution, which involves only the odd harmonics, usually is stated alternatively as:

$$C(x, \theta) = (4C_0/\pi) \sum_{n=0}^{\infty} \frac{1}{2n+1} \sin \frac{(2n+1)\pi x}{L} e^{-[(2n+1)\pi/L]^2 D \theta} \quad (42)$$

As derived from equation 42 the concentration gradient within the slab is given by:

$$\partial C / \partial x = (4C_0/L) \sum_{n=0}^{\infty} \cos \frac{(2n+1)\pi x}{L} e^{-[(2n+1)\pi/L]^2 D \theta} \quad (43)$$

which yields surface and midplane concentration gradients of:

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17. "Diffusion in and Through Solids," R. M. Barrer, Cambridge University Press (1951)
 18. "The Mathematics of Diffusion", J. Crank, Oxford University Press (1957), p. 45-47

$$(\partial C / \partial x)_{x=0} = (4C_o / L) \sum_{n=0}^{\infty} e^{-[(2n+1)\pi/L]^2 D \theta} \quad (\text{vacuum side}) \quad (44a)$$

$$(\partial C / \partial x)_{x=L} = -(4C_o / L) \sum_{n=0}^{\infty} e^{-[(2n+1)\pi/L]^2 D \theta} \quad (\text{air side}) \quad (44b)$$

$$(\partial C / \partial x)_{x=L/2} = 0 \quad (\text{midplane}) \quad (44c)$$

The working relationships for making the four aforementioned assessments of outgassing are generated by further manipulations with equations 42, 44a, and 44b. The working relationships utilized are:

1. Instantaneous Rate of Hydrogen Evolution from Slab Face at Pulsing Conditions for As-Fabricated Steel without Prior Bakeout

$$G_p = (4C_o D_p / L) \sum_{n=0}^{\infty} e^{-\pi^2 (2n+1)^2 D_p \theta / L^2} \quad \text{STP cm}^2 \text{ H}_2 / \text{sec cm}^2 \quad (45)$$

2. Instantaneous Rate of Hydrogen Evolution from Slab Face at Bakeout Conditions, Starting with As-Fabricated Steel

$$G_b = (4C_o D_b/L) \sum_{n=0}^{\infty} e^{-\pi^2 (2n+1)^2 D_b \theta_b / L^2} \quad \text{STP cm}^3 \text{ H}_2 / \text{sec cm}^2 \quad (46)$$

3. Initial Hydrogen Outgassing Rate from Slab Face at Pulsing Conditions Following Prior Bakeout of the As Fabricated Steel

$$G_{p_o} = (4C_o D_p/L) \sum_{n=0}^{\infty} e^{-\pi^2 (2n+1)^2 D_b \theta_b / L^2} \quad \text{STP cm}^3 \text{ H}_2 / \text{sec cm}^2 \quad (47)$$

4. Fraction of Hydrogen Quantity Still Retained in Slab Subsequent to Bakeout of the As-Fabricated Steel

$$F_b = (8/\pi^2) \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{-\pi^2 (2n+1)^2 D_b \theta_b / L^2} \quad (48)$$

where the meaning of the symbols are:

C_o = initial uniform hydrogen content of the as-fabricated steel,
STP cm³ H₂/cm³ steel

D = steel diffusivity for hydrogen at temperature T , cm²/sec

D_b = steel diffusivity for hydrogen at the bake-out temperature, cm²/sec

D_p = steel diffusivity for hydrogen at the pulsing tests temperature, cm²/sec

F_b = fraction of initially contained hydrogen in the as-fabricated steel
still retained after bakeout at for time θ_b at temperature T_b

G_b = instantaneous hydrogen outgassing rate during bakeout at temperature
 T_b , STP cm³ H₂/sec cm²

G_p = instantaneous hydrogen outgassing rate during pulsing tests at temperature T_p , STP $\text{cm}^3 \text{H}_2/\text{sec cm}^2$

G_{p_o} = initial hydrogen outgassing rate at start of pulsing tests at temperature T_p immediately following a bakeout conducted at temperature T_b for a time interval θ_b , STP $\text{cm}^3 \text{H}_2/\text{sec cm}^2$

L = steel thickness, cm

T = temperature, $^{\circ}\text{K}$

T_b = temperature maintained during bakeout, $^{\circ}\text{K}$

T_p = temperature maintained during pulsing operations, $^{\circ}\text{K}$

x = variable depth into steel below surface exposed to vacuum, cm

θ = variable time, sec

θ_b = duration of isothermal bakeout at temperature T_b , sec

θ_p = duration of isothermal pulsing operations temperature T_p

In connection with stating the estimates in terms most commonly used in ultra-high vacuum technology, conversion from STP $\text{cm}^3 \text{H}_2/\text{sec cm}^2$ to torr liters/sec cm^2 at 0°C is accomplished by multiplying the STP $\text{cm}^3 \text{H}_2/\text{sec cm}^2$ by 0.760.

It is pertinent to note that considerable difficulty arises when using equations 45, 46, 47, and 48 due to the very slow convergence of the series for small value of the "dimensionless time" term, $D\theta/L^2$. This situation and means to circumvent it has been suggested in the vacuum technology literature.⁽¹⁹⁾ The technique involved⁽²⁰⁾ to convert the slowly

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19. "Diffusion Coefficient, Solubility, and Permeability for Helium in Glass," W. A. Rogers, R. S. Buritz and D. Alpert, Journal of Applied Physics, 25: 868-875 (1954).
20. "Solution of a Diffusion Problem," T. Holstein, Research Report 60-94411-9-D, Westinghouse R & D Laboratories (December 20, 1951).

converging series into a rapidly converging series utilizes a transformation theorem of mathematical physics⁽²¹⁾:

$$\sum_{n=-\infty}^{\infty} e^{2\pi i n y} e^{-\pi n^2 / Z} = Z^{1/2} \sum_{n=-\infty}^{\infty} e^{-\pi (n+y)^2 Z} \quad (49)$$

Involvement of equation 49 is conveniently accomplished by starting with equation 41 and generating equation 44a in the alternative forms:

$$\begin{aligned} (\partial C / \partial x)_{x=0} &= 2 C_o / L \sum_{n=1}^{\infty} [1 - (-1)^n] e^{-(n\pi/L)^2 D \theta} \\ &= (2 C_o / L) \left[\sum_{n=1}^{\infty} e^{-(n\pi/L)^2 D \theta} - \sum_{n=1}^{\infty} (-1)^n e^{-(n\pi/L)^2 D \theta} \right] \\ &= (2 C_o / L) [s_1 - s_2] \end{aligned} \quad (50)$$

where:

$$s_1 = \sum_{n=1}^{\infty} e^{-(n\pi/L)^2 D \theta} \quad (51a)$$

$$s_2 = \sum_{n=1}^{\infty} (-1)^n e^{-(n\pi/L)^2 D \theta} \quad (51b)$$

The series s_1 and s_2 , which are also very slowly convergent for low values of $D\theta / L^2$,

21. "Methods of Mathematical Physics," volume I, R. Courant and D. Hilbert, Interscience Publishers, Inc. (1953), p. 75-76.

via transformation through application of equation 49 are converted into the following very rapidly convergent equivalents:

$$s_1 = \left[L/(\pi D \theta)^{1/2} \right] \left[\sum_{n=0}^{\infty} e^{-(n+1)^2 L^2 / D \theta} + 1/2 \right] - 1/2 \quad (52a)$$

$$s_2 = \left[L/(\pi D \theta)^{1/2} \right] \left[\sum_{n=0}^{\infty} e^{-(2n+1)^2 L^2 / 4 D \theta} \right] - 1/2 \quad (52b)$$

Utilization of equations 52a and 52b is much preferred over equations 51a and 51b for small values of $D \theta / L^2$ because of the exceedingly rapid convergence, whereas for large values of $D \theta / L^2$ equations 51a and 51b are the preferred forms.

6.2 OUTGASSING RATES FOR AS-FABRICATED VESSEL SECTIONS

Application of equation 45 affords a basis for estimating the hydrogen outgassing rates that would be experienced in the event that the as-fabricated torus is operated without prior bakeout. The results of such estimates for operations at 21.1°C and 100°C are summarized in Tables 6-2 and 6-3, covering cumulative operating periods of 10-1000 days.

TABLE 6-2

OUTGASSING RATES AT 21.1°C FOR AS-FABRICATED VESSEL WITHOUT PRIOR BAKEOUT

Days After Operations Start	G_p , Torr · liter/sec cm ²		
	$L = 0.102$ cm	$L = 0.675$ cm	$L = 7.62$ cm
10	1.6×10^{-9}	1.6×10^{-9}	1.6×10^{-9}
50	7.0×10^{-10}	7.0×10^{-10}	7.0×10^{-10}
100	5.0×10^{-10}	5.0×10^{-10}	5.0×10^{-10}
200	3.5×10^{-10}	3.5×10^{-10}	3.5×10^{-10}
400	2.4×10^{-10}	2.5×10^{-10}	2.5×10^{-10}
700	1.6×10^{-10}	1.9×10^{-10}	1.9×10^{-10}
1000	1.1×10^{-10}	1.6×10^{-10}	1.6×10^{-10}

TABLE 6-3

OUTGASSING RATES AT 100°C FOR AS-FABRICATED VESSEL WITHOUT PRIOR BAKEOUT

Days After Operations Start	G_p , Torr · liter/sec cm ²		
	$L = 0.102$ cm	$L = 0.675$ cm	$L = 7.62$ cm
10	1.0×10^{-8}	1.1×10^{-8}	1.1×10^{-8}
50	8.1×10^{-10}	4.8×10^{-9}	4.8×10^{-9}
100	3.4×10^{-11}	3.4×10^{-9}	3.4×10^{-9}
200	6.2×10^{-14}	2.4×10^{-9}	2.4×10^{-9}
400	2.9×10^{-18}	1.6×10^{-9}	1.7×10^{-9}
700	0	1.1×10^{-9}	1.3×10^{-9}
1000	0	6.8×10^{-10}	1.1×10^{-9}

In actual practice the calculated improvements in outgassing rate shown in Tables 6-2 and 6-3 are not fully achieved due to the presence of hydrogen and moisture on the air-side of the equipment and hydrogen and sundry "debris" on the vacuum side. The calculated outgassing rates (G_p) for operation at 21.1°C are comparable to the 10^{-10} torr · liter/sec cm² used in the TFTR conceptual design calculations (see Table 4-2).

As is evident from a comparison of the entries in Tables 6-2 and 6-3, the early outgassing rates for as-fabricated material are larger at higher operating temperatures than they are at lower operating temperatures. However, with increased operating time this situation becomes reversed. This means that at one point in time the instantaneous outgassing rates for the two temperatures are identical. This situation occurs for the bellows stock ($L = 0.102$ cm) within the 50-100 day time interval at an operating time of ~ 54 days for an equal $G_p \approx 6.7 \times 10^{-10}$ torr · liter/sec cm². For thick sections the improvement does not occur until far into the future, much in excess of 1000 days for the TFTR torus body sections ($L = 0.675$ cm) and reinforcing rings ($L = 7.62$ cm). This behavior is a consequence of the large quantity of stored hydrogen in these thick sections which behaves so as to delay the flattening of the concentration distribution within the stock, thereby maintaining a steeper concentration gradient at the stock surfaces for a longer time.

For the thinner stock the substantial improvement (decrease) in outgassing rate is a consequence of the fact that operation at 100°C amounts to a "low temperature bakeout." The earlier high outgassing rate in this case compared to 21.1°C operation is mainly the effect of a higher hydrogen diffusivity ($D_{100^\circ\text{C}}/D_{21.1^\circ\text{C}} = 46$).

6.3 VARIATION OF OUTGASSING RATES DURING ISOTHERMAL BAKEOUT

Very rapid elimination of the initially contained hydrogen occurs for high temperature bakeout of thin stock. For example, for the bellows ($L = 0.102$ cm) a 500°C bakeout yields an outgassing rate (G_b) of 3.9×10^{-9} torr · liter/sec cm² at the one hour point, whereas at the five hour stage the calculated outgassing rate has dropped to 1.9×10^{-22} torr · liter/sec cm². In contrast, for a low temperature bakeout at 200°C for $L = 0.102$ cm stock the corresponding calculated outgassing rates are $G_b(200^\circ\text{C}, 1 \text{ hr}) = 8.2 \times 10^{-7}$ torr · liter/sec cm² and $G_b(200^\circ\text{C}, 5 \text{ hr}) = 3.7 \times 10^{-7}$ torr · liter/sec cm². Furthermore, a 400 hour 200°C bakeout of $L = 0.102$ cm stock is required to yield a low calculated outgassing rate as 2.7×10^{-18} torr · liter/sec cm². This huge disparity between mild and high temperature bakeouts is due to a combination of effects stemming from the much higher diffusivity ($D_{500^\circ\text{C}}/D_{200^\circ\text{C}} \approx 156$.) The magnitude of D_b exerts a double impact on the value of G_b (see equations 2 and 46), both as a multiplier plus an exponential contributor in the hydrogen transport phenomena.

Outgassing of thick stock is very sluggish in comparison to thin stock. This can be readily appreciated by comparing G_b (24 hour) values for $L = 0.675$ cm stock for bakeouts at 500°C and 200°C, for example. The calculated G_b values in torr · liter/sec cm² are $G_b(500^\circ\text{C}, 24 \text{ hr}) = 1.1 \times 10^{-8}$ and $G_b(200^\circ\text{C}, 24 \text{ hr}) = 1.7 \times 10^{-7}$.

Tables 6-4 and 6-5 show the variation of the instantaneous outgassing rates during isothermal bakeouts in the temperature range 200–500°C for TFTR bellows stock and torus body thicknesses, based on an initial uniform hydrogen content of $0.833 \text{ STP cm}^3 \text{ H}_2/\text{cm}^3 \text{ steel}$.

TABLE 6-4

OUTGASSING RATES (G_b) DURING BAKEOUT AT VARIOUS TEMPERATURESBellow Stock ($L = 0.102$ cm); G_b in torr·liter/sec cm²

Bakeout Temperature, °C

Bakeout Time Hours	200°	250°	300°	350°	400°	450°	500°
1	8.2×10^{-7}	1.5×10^{-6}	2.4×10^{-6}	2.5×10^{-6}	1.1×10^{-6}	1.4×10^{-7}	3.0×10^{-9}
2	5.8×10^{-7}	1.0×10^{-6}	1.3×10^{-6}	6.2×10^{-7}	5.7×10^{-8}	4.6×10^{-10}	1.2×10^{-13}
3	4.7×10^{-7}	8.2×10^{-7}	7.3×10^{-7}	1.5×10^{-7}	2.9×10^{-9}	1.5×10^{-12}	4.8×10^{-18}
4	4.1×10^{-7}	6.6×10^{-7}	4.0×10^{-7}	3.7×10^{-8}	1.5×10^{-10}	5.1×10^{-15}	1.9×10^{-22}
5	3.7×10^{-7}	5.3×10^{-7}	2.2×10^{-7}	9.1×10^{-9}	7.8×10^{-12}	1.5×10^{-17}	
10	2.5×10^{-7}	1.8×10^{-7}	1.2×10^{-8}	8.2×10^{-12}	2.8×10^{-18}		
15	1.8×10^{-7}	6.3×10^{-8}	6.1×10^{-10}	7.3×10^{-15}	1.0×10^{-24}		
20	1.3×10^{-7}	2.1×10^{-8}	3.2×10^{-11}	6.6×10^{-18}			
25	9.3×10^{-8}	7.3×10^{-9}	1.7×10^{-12}	5.9×10^{-21}			
30	6.7×10^{-8}	2.5×10^{-9}	8.8×10^{-14}				
35	4.9×10^{-8}	8.6×10^{-10}	4.6×10^{-15}				
40	3.5×10^{-8}	2.9×10^{-10}	2.4×10^{-16}				
60	9.7×10^{-9}	4.0×10^{-12}	1.8×10^{-21}				
80	2.6×10^{-9}	5.5×10^{-14}					
100	7.3×10^{-10}	7.6×10^{-16}					
120	2.0×10^{-10}	1.0×10^{-17}					
140	5.4×10^{-11}	1.4×10^{-19}					
160	1.5×10^{-11}						
180	4.1×10^{-12}						
200	1.1×10^{-12}						
250	4.4×10^{-14}						
300	1.7×10^{-15}						
350	6.8×10^{-17}						
400	2.7×10^{-18}						

TABLE 6-5
OUTGASSING RATES (G_b) DURING BAKEOUT AT VARIOUS TEMPERATURES
Vessel Shell Stock (L = 0.675 cm); G_b in torr-liter/sec cm²

Bakeout Time Days	200°C	250°C	300°C	350°C	400°C	450°C	500°C
.42 (10 hr)	2.6×10^{-7}	4.7×10^{-7}	7.8×10^{-7}	1.2×10^{-6}	1.7×10^{-6}	1.7×10^{-6}	1.1×10^{-6}
1	1.7×10^{-7}	3.0×10^{-7}	5.0×10^{-7}	7.2×10^{-7}	6.4×10^{-7}	2.8×10^{-7}	1.1×10^{-8}
2	1.2×10^{-7}	2.2×10^{-7}	3.4×10^{-7}	3.3×10^{-7}	1.3×10^{-7}	1.2×10^{-8}	4.2×10^{-11}
3	9.7×10^{-8}	1.8×10^{-7}	2.5×10^{-7}	1.5×10^{-7}	2.5×10^{-8}	5.3×10^{-10}	6.6×10^{-13}
4	8.4×10^{-8}	1.5×10^{-7}	1.8×10^{-7}	7.1×10^{-8}	4.9×10^{-9}	2.3×10^{-11}	2.6×10^{-15}
5	7.5×10^{-8}	1.3×10^{-7}	1.3×10^{-7}	3.3×10^{-8}	9.6×10^{-10}	1.0×10^{-12}	1.0×10^{-17}
6	6.8×10^{-8}	1.2×10^{-7}	9.3×10^{-8}	1.5×10^{-8}	1.9×10^{-10}	4.5×10^{-14}	3.9×10^{-20}
7	6.3×10^{-8}	1.0×10^{-7}	6.7×10^{-8}	7.1×10^{-9}	3.7×10^{-11}	2.0×10^{-15}	
8	5.9×10^{-8}	9.2×10^{-8}	4.9×10^{-8}	3.3×10^{-9}	7.3×10^{-12}	8.7×10^{-17}	
9	5.6×10^{-8}	8.2×10^{-8}	3.5×10^{-8}	1.5×10^{-9}	1.4×10^{-12}	3.8×10^{-18}	
10	5.3×10^{-8}	7.3×10^{-8}	2.6×10^{-8}	7.0×10^{-10}	2.8×10^{-13}	1.7×10^{-19}	
12	4.8×10^{-8}	5.8×10^{-8}	1.3×10^{-8}	1.5×10^{-10}	1.1×10^{-14}	3.2×10^{-22}	
14	4.4×10^{-8}	4.5×10^{-8}	7.0×10^{-9}	3.2×10^{-11}	4.2×10^{-16}		
16	4.1×10^{-8}	3.6×10^{-8}	3.7×10^{-9}	7.0×10^{-12}	1.6×10^{-17}		
18	3.8×10^{-8}	2.8×10^{-8}	1.9×10^{-9}	1.5×10^{-12}	6.3×10^{-19}		
20	3.5×10^{-8}	2.2×10^{-8}	1.0×10^{-9}	3.2×10^{-13}	2.4×10^{-20}		
25	2.9×10^{-8}	1.2×10^{-8}	2.0×10^{-10}	6.9×10^{-15}			
30	2.5×10^{-8}	6.9×10^{-9}	4.0×10^{-11}	1.5×10^{-18}			
35	2.1×10^{-8}	3.9×10^{-9}	7.9×10^{-12}	3.1×10^{-18}			
40	1.7×10^{-8}	2.1×10^{-9}	1.6×10^{-12}	6.7×10^{-20}			
50	1.2×10^{-8}	6.6×10^{-10}	6.2×10^{-14}				
60	8.5×10^{-9}	2.0×10^{-10}	2.4×10^{-15}				
70	5.9×10^{-9}	6.3×10^{-11}	9.6×10^{-17}				
80	4.2×10^{-9}	1.9×10^{-11}					
100	2.0×10^{-9}	1.9×10^{-12}					

The outgassing rates shown in Table 6-5 for bakeout of thicker stock highlight the fact that bakeout at higher temperature, or bakeout for much longer time periods, or a combination of both of these is required to effect a substantial elimination of the initially contained hydrogen when attempting bakeout of thick stock. From the numbers displayed in Tables 6-4 and 6-5 it is also evident that a bakeout that subjects the thin and thick section of the device to the same temperature and time-at-temperature will result in a range of outgassing rates for the various sections during pulsing operations.

For purposes of assessing what bakeout temperature and bakeout time combinations are required to achieve a desired outgassing rate at the device operating temperature (G_{p_o} as defined by equation 47), the important parameter is the concentration gradient at the stock faces established by the bakeout, $(\partial C / \partial x)_{x=0}$ rather than G_b . Values of these concentration gradients are listed in Tables 6-6 and 6-7.

Plots of $(\partial C / \partial x)_{x=0}$ versus θ_b for selected T_b values are helpful in determining the array of $T_b - \theta_b$ combinations leading to the desired initial outgassing rate G_{p_o} for operations at temperature T_p , utilizing equation 47.

6.4 OUTGASSING RATES FOR VESSEL SECTIONS FOLLOWING BAKEOUTS

There are many reasons for attempting to attain a low outgassing rate in TFTR operations, such as: (a) low rates are conducive to achieving a low system base pressure without requiring disproportionately large pumping rates; (b) low rates connote that the system is quite "clean" from an ultra-high vacuum viewpoint and this implies that there will be less propensity for impurities to pass from the walls into the plasma. Low outgassing rates can be achieved through a number of approaches such as: (a) vacuum or air bakeout of the steel stock or the fabricated hardware pieces prior to assembly; (b) in-situ vacuum bakeout of the assembled equipment; (c) discharge cleaning of the device walls; (d) combinations of these procedures. The many problems and considerations relevant to the vacuum vessel cleanup issue are treated elsewhere^(13, 14). On the other hand, the concern of this subsection is an estimation of the kind of outgassing rates that can be anticipated from bakeouts in general, by calculating hydrogen outgassing rates (via equation 46) at expected device operating temperatures.

TABLE 6-6
FACE CONCENTRATION GRADIENTS GENERATED BY 200-350°C BAKEOUTS
Values of $(\partial C/\partial x)_{x=0}$ in STP $\text{cm}^3 \text{H}_2/\text{cm}^3 \text{steel cm}$

Bakeout Time	200°C		250°C		300°C		350°C	
	L = .102 cm	L = .675 cm	L = .102 cm	L = .675 cm	L = .102 cm	L = .675 cm	L = .102 cm	L = .675 cm
Hours								
3	3.28×10^1	3.28×10^1	1.73×10^1	1.80×10^1	5.56	1.09×10^1	4.85×10^{-1}	7.05
6	2.31×10^1	2.32×10^1	9.02	1.28×10^1	9.47×10^{-1}	7.69	7.19×10^{-3}	4.99
9	1.84×10^1	1.90×10^1	4.74	1.04×10^1	1.61×10^{-1}	6.28	1.07×10^{-4}	4.07
12	1.50×10^1	1.64×10^1	2.49	9.02	2.75×10^{-2}	5.44	1.58×10^{-6}	3.52
15	1.24×10^1	1.47×10^1	1.31	8.07	4.64×10^{-3}	4.87	2.35×10^{-8}	3.12
18	1.02×10^1	1.34×10^1	6.88×10^{-1}	7.37	7.96×10^{-4}	4.44	3.48×10^{-10}	2.80
21	8.39	1.24×10^1	3.62×10^{-1}	6.82	1.36×10^{-4}	4.11	5.16×10^{-12}	2.53
Days								
1	6.91	1.16×10^1	1.90×10^{-1}	6.38	2.31×10^{-5}	3.84	7.66×10^{-14}	2.29
2	1.46	8.21	1.11×10^{-3}	4.51	1.63×10^{-11}	2.60	1.80×10^{-28}	1.06
3	3.09×10^{-1}	6.70	6.44×10^{-6}	3.68	1.15×10^{-17}	1.87		4.91×10^{-1}
4	6.52×10^{-2}	5.81	3.75×10^{-8}	3.16		1.35		2.28×10^{-1}
5	1.38×10^{-2}	5.19	2.18×10^{-10}	2.77		9.80×10^{-1}		1.05×10^{-1}
6	2.92×10^{-3}	4.74	1.27×10^{-12}	2.45		7.09×10^{-1}		4.89×10^{-2}
7	6.16×10^{-4}	4.39		2.17		5.13×10^{-1}		2.26×10^{-2}
8	1.30×10^{-4}	4.10		1.93		3.71×10^{-1}		1.05×10^{-2}
9	2.75×10^{-5}	3.87		1.71		2.69×10^{-1}		4.86×10^{-3}
10	5.82×10^{-6}	3.66		1.52		1.94×10^{-1}		2.26×10^{-3}
12	2.60×10^{-7}	3.33		1.20		1.02×10^{-1}		4.84×10^{-4}
14	1.16×10^{-8}	3.06		9.53×10^{-1}		5.33×10^{-2}		1.04×10^{-4}
16	3.20×10^{-10}	2.83		7.53×10^{-1}		2.79×10^{-2}		2.23×10^{-5}
18	2.32×10^{-11}	2.62		5.95×10^{-1}		1.46×10^{-2}		4.79×10^{-6}
20	1.04×10^{-12}	2.44		4.71×10^{-1}		7.66×10^{-3}		1.03×10^{-6}
25		2.03		2.62×10^{-1}		1.52×10^{-3}		2.20×10^{-8}
30		1.70		1.45×10^{-1}		3.02×10^{-4}		4.69×10^{-10}
35		1.43		8.07×10^{-2}		5.99×10^{-5}		1.00×10^{-11}
40		1.19		4.49×10^{-2}		1.19×10^{-5}		2.14×10^{-13}
50		8.37×10^{-1}		1.39×10^{-2}		4.68×10^{-7}		
60		5.87×10^{-1}		4.28×10^{-3}		1.84×10^{-8}		
70		4.12×10^{-1}		1.32×10^{-3}		7.27×10^{-10}		
80		2.89×10^{-1}		4.08×10^{-4}				
90		2.02×10^{-1}		1.26×10^{-4}				
100		1.42×10^{-1}		3.89×10^{-5}				

TABLE 6-7
FACE CONCENTRATION GRADIENTS GENERATED BY 400-500°C BAKEOUTS
Values of $(\partial C / \partial x)_{x=0}$ in STP $\text{cm}^3 \text{H}_2 / \text{cm}^3 \text{Steel cm}$

Bakeout Time	400°C		450°C		500°C	
	L = .102 cm	L = .675 cm	L = .102	L = .675 cm	L = .102 cm	L = .675 cm
Hours						
1	1.68	8.40	1.09×10^{-1}	6.06	1.32×10^{-3}	4.55
2	8.64×10^{-2}	5.94	3.63×10^{-4}	4.29	5.31×10^{-8}	3.19
3	4.45×10^{-3}	4.85	1.21×10^{-6}	3.49	2.14×10^{-12}	2.48
4	2.29×10^{-4}	4.20	4.04×10^{-9}	2.98	8.63×10^{-17}	1.96
5	1.18×10^{-5}	3.75	1.35×10^{-11}	2.59	3.48×10^{-21}	1.55
6	6.05×10^{-7}	3.41	4.50×10^{-14}	2.26	1.40×10^{-25}	1.23
7	3.11×10^{-8}	3.14	1.50×10^{-16}	1.99	5.65×10^{-30}	9.79×10^{-1}
8	1.60×10^{-9}	2.91	5.00×10^{-19}	1.74		7.77×10^{-2}
9	8.24×10^{-11}	2.70	1.67×10^{-21}	1.53		6.17×10^{-1}
12	1.12×10^{-14}	2.19	6.19×10^{-29}	1.03		3.08×10^{-1}
15	1.53×10^{-18}	1.79		7.00×10^{-1}		1.54×10^{-1}
18	2.08×10^{-22}	1.46		4.74×10^{-1}		7.71×10^{-2}
21	2.83×10^{-26}	1.19		3.20×10^{-1}		3.86×10^{-2}
Days						
1	3.85×10^{-30}	9.71×10^{-1}		2.17×10^{-1}		1.93×10^{-2}
2		1.91×10^{-1}		9.52×10^{-3}		7.53×10^{-5}
3		3.76×10^{-2}		4.18×10^{-4}		2.94×10^{-7}
4		7.39×10^{-3}		1.84×10^{-5}		1.15×10^{-9}
5		1.45×10^{-3}		8.06×10^{-7}		4.48×10^{-12}
6		2.86×10^{-4}		3.54×10^{-8}		1.75×10^{-14}
7		5.62×10^{-5}		1.55×10^{-9}		6.84×10^{-17}
8		1.11×10^{-5}		6.83×10^{-11}		
9		2.17×10^{-6}		3.00×10^{-12}		
10		4.27×10^{-7}		1.32×10^{-13}		
12		1.65×10^{-8}		2.54×10^{-13}		
14		6.40×10^{-10}				
16		2.47×10^{-11}				
18		9.57×10^{-13}				
20		3.70×10^{-14}				

Tables 6-8 and 6-9 summarize the results of such calculations for two metal thicknesses corresponding to the bellows plate and torus body, for bakeouts conducted in the range 200-500°C, and with subsequent device operation at 21.1 or 100°C.

As shown in Table 6-8, calculated low outgassing rates, as 10^{-16} torr·liter/sec cm² can be achieved for thin stock (L = 0.102 cm) for a range of reasonable temperature-time exposures for temperatures greater than 250°C. On the other hand, for the torus body stock (L = 0.675 cm) long bakeout times are required even for the 500°C case. For a calculated G_p value of 10^{-16} torr·liter/sec cm² for 21.1°C operations the required temperature-bakeout times are as indicated below, rounded to the nearest whole hour:

Bakeout Temperature °C	Bakeout Time Required, hr	
	L = 0.102 cm	L = 0.675 cm
300	26	--
350	11	415
400	5	197
450	3	102
500	2	57

6.5 HYDROGEN RETENTION DURING BAKEOUTS

As indicated by equation 43, during a bakeout the hydrogen currents out of the stock faces are identical. This results in a symmetrical depletion of hydrogen with respect to the stock central plane, with the transport occurring equally and in opposite directions from the center ($x = L/2$), where the concentration is greatest. This concentration recession proceeds very slowly in the case of thick materials, with the consequence that very long bakeout periods are required to degas such items. This behavior is displayed by the numbers listed in Table 6-10, which shows the variation of total retained hydrogen with bakeout temperature and time for the principal steel thicknesses of the vacuum vessel. As can be seen from the entries in Table 6-10 the bakeout temperature and the stock thickness are the dominant parameters as regards extent of degassing achieved. The extremes shown in Table 6-10 are striking-- a four day bakeout at 200°C results in a hydrogen retention of 73 percent for the torus shell

TABLE 6-8
INITIAL OUTGASSING RATE FOR PULSING OPERATIONS FOLLOWING BAKEOUT

BELLOWS, $L = 0.102 \text{ cm}$
Outgassing Rate (G_p) in torr-liter/sec cm^2
Upper Entry $T_p \sim 21.1^\circ\text{C}$, Lower Entry $T_p = 100^\circ\text{C}$

Bakeout Time Hours	Bakeout Temperature, $^\circ\text{C}$					
	200	250	300	350	400	450 500
3	4.2×10^{-10}	2.2×10^{-10}	7.1×10^{-11}	6.2×10^{-12}	5.6×10^{-14}	1.5×10^{-17}
	1.9×10^{-8}	1.0×10^{-8}	3.3×10^{-9}	2.8×10^{-10}	2.6×10^{-12}	27×10^{-23}
6	2.9×10^{-10}	1.1×10^{-10}	1.2×10^{-11}	9.1×10^{-14}	7.7×10^{-18}	5.7×10^{-25}
	1.4×10^{-8}	5.3×10^{-9}	5.5×10^{-10}	4.2×10^{-12}	3.5×10^{-16}	2.6×10^{-23}
9	2.3×10^{-10}	6.0×10^{-11}	2.0×10^{-12}	1.4×10^{-15}	1.0×10^{-21}	
	1.1×10^{-8}	2.8×10^{-9}	9.4×10^{-11}	6.3×10^{-14}	4.8×10^{-20}	
12	1.9×10^{-10}	3.2×10^{-11}	3.5×10^{-13}	2.0×10^{-17}		
	8.8×10^{-9}	1.5×10^{-9}	1.6×10^{-11}	9.3×10^{-16}		
15	1.6×10^{-10}	1.7×10^{-11}	5.9×10^{-14}	3.0×10^{-19}		
	7.3×10^{-9}	7.7×10^{-10}	2.7×10^{-12}	1.4×10^{-17}		
18	1.3×10^{-10}	8.7×10^{-12}	1.0×10^{-14}	4.4×10^{-21}		
	6.0×10^{-9}	4.0×10^{-10}	4.7×10^{-13}	2.0×10^{-19}		
24	8.8×10^{-11}	2.4×10^{-12}	2.9×10^{-16}			
	4.0×10^{-9}	1.1×10^{-10}	1.4×10^{-14}			
48	1.9×10^{-11}	1.4×10^{-14}	2.1×10^{-22}			
	8.6×10^{-10}	6.5×10^{-13}	9.6×10^{-21}			
72	3.9×10^{-12}	8.2×10^{-17}				
	1.8×10^{-10}	3.8×10^{-15}				
96	8.3×10^{-13}	4.7×10^{-19}				
	3.8×10^{-11}	2.2×10^{-17}				
120	1.7×10^{-13}	2.8×10^{-21}				
	8.1×10^{-12}	1.3×10^{-19}				
144	3.7×10^{-14}					
	1.7×10^{-12}					
168	7.8×10^{-15}					
	3.6×10^{-13}					
192	1.7×10^{-15}					
	7.6×10^{-14}					
216	3.5×10^{-16}					
	1.6×10^{-14}					
240	7.4×10^{-17}					
	3.4×10^{-15}					
288	3.3×10^{-18}					
	1.5×10^{-16}					

TABLE 6-9
INITIAL OUTGASSING RATE FOR PULSING OPERATIONS FOLLOWING BAKEOUT

TORUS BODY, L = 0.675 cm
Outgassing Rate (G_p) in torr-liter/sec cm²

Upper Entry $T_p = 21.1^\circ\text{C}$, Lower Entry $T_p = 100^\circ\text{C}$

Bakeout Time	Bakeout Temperature, $^\circ\text{C}$					
	200	250	300	350	400	500
3	4.2×10^{-10}	2.3×10^{-10}	1.4×10^{-10}	8.9×10^{-11}	5.3×10^{-11}	4.4×10^{-11}
	1.9×10^{-8}	1.1×10^{-8}	6.4×10^{-9}	4.1×10^{-9}	2.5×10^{-9}	2.0×10^{-9}
6	2.9×10^{-10}	1.6×10^{-10}	9.8×10^{-11}	6.3×10^{-11}	4.3×10^{-11}	2.9×10^{-11}
	1.4×10^{-8}	7.5×10^{-9}	4.5×10^{-9}	2.9×10^{-9}	2.0×10^{-9}	1.3×10^{-9}
9	2.4×10^{-10}	1.3×10^{-10}	8.0×10^{-11}	5.2×10^{-11}	3.4×10^{-11}	1.9×10^{-11}
	1.1×10^{-8}	6.1×10^{-9}	3.7×10^{-9}	2.4×10^{-9}	1.6×10^{-9}	9.0×10^{-10}
12	2.1×10^{-10}	1.1×10^{-10}	6.9×10^{-11}	4.5×10^{-11}	2.8×10^{-11}	1.3×10^{-11}
	9.6×10^{-9}	5.3×10^{-9}	3.2×10^{-9}	2.1×10^{-9}	1.3×10^{-9}	6.0×10^{-10}
24	1.5×10^{-10}	8.1×10^{-11}	4.9×10^{-11}	2.9×10^{-11}	1.2×10^{-11}	2.8×10^{-12}
	6.8×10^{-9}	3.7×10^{-9}	2.3×10^{-9}	1.3×10^{-9}	5.7×10^{-10}	1.3×10^{-10}
48	1.0×10^{-10}	5.7×10^{-11}	3.3×10^{-11}	1.3×10^{-11}	2.4×10^{-12}	1.2×10^{-13}
	4.8×10^{-9}	2.6×10^{-9}	1.5×10^{-9}	6.2×10^{-10}	1.1×10^{-10}	5.6×10^{-12}
72	8.5×10^{-11}	4.7×10^{-11}	2.4×10^{-11}	6.2×10^{-12}	4.8×10^{-13}	5.3×10^{-15}
	3.9×10^{-9}	2.2×10^{-9}	1.1×10^{-9}	2.9×10^{-10}	2.2×10^{-11}	2.4×10^{-13}
96	7.4×10^{-11}	4.0×10^{-11}	1.7×10^{-11}	2.9×10^{-12}	9.4×10^{-14}	2.3×10^{-16}
	3.4×10^{-9}	1.9×10^{-9}	7.9×10^{-10}	1.3×10^{-10}	4.3×10^{-12}	1.1×10^{-14}
120	6.6×10^{-11}	3.5×10^{-11}	1.2×10^{-11}	1.3×10^{-12}	1.8×10^{-14}	1.0×10^{-17}
	3.0×10^{-9}	1.6×10^{-9}	5.7×10^{-10}	6.2×10^{-11}	8.5×10^{-13}	4.7×10^{-16}
144	6.0×10^{-11}	3.1×10^{-11}	9.0×10^{-12}	6.2×10^{-13}	3.6×10^{-15}	4.5×10^{-19}
	2.8×10^{-9}	1.4×10^{-9}	4.2×10^{-10}	2.9×10^{-11}	1.7×10^{-13}	2.1×10^{-17}
168	5.6×10^{-11}	2.8×10^{-11}	6.5×10^{-12}	2.9×10^{-13}	7.1×10^{-16}	
	2.6×10^{-9}	1.3×10^{-9}	3.0×10^{-10}	1.3×10^{-11}	3.3×10^{-14}	
192	5.2×10^{-11}	2.4×10^{-11}	4.7×10^{-12}	1.3×10^{-13}	1.4×10^{-16}	
	2.4×10^{-9}	1.1×10^{-9}	2.2×10^{-10}	6.2×10^{-12}	6.5×10^{-15}	
216	4.9×10^{-11}	2.2×10^{-11}	3.4×10^{-12}	6.2×10^{-14}	2.8×10^{-17}	
	2.3×10^{-9}	1.0×10^{-9}	1.6×10^{-10}	2.8×10^{-12}	1.3×10^{-15}	
240	4.6×10^{-11}	1.9×10^{-11}	2.5×10^{-12}	2.9×10^{-14}	5.4×10^{-18}	
	2.1×10^{-9}	8.9×10^{-10}	1.1×10^{-10}	1.3×10^{-12}	2.5×10^{-16}	
288	4.2×10^{-11}	1.5×10^{-11}	1.3×10^{-12}	6.1×10^{-15}	2.1×10^{-19}	
	2.0×10^{-9}	7.0×10^{-10}	6.0×10^{-11}	2.8×10^{-13}	9.7×10^{-18}	
336	3.9×10^{-11}	1.2×10^{-11}	6.8×10^{-13}	1.3×10^{-15}		
	1.8×10^{-9}	5.6×10^{-10}	3.1×10^{-11}	6.1×10^{-14}		
384	3.6×10^{-11}	9.6×10^{-12}	3.5×10^{-13}	2.8×10^{-16}		
	1.7×10^{-9}	4.4×10^{-10}	1.6×10^{-11}	1.3×10^{-14}		
432	3.5×10^{-11}	7.6×10^{-12}	1.9×10^{-13}	6.1×10^{-17}		
	1.5×10^{-9}	3.5×10^{-10}	8.6×10^{-12}	2.8×10^{-15}		
480	3.1×10^{-11}	6.0×10^{-12}	9.7×10^{-14}	1.3×10^{-17}		
	1.4×10^{-9}	2.8×10^{-10}	4.5×10^{-12}	6.0×10^{-16}		

TABLE 6-10
FRACTION OF ORIGINALLY CONTAINED HYDROGEN RETAINED AFTER BAKEOUT
Upper Entry ~ L = 0.102 cm, Lower Entry ~ L = 0.675 cm

Bakeout Time Hours	Bakeout Temperature, °C						
	200	250	300	350	400	450	500
1	8.2×10^{-1}	6.7×10^{-1}	4.5×10^{-1}	2.0×10^{-1}	4.2×10^{-2}	2.7×10^{-3}	3.3×10^{-5}
	9.8×10^{-1}	9.5×10^{-1}	9.2×10^{-1}	8.7×10^{-1}	8.1×10^{-1}	7.4×10^{-1}	6.5×10^{-1}
2	7.4×10^{-1}	5.3×10^{-1}	2.5×10^{-1}	4.9×10^{-2}	2.1×10^{-3}	9.0×10^{-6}	1.3×10^{-9}
	9.7×10^{-1}	9.3×10^{-1}	8.8×10^{-1}	8.2×10^{-1}	7.4×10^{-1}	6.3×10^{-1}	5.1×10^{-1}
3	6.8×10^{-1}	4.3×10^{-1}	1.4×10^{-1}	1.2×10^{-2}	1.1×10^{-4}	3.0×10^{-8}	
	9.6×10^{-1}	9.1×10^{-1}	8.6×10^{-1}	7.8×10^{-1}	6.8×10^{-1}	5.5×10^{-1}	4.1×10^{-1}
4	6.3×10^{-1}	3.4×10^{-1}	7.6×10^{-2}	3.0×10^{-3}	5.7×10^{-6}		
	9.5×10^{-1}	9.0×10^{-1}	8.3×10^{-1}	7.4×10^{-1}	6.3×10^{-1}	4.8×10^{-1}	3.2×10^{-1}
8	4.8×10^{-1}	1.5×10^{-1}	1.6×10^{-2}	1.1×10^{-5}	4.0×10^{-11}		
	9.2×10^{-1}	8.6×10^{-1}	7.6×10^{-1}	6.4×10^{-1}	4.7×10^{-1}	2.9×10^{-1}	1.3×10^{-1}
12	3.7×10^{-1}	6.2×10^{-2}	6.8×10^{-4}	3.9×10^{-8}			
	9.0×10^{-1}	8.3×10^{-1}	7.1×10^{-1}	5.6×10^{-1}	3.6×10^{-1}	1.7×10^{-1}	5.1×10^{-2}
16	2.9×10^{-1}	2.6×10^{-2}	6.4×10^{-5}				
	9.0×10^{-1}	8.0×10^{-1}	6.7×10^{-1}	4.9×10^{-1}	2.7×10^{-1}	1.0×10^{-1}	2.0×10^{-2}
20	2.2×10^{-1}	1.1×10^{-2}	6.1×10^{-6}				
	8.8×10^{-1}	7.8×10^{-1}	6.3×10^{-1}	4.3×10^{-1}	2.1×10^{-1}	6.0×10^{-2}	8.0×10^{-3}
24	1.7×10^{-1}	4.7×10^{-3}	5.7×10^{-7}				
	8.7×10^{-1}	7.5×10^{-1}	5.9×10^{-1}	3.8×10^{-1}	1.6×10^{-1}	3.6×10^{-2}	3.2×10^{-3}
28	1.3×10^{-1}	2.0×10^{-3}					
	8.5×10^{-1}	7.3×10^{-1}	5.6×10^{-1}	3.3×10^{-1}	1.2×10^{-2}	2.1×10^{-2}	1.3×10^{-3}
32	1.0×10^{-1}	8.5×10^{-4}					
	8.4×10^{-1}	7.2×10^{-1}	5.3×10^{-1}	2.9×10^{-1}	9.3×10^{-2}	1.3×10^{-2}	5.0×10^{-4}
36	7.9×10^{-2}	3.6×10^{-4}					
	8.3×10^{-1}	7.0×10^{-1}	5.0×10^{-1}	2.6×10^{-1}	7.1×10^{-2}	7.5×10^{-3}	2.0×10^{-4}
40	6.1×10^{-2}	1.5×10^{-4}					
	8.3×10^{-1}	6.8×10^{-1}	4.7×10^{-1}	2.3×10^{-1}	5.4×10^{-2}	4.4×10^{-3}	7.9×10^{-5}
44	4.7×10^{-2}	6.5×10^{-5}					
	8.2×10^{-1}	6.7×10^{-1}	4.5×10^{-1}	2.0×10^{-1}	4.1×10^{-2}	2.6×10^{-3}	3.1×10^{-5}
48	3.6×10^{-2}	2.8×10^{-5}					
	8.1×10^{-1}	6.5×10^{-1}	4.3×10^{-1}	1.7×10^{-1}	3.1×10^{-2}	1.6×10^{-3}	1.2×10^{-5}
60	1.7×10^{-2}	2.1×10^{-6}					
	7.9×10^{-1}	6.1×10^{-1}	3.6×10^{-1}	1.2×10^{-1}	1.4×10^{-2}	3.3×10^{-4}	7.8×10^{-7}
72	7.7×10^{-3}	1.6×10^{-7}					
	7.7×10^{-1}	5.7×10^{-1}	3.1×10^{-1}	8.1×10^{-2}	6.2×10^{-3}	6.9×10^{-4}	
96	1.6×10^{-3}						
	7.3×10^{-1}	5.1×10^{-1}	2.2×10^{-1}	3.7×10^{-2}	1.2×10^{-3}	3.0×10^{-6}	

sections ($L = 0.675$ cm) whereas this kind of bakeout results in a retention of only 0.16 per-cent for the bellows plates ($L = 0.102$ cm). This and the figures shown in Table 6-9 tend to indicate that in-situ bakeouts in the range $200-350^{\circ}\text{C}$ will be relatively ineffective.

The tabulations of estimated outgassing phenomena presented in this section should provide guidance with regard to resolving the pre-bakeout versus in-situ bakeout question and related issues.

7.0 ESTIMATION OF TRITIUM DIFFUSION TRANSIENTS

As indicated previously, precise calculation of the normal tritium releases to be expected for TFTR operations is exceedingly complex. Such computations, which require prior specification of the details of the operations schedule and experimental scenarios, involve consideration of such items as the tritium concentration distribution in the various elements of the vacuum vessel and its auxiliaries, the diffusion currents at the air and vacuum sides of the elements, and the time integration of these diffusion currents over the operating and outage periods to be encountered. The state of the system with respect to tritium inventory residing in the metal elements and concentration distribution at any instant is determined by the previous history of the system. This in turn also specifies the instantaneous tritium release rate from the equipment.

The main objective of this section is to provide guidance for making estimations for tritium diffusion transients. Formulas are presented to serve as the basis for making such estimates, as derived from classical diffusion theory. In the way of demonstrating how these formulations can be applied, computations are shown for the tritium transients that occur during the first operation of TFTR with reference full power D-T pulsing experiments. These computations are engineering estimates rather than precise calculations in that the system is treated on a "smeared" basis and because a number of simplifying assumptions are invoked. The approach utilized is deemed to produce numbers on the conservative side, that is it is expected that these overstate the normal releases to be encountered, barring equipment leaks. The nature of the assumptions involved are outlined in the following subsection.

7.1 ESTIMATIONS MODEL AND ASSUMPTIONS

The starting point for conducting the estimates is Fick's formula for one dimensional diffusion for an infinite extent slab of thickness L cm and unit area 1 cm^2 for a variable time duration of θ seconds, as given previously by equation 40. The orientation of the x - axis is taken to be such that the air side is at the origin ($x = 0$), whereas the torus

interior (vacuum side) is located at $x = L$.

In general three types of transients will occur for TFTR operations with tritium. Each of these will have its own special initial and boundary conditions. The first of these occurs at the on-set of tritium operations, for which the boundary conditions are:

First Exposure of Duration $\theta = \epsilon_1$

$$\begin{aligned} C &= 0 & \text{at } 0 < x < L & \text{for } \theta = 0 \\ C &= C_1^* & \text{at } x = L & \text{for } \theta > 0 \quad (\text{Vacuum side}) \\ C &= 0 & \text{at } x = 0 & \text{for } \theta > 0 \quad (\text{Air side}) \end{aligned}$$

where C_1^* is the equilibrium concentration (solubility) of tritium in steel as determined by the effective tritium partial pressure in the atmosphere in contact with the metal surface, as specified by equation 4 (replacing the solubility symbol S by C^* , in that S in this section is to connote the surface exposed to the vacuum side). At the conclusion of this first exposure to tritium for duration $\theta = \epsilon_1$ a tritium concentration distribution within the slab will have been generated, designated symbolically by $C_1(x, \epsilon_1)$.

Subsequent to the first exposure to tritium the system conditions may be altered by either establishing a different tritium pressure (higher or lower) for an exposure period ϵ_2 or eliminating the tritium pressure entirely for a tritium outage period of duration ω_1 .

The boundary conditions for these operations phases are:

Second Exposure of Duration $\theta = \epsilon_2$

$$\begin{aligned} C &= C_1(x, \epsilon_1) & \text{at } 0 < x < L & \text{for } \theta = 0 \\ C &= C_2^* & \text{at } x = L & \text{for } \theta > 0 \quad (\text{Vacuum side}) \\ C &= 0 & \text{at } x = 0 & \text{for } \theta > 0 \quad (\text{Air side}) \end{aligned}$$

Or First Outage of Duration $\theta = \omega_1$

$$\begin{aligned} C &= C_1(x, \epsilon_1) & \text{at } 0 < x < L & \text{for } \theta = 0 \\ C &= 0 & \text{at } x = L & \text{for } \theta > 0 \quad (\text{Vacuum side}) \\ C &= 0 & \text{at } x = 0 & \text{for } \theta > 0 \quad (\text{Air side}) \end{aligned}$$

All of the operations, as regards tritium concentration distribution and the related quantities derived therefrom, will follow the same boundary condition format as shown above. It is clear, therefore, from a contained tritium standpoint, that at any stage of the system its description will have within it remnants of the history of all previous operations due to the chain-nature of the successive boundary conditions.

The assumption of an equilibrium state at the metal surfaces in contact with the gas phase based on solubility equation 4 has other connotations. This presumes the lack of other diffusion impedances at the surfaces as metal oxide barriers, or interfering "boundary layer" films, or desorption retarding zones.

All operations are assumed to be conducted at 21.1°C (70°F), so that the "effective" diffusivity for the steel-tritium system (accounting for a grain boundary contribution in accordance with equations 2, 6, and 7) is $D = 9.328 \times 10^{-12} \text{ cm}^2/\text{sec}$. This is presumed to be concentration independent. Incorporation of the grain boundary contribution in the manner described in Section 1 results in a diffusivity that is greater than the extrapolated lattice diffusivity by a factor of 13.8. Alterations in the steel properties due to neutron bombardment, helium entrapment, or other phenomena are neglected.

Potential tritium holdup complications due to helium entrapment, void formation, metal tritide production, isotopic combinations, and the like are not accounted for. Similarly, the accumulation of tritium in the metal by embedment during plasma discharge is ignored, on the assumption that essentially all of the embedment will occur on the tungsten-molybdenum beam catcher sections and limiters. In this regard, the bellows plates, which comprise about 62 percent of the system internal surface, are insulated against embedment from plasma discharges by the bellows protection ring (see Figure 2-2). The complications due to radioactive decay of the tritium are also side-tracked.

A precise treatment of tritium diffusion would require analysis of a new transport regime every time the tritium pressure in the gas phase is changed. For practical purposes this is unduly

complicated, even when keeping account of the tritium inventory details with a programmed computer routine. The alternative to this detailed approach is one which handles the tritium pressure changes on a "smeared" or averaged basis, with the degree of averaging incorporated keyed to the urgency for precise versus adequately representative answers. For the tritium transport numbers presented here a high degree of averaging is quite satisfactory. The elements of this averaging routine for the reference operating schedule is as described below:

1. Based on a reference operating schedule of 1000 full power D-T pulses per year conducted in sequences of 40 D-T pulses in an operating day, there are 25 such pulse operating days per year. Each of these D-T pulsing operations days has an associated tritium gas pressure variation as outlined previously in Section 4.1.
2. Associated with each of the D-T pulsing operation days there are two adjunct days, one for tritium build-up involving 22 build-ups, and one for tritium-flushout involving 140 flush-outs as described in Section 4. Each of these days is characterized by its own tritium gas pressure variation as detailed in Sections 4.2 and 4.3.
3. For each of the three aforementioned days an integral mean tritium "effective" pressure is determined, and these in turn are lumped together to give an average "effective" tritium pressure over a three day duration tritium exposure period ($\epsilon = 2.5920 \times 10^5$ sec). The "effective" tritium pressure includes a contribution due to the surface adsorbed tritium, as described previously in Section 4.1. During these exposure periods tritium can diffuse into the metal elements from the vacuum side and diffuse out through the air exposed side.
4. Sandwiched in between the 25 clusters of three-day operations sequences there are 25 clusters of 11.6 day-duration ($\omega = 1.0022 \times 10^6$ sec) "outage"

periods during which the tritium content in the gas phase is negligible, with the "effective" tritium pressure for this period therefore taken as zero. During these outage periods tritium residing within the metal elements can counter-diffuse out through both the vacuum and air exposed sides.

The basis for including a pressure contribution for the surface adsorbed tritium has been aired briefly in Section 4.1. Such contributions are not necessary in high pressure systems in that the gas bombardment frequency at a surface overshadows the impingement oscillations of the adsorbed layer. This situation is otherwise for high vacuum situations. Because the adsorbed hydrogenous molecules are not firmly bound to the surface in a static state but instead are relatively loosely attached in a dynamic configuration, ever interchanging with the gas phase molecules, in terms of impingement on the surface the net behavior is as though they traveled in from the gas phase. In the absence of a firm theoretical basis for quantifying this contribution, in this instance this is done arbitrarily by adding in the pressure increment associated with distributing the adsorbed population into the system volume. This contribution has the effect of increasing the C^* value substantially, and therefore increasing the calculated tritium diffusion.

As in the case of the permeation estimates described in Section 4.0, the estimates for the transport through the bellows sections are made as though their outside is exposed to the air, i.e. no credit is taken for the transport impedance of the bellows assembly cover plates.

Table 7-1 lists details regarding the mean values of the tritium pressure throughout various periods of the three operation days during which exposure to tritium occurs. Based on the numbers shown in Table 7-1, the mean tritium pressure during the reference exposure period of three days ($\epsilon = 2.5920 \times 10^5$ sec) is 1.655×10^{-3} torr. The corresponding mean tritium pressure is 8.062×10^{-7} torr when the adsorbed layer contribution is neglected. Insertion of these mean tritium pressure values into the solubility relationship as given by equation 4 leads to C^* values of

TABLE 7-1
MEAN VALUE OF EFFECTIVE TRITIUM PRESSURES
Pressure in torr

<u>Item</u>	<u>Tritium Build-Up</u>	<u>D-T Pulsing Experiments</u>	<u>Tritium Flushout</u>
Number of operations/day	22	40	140
Total operations time/day, min	110	200	700
Outage time/day, min	1330	1240	740
Tritium pressure over 5 minute operation, torr			
1 sec	1.831×10^{-3}	2.822×10^{-3}	5.881×10^{-5}
5 sec	1.828×10^{-3}	2.817×10^{-3}	5.871×10^{-5}
77 sec	1.633×10^{-3}	2.516×10^{-3}	5.243×10^{-5}
217 sec	1.624×10^{-3}	2.503×10^{-3}	5.216×10^{-5}
Tritium pressure during outage, torr	2.503×10^{-3}	2.503×10^{-3}	3.039×10^{-9}
Mean tritium pressure over 24 hours, torr	2.436×10^{-3}	2.504×10^{-3}	2.546×10^{-5}

$$C^* = 6.687 \times 10^{-5} \text{ STP cm}^3 \text{ T}_2/\text{cm}^3 \text{ steel} \quad (\text{includes adsorption contribution})$$

$$C^* = 1.476 \times 10^{-6} \text{ STP cm}^3 \text{ T}_2/\text{cm}^3 \text{ steel} \quad (\text{omits adsorption contribution})$$

As is evident from these C^* magnitudes, incorporation of the adsorption contribution increases the working C^* value by a factor of 45.3.

7.2 RELATIONSHIPS APPLICABLE TO TRITIUM DIFFUSION

This section develops the working relationships applicable to the diffusion transients that occur, in conformity to the postulates set forth previously.

When the system is first exposed to tritium, each of the different steel sections comprising the device will experience transport of tritium across the surface exposed to the vacuum side of the equipment, and the concentration waves within these sections will build up according to:

$$C(x, \theta) = \frac{C^*}{L} x + \frac{2C^*}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \sin \frac{n\pi x}{L} e^{-(n\pi/L)^2 D\theta} = \mathcal{X}(x, \theta) \quad (53)$$

where x is the distance into the section measured from the air side. Inasmuch as expressions having the same form as equation 53 arise when treating successions of exposures and out-ages, for the sake of compactness it is convenient to denote this form by the abbreviation $\mathcal{X}(x, \theta)$. The transient behavior of the concentration wave is determined by the magnitude of the "dimensionless time" $D\theta/L^2$ (akin to the Fourier number in heat transfer).

During the tritium concentration buildup in the various steel sections the point concentration gradient, $\partial C/\partial x$, varies according to:

$$\frac{\partial C}{\partial x} = \frac{C^*}{L} + \frac{2C^*}{L} \sum_{n=1}^{\infty} (-1)^n \cos \frac{n\pi x}{L} e^{-(n\pi/L)^2 D\theta} \quad (54)$$

Inasmuch as the diffusion current ($\text{STP cm}^3 \text{ T}_2/\text{sec cm}^2 \text{ steel surface}$) is $G = D\partial C/\partial x$, the

magnitudes of the currents (flowing into the section) at the faces of a steel section are given by:

$$\text{Air Side } G(0, \theta) = -\frac{DC^*}{L} \left[1 + 2 \sum_{n=1}^{\infty} (-1)^n e^{-(n\pi/L)^2 D\theta} \right] \quad (55a)$$

$$= -\frac{DC^*}{L} \left[1 + 2 s_2(\theta) \right] \quad (55b)$$

$$\text{Vacuum Side } G(L, \theta) = \frac{DC^*}{L} \left[1 + 2 \sum_{n=1}^{\infty} e^{-(n\pi/L)^2 D\theta} \right] \quad (56a)$$

$$= \frac{DC^*}{L} \left[1 + 2 s_1(\theta) \right] \quad (56b)$$

where $s_1(\theta)$ and $s_2(\theta)$ also have alternative forms as indicated previously by equations 51a, 51b, 52a and 52b.

The total quantity of tritium per unit surface ($\text{STP cm}^3 \text{ T}_2/\text{cm}^2$) that passes a plane located at distance x over a time interval θ , $Q(x, \theta)$, is given by:

$$Q(x, \theta) = \int_0^{\theta} D(\partial C / \partial x) d\theta \quad (57)$$

Application of equation 57 to equations 55a and 56a leads to the following cumulative specific tritium flows out of the air side and into the vacuum side of a steel element:

$$\text{Air Side : } Q(0, \theta) = C^* L \left[\frac{D\theta}{L^2} - \frac{1}{6} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-(n\pi/L)^2 D\theta} \right] \quad (58a)$$

$$= C^* L \left[\frac{D\theta}{L^2} - \frac{1}{6} - \frac{2}{\pi^2} s_4(\theta) \right] \quad (58b)$$

$$\text{Vacuum Side : } Q(L, \theta) = C^* L \left[\frac{D\theta}{L^2} + \frac{1}{3} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-(n\pi/L)^2 D\theta} \right] \quad (59a)$$

$$= C^* L \left[\frac{D \theta}{L^2} + \frac{1}{3} - \frac{2}{\pi^2} s_3(\theta) \right] \quad (59b)$$

where

$$s_3(\theta) = \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-(n\pi/L)^2 D \theta} \quad (60)$$

$$s_4(\theta) = \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-(n\pi/L)^2 D \theta} \quad (61)$$

The instantaneous specific tritium accumulation (STP $\text{cm}^3 \text{T}_2/\text{cm}^3 \text{ steel}$) within the steel during the exposure period, $\Delta \Gamma_{\epsilon}(\theta) = Q(L, \theta) - Q(0, \theta)$, is given by :

$$\Delta \Gamma_{\epsilon}(\theta) = C^* L \left[\frac{1}{2} + \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-(n\pi/L)^2 D \theta} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-(n\pi/L)^2 D \theta} \right] \quad (62a)$$

$$= C^* L \left\{ \frac{1}{2} - \frac{2}{\pi^2} [s_3(\theta) - s_4(\theta)] \right\} \quad (62b)$$

where the distribution of this quantity of tritium within the steel is according to equation 53.

For the reference operating schedule the value of θ for the first exposure period is $\epsilon_1 = 2.5920 \times 10^5$ seconds.

Focussing next on the first outage period, the initial condition (at $\theta = 0$) for this operations phase is:

$$\begin{aligned} C(x, 0) &= \frac{C^* x}{L} + \frac{2C^*}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \sin \frac{n\pi x}{L} e^{-(n\pi/L)^2 D \epsilon_1} \\ &= X(x, \epsilon_1) \end{aligned} \quad (63)$$

The other applicable boundary conditions for the outage period, as indicated previously in Section 7.1, are:

$$\begin{array}{llllll} C = 0 & \text{at} & x = L & \text{for} & \theta > 0 & \text{(Vacuum Side)} \\ C = 0 & \text{at} & x = 0 & \text{for} & \theta > 0 & \text{(Air Side)} \end{array}$$

The general solution of Fick's equation that meets the two boundary conditions can be shown⁽²²⁾ to have the implicit form:

$$C(x, \theta) = \frac{2}{L} \int_0^L \mathcal{X}(x', \epsilon_1) \sum_{n=1}^{\infty} \left[\sin \frac{n\pi x'}{L} \sin \frac{n\pi x}{L} e^{-(n\pi/L)^2 D \theta} \right] dx' \quad (64)$$

Upon conducting the manipulations indicated in equation 64, the following expression is generated for the tritium concentration variation in the slab during the outage period:

$$\begin{aligned} C(x, \theta) = & \left[\frac{C^* x}{L} + \frac{2C^*}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \sin \frac{n\pi x}{L} e^{-(n\pi/L)^2 D (\epsilon_1 + \theta)} \right] - \\ & \left[\frac{C^* x}{L} + \frac{2C^*}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \sin \frac{n\pi x}{L} e^{-(n\pi/L)^2 D \theta} \right] \end{aligned} \quad (65)$$

This can be stated more succinctly, using the $\mathcal{X}(x, \theta)$ abbreviation defined by equation 53 as:

$$C(x, \theta) = \mathcal{X}(x, \epsilon_1 + \theta) - \mathcal{X}(x, \theta) \quad (66)$$

The time span of the first outage period is $\theta = \omega_1$, so the tritium concentration distribution within a slab at the end of the first outage period is given in succinct form by:

$$C_{\omega_1} = \mathcal{X}(x, \epsilon_1 + \omega_1) - \mathcal{X}(x, \omega_1) \quad (67)$$

whereas the tritium concentration distribution within a slab at the end of the first exposure period in this same notation is given by:

$$C_{\epsilon_1} = \bar{X}(x, \epsilon_1) \quad (68)$$

In some respects the form of equation 67 is remarkable and possibly surprising, in that it describes a real situation in terms of the difference between two unreal situations (i.e. events that do not occur). This can be realized by noting that: (a) the $\bar{X}(x, \epsilon_1 + \omega_1)$ term corresponds to the concentration distribution that would be generated by an exposure of duration $\epsilon_1 + \omega_1$; (b) $\bar{X}(x, \omega_1)$ corresponds to the concentration that would be generated by an exposure of duration ω_1 ; (c) neither of these exposures actually occur, in a physical sense.

Formulation of the terminal concentration distributions that are generated by successions of exposures and outages can be accomplished by repeated application of equation 64. The result of such iterations leads to following pattern for the relationships for the concentration distributions at the end of the various operations periods (the x is omitted in the interest of brevity) :

$$\text{Exposure 1: } C_{\epsilon_1} = \bar{X}(\epsilon_1) \quad (69a)$$

$$\text{Outage 1: } C_{\omega_1} = \bar{X}(\epsilon_1 + \omega_1) - \bar{X}(\omega_1) \quad (69b)$$

$$\text{Exposure 2: } C_{\epsilon_2} = \bar{X}(\epsilon_2) + \bar{X}(\epsilon_1 + \omega_1 + \epsilon_2) - \bar{X}(\epsilon_2) \quad (69c)$$

$$\text{Outage 2: } C_{\omega_2} = \bar{X}(\epsilon_1 + \omega_1 + \epsilon_2 + \omega_2) + \bar{X}(\epsilon_2 + \omega_2) - \bar{X}(\omega_1 + \epsilon_2 + \omega_2) - \bar{X}(\omega_2) \quad (69d)$$

$$\begin{aligned} \text{Exposure 3: } C_{\epsilon_3} = & \bar{X}(\epsilon_3) + \bar{X}(\epsilon_1 + \omega_1 + \epsilon_2 + \omega_2 + \epsilon_3) + \bar{X}(\epsilon_2 + \omega_2 + \epsilon_3) \\ & - \bar{X}(\omega_1 + \epsilon_2 + \omega_2 + \epsilon_3) - \bar{X}(\omega_2 + \epsilon_3) \end{aligned} \quad (69e)$$

$$\begin{aligned} \text{Outage 3: } C_{\omega_3} = & \bar{X}(\epsilon_1 + \omega_1 + \epsilon_2 + \omega_2 + \epsilon_3 + \omega_3) + \bar{X}(\epsilon_2 + \omega_2 + \epsilon_3 + \omega_3) \\ & + \bar{X}(\epsilon_3 + \omega_3) - \bar{X}(\omega_1 + \epsilon_2 + \omega_2 + \epsilon_3 + \omega_3) - \bar{X}(\omega_2 + \epsilon_3 + \omega_3) \\ & - \bar{X}(\omega_3) \end{aligned} \quad (69f)$$

22. Conduction of Heat In Solids, H. S. Carslaw and J. C. Jaeger, Oxford University Press (1947), p. 78.

$$\begin{aligned}
\text{Exposure 4: } C_{\epsilon_4} &= \underline{X}(\epsilon_4) + \underline{X}(\epsilon_1 + \omega_1 + \epsilon_2 + \omega_2 + \epsilon_3 + \omega_3 + \epsilon_4) \\
&+ \underline{X}(\epsilon_2 + \omega_2 + \epsilon_3 + \omega_3 + \epsilon_4) + \underline{X}(\epsilon_3 + \omega_3 + \epsilon_4) \\
&- \underline{X}(\omega_1 + \epsilon_2 + \omega_2 + \epsilon_3 + \omega_3 + \epsilon_4) - \underline{X}(\omega_2 + \epsilon_3 + \omega_3 + \epsilon_4) \\
&- \underline{X}(\omega_3 + \epsilon_4)
\end{aligned} \tag{69g}$$

$$\begin{aligned}
\text{Outage 4: } C_{\omega_4} &= \underline{X}(\epsilon_1 + \omega_1 + \epsilon_2 + \omega_2 + \epsilon_3 + \omega_3 + \epsilon_4 + \omega_4) \\
&+ \underline{X}(\epsilon_2 + \omega_2 + \epsilon_3 + \omega_3 + \epsilon_4 + \omega_4) + \underline{X}(\epsilon_3 + \omega_3 + \epsilon_4 + \omega_4) \\
&+ \underline{X}(\epsilon_4 + \omega_4) - \underline{X}(\omega_1 + \epsilon_2 + \omega_2 + \epsilon_3 + \omega_3 + \epsilon_4 + \omega_4) \\
&- \underline{X}(\omega_2 + \epsilon_3 + \omega_3 + \epsilon_4 + \omega_4) - \underline{X}(\omega_3 + \epsilon_4 + \omega_4) - \underline{X}(\omega_4)
\end{aligned} \tag{69h}$$

For the reference operations schedule the magnitude of the exposure periods are all alike at ϵ ; similarly the duration of the outage periods are all alike at ω .

Accordingly, for the reference operating mode equations 69 simplify to the following:

$$\text{Exposure 1: } C_{\epsilon_1} = \underline{X}(\epsilon) \tag{70a}$$

$$\text{Outage 1: } C_{\omega_1} = \underline{X}(\epsilon + \omega) - \underline{X}(\omega) \tag{70b}$$

$$\text{Exposure 2: } C_{\epsilon_2} = \underline{X}(\epsilon) + \underline{X}(2\epsilon + \omega) - \underline{X}(\epsilon + \omega) \tag{70c}$$

$$\text{Outage 2: } C_{\omega_2} = \underline{X}(2\epsilon + 2\omega) + \underline{X}(\epsilon + \omega) - \underline{X}(\epsilon + 2\omega) - \underline{X}(\omega) \tag{70d}$$

$$\text{Exposure 3: } C_{\epsilon_3} = \underline{X}(\epsilon) + \underline{X}(3\epsilon + 2\omega) + \underline{X}(2\epsilon + \omega) - \underline{X}(2\epsilon + 2\omega) - \underline{X}(\epsilon + \omega) \tag{70e}$$

$$\begin{aligned}
\text{Outage 3: } C_{\omega_3} &= \underline{X}(3\epsilon + 3\omega) + \underline{X}(2\epsilon + 2\omega) + \underline{X}(\epsilon + \omega) - \underline{X}(2\epsilon + 3\omega) \\
&- \underline{X}(\epsilon + 2\omega) - \underline{X}(\omega)
\end{aligned} \tag{70f}$$

$$\begin{aligned}
\text{Exposure 4: } C_{\epsilon_4} &= \underline{X}(\epsilon) + \underline{X}(4\epsilon + 3\omega) + \underline{X}(3\epsilon + 2\omega) + \underline{X}(2\epsilon + \omega) - \underline{X}(3\epsilon + 3\omega) \\
&- \underline{X}(2\epsilon + 2\omega) - \underline{X}(\epsilon + \omega)
\end{aligned} \tag{70g}$$

$$\begin{aligned} \text{Outage 4: } C_{\omega 4} = & \sum (4\epsilon + 4\omega) + \sum (3\epsilon + 3\omega) + \sum (2\epsilon + 2\omega) + \sum (\epsilon + \omega) \\ & - \sum (3\epsilon + 4\omega) - \sum (2\epsilon + 3\omega) - \sum (\epsilon + 2\omega) - \sum (\omega) \end{aligned} \quad (70h)$$

By treating the ϵ_i 's and ω_i 's as variable time (θ) equations 69 and 70 can be manipulated by the procedures previously described to generate complex expressions similar in general form to equations 55, 56, 58, 59 and 62, thereby providing a means for estimating the tritium release and retention in the steel at each stage of the experimental program. It is clear that the computer scheme required to accomplish this accounting function can be quite complicated. On the other hand, the matter of whether or not such an accounting function is desirable is a debatable question, in view of the low values estimated for the tritium releases and retention by the steel elements of the device, both on the basis of quasi-steady state permeations and transient diffusion for the "smeared" model outlined in Section 7.1. In this connection, it is pertinent to note that assessment of some of the maintenance problems and procedures can hinge on the tritium content and distribution within the equipment under consideration.

Explicit formulations for the diffusion currents (out of the faces of the sections) and tritium depletions that occur during the first outage period, can be generated by manipulations on equation 65, as follows:

$$\text{Air Side: } G(0, \theta) = \frac{2DC^*}{L} \left[s_2(\theta) - s_2(\epsilon_1 + \theta) \right] \quad (71)$$

$$\text{Vacuum Side: } G(L, \theta) = \frac{2DC^*}{L} \left[s_1(\theta) - s_1(\epsilon_1 + \theta) \right] \quad (72)$$

$$\text{Air Side: } Q(0, \theta) = C^* L \left\{ \frac{1}{6} - \frac{2}{\pi^2} \left[s_4(\epsilon_1 + \theta) - s_4(\epsilon_1) - s_4(\theta) \right] \right\} \quad (73)$$

$$\text{Vacuum Side: } Q(L, \theta) = C^* L \left\{ \frac{1}{3} + \frac{2}{\pi^2} \left[s_3(\epsilon_1 + \theta) - s_3(\epsilon_1) - s_3(\theta) \right] \right\} \quad (74)$$

$$\Delta \Gamma_{\omega}(\theta) = Q(0, \theta) + Q(L, \theta) = C^* L \left\{ \frac{1}{2} + \frac{2}{\pi^2} \left[s_3(\epsilon_1 + \theta) - s_3(\epsilon_1) - s_3(\theta) - s_4(\epsilon_1 + \theta) + s_4(\epsilon_1) + s_4(\theta) \right] \right\} \quad (75)$$

Accordingly, the net quantity of tritium contained within a unit volume of section during the outage period, $\Gamma(\epsilon + \theta) = \Delta \Gamma_{\epsilon}(\epsilon) - \Delta \Gamma_{\omega}(\theta)$, is given by:

$$\Gamma(\epsilon_1 + \theta) = \frac{2C^* L}{\pi^2} \left[s_4(\epsilon_1 + \theta) - s_4(\theta) - s_3(\epsilon_1 + \theta) + s_3(\theta) \right] \quad (76)$$

The working relationships that apply for the first tritium exposure and outage operations, with regard to face specific tritium currents, release to the air and vacuum, and retention in the steel are:

At End of Exposure Period, $\theta = \epsilon$

Air Side, $x = 0$

$$G(0, \epsilon) = \frac{-DC^*}{L} \left[1 + 2s_2(\epsilon) \right] \quad (77)$$

$$Q(0, \epsilon) = C^* L \left[\frac{D\epsilon}{L^2} - \frac{1}{6} - \frac{2}{\pi^2} s_4(\epsilon) \right] \quad (78)$$

Vacuum Side, $x = L$

$$G(L, \epsilon) = \frac{DC^*}{L} \left[1 + 2s_1(\epsilon) \right] \quad (79)$$

$$Q(L, \epsilon) = C^* L \left[\frac{D\epsilon}{L^2} + \frac{1}{3} - \frac{2}{\pi^2} s_3(\epsilon) \right] \quad (80)$$

Within Section, $0 < x < L$

$$\Delta \Gamma_{\epsilon}(\epsilon) = \Gamma(\epsilon) = C^* L \left\{ \frac{1}{2} - \frac{2}{\pi^2} \left[s_3(\epsilon) - s_4(\epsilon) \right] \right\} \quad (81)$$

At End of Outage Period, $\theta = \omega$

Air Side $x = 0$

$$G(0,\omega) = \frac{2DC^*}{L} \left[s_2(\omega) - s_2(\epsilon + \omega) \right] \quad (82)$$

$$Q(0,\omega) = C^* L \left\{ \frac{1}{6} - \frac{2}{\pi^2} \left[s_4(\epsilon + \omega) - s_4(\epsilon) - s_4(\omega) \right] \right\} \quad (83)$$

Vacuum Side, $x = L$

$$G(L,\omega) = \frac{2DC^*}{L} \left[s_1(\omega) - s_1(\epsilon + \omega) \right] \quad (84)$$

$$Q(L,\omega) = C^* L \left\{ \frac{1}{3} + \frac{2}{\pi^2} \left[s_3(\epsilon + \omega) - s_3(\epsilon) - s_3(\omega) \right] \right\} \quad (85)$$

Within Section, $0 < x < L$

$$\Delta \Gamma_\omega(\omega) = C^* L \left\{ \frac{1}{2} + \frac{2}{\pi^2} \left[s_3(\epsilon + \omega) - s_3(\epsilon) - s_3(\omega) - s_4(\epsilon + \omega) + s_4(\epsilon) + s_4(\omega) \right] \right\} \quad (86)$$

$$\Gamma(\epsilon + \omega) = \frac{2C^* L}{\pi^2} \left[s_4(\epsilon + \omega) - s_4(\omega) - s_3(\epsilon + \omega) + s_3(\omega) \right] \quad (87)$$

Similar explicit expressions can be developed for treating subsequent operations on TFTR with tritium. As indicated, these formulations become progressively bulkier with each additional operation. There is an additional complication on two points, when the transport computations are undertaken. The first of these is the need to determine the values of the various series to many significant figures (like 10) because the computations involve differences between almost identical quantities. The second difficulty is the agonizingly slow convergence of the s_3 and s_4 series, to the point that many hundreds (and even thousands) of terms are required, for the low values encountered for the dimensionless time, to adequately sum these series.

Some numbers are made in the following section in the way of scoping tritium release estimates for the first tritium operations of TFTR based on a transient diffusion approach.

7.3 DIFFUSION BASED TRITIUM TRANSPORT ESTIMATES

The results of some estimates made for tritium releases from the air and vacuum sides of the device and tritium retentions in the various steel sections of the torus during the initial operations of TFTR with tritium are presented. The estimates are based on the "smeared" model described previously and the operations schedule shown in Table 7-1, with application of the parameters shown in Table 7-2.

Dimensional characteristics of the principal SS-305 sections of the torus and vacuum system are as shown in Table 2-1. These dimensional characteristics and other quantities relevant to estimation of the tritium transport are listed in Table 7-3.

Table 7-4 lists the values of the various series required for making the tritium transport estimates for the relevant metal section thicknesses and dimensionless times involved.

Tables 7-5 and 7-6 summarize the results of the tritium diffusion transient estimates for the first exposure and outage operations of TFTR. The tables show the magnitudes of the relevant tritium quantities for each of the relevant metal components of the vacuum vessel. The more note-worthy features of the tritium diffusion estimations for the first operations with tritium are:

- No tritium is released to the test cell atmosphere, either during the three day exposure period or the subsequent 11.6 day reference outage period.
- Of the 3.128 Ci of tritium that are diffused into the steel sections during the exposure, 2.368 Ci (75.7%) counter-diffuses back into the vacuum during the 11.6 day outage period, leaving a residue of 0.760 Ci in the steel.
- Of the 3.128 Ci of tritium that are diffused into the steel sections during the exposure, 1.937 Ci (61.9%) are located within the bellows section which

TABLE 7-2

SYSTEM AND ESTIMATIONS MODEL PARAMETERS

Mean tritium pressure during exposure period ($\bar{P}_{T_2}$)	1.655×10^{-3} torr
System temperature during all operations	21.1°C (70°F)
Tritium solubility in steel at system operating temperature and mean tritium pressure (C^*)	6.687×10^{-5} STPcm ³ /cm ³
Duration of tritium exposure period/sequence (ϵ)	3 days
Duration of outage period/sequence (ω)	11.6 days
Number of tritium exposure sequences/yr	25
Number of outage (no tritium based experiment) sequences/yr	25
Tritium diffusivity (D)	9.328×10^{-12} cm ² /sec
Number of full power D-T pulses/yr	1000
Number of full power D-T pulses/sequence	40
Number of tritium build-ups/sequence	22
Number of tritium flush-outs/sequence	140
Repetition period for pulsings, build-ups, and flush-outs	5 minutes
Time per sequence for tritium build-ups	1 day
Time per sequence for D-T pulsings	1 day
Time per sequence for tritium flush-outs	1 day
Steel density	7.879 g/cm ³
Adsorbed layer population density	8.5×10^{14} molecules/cm ²
Mean tritium mole fractions in the gas phase during	
Tritium build-ups	5.344×10^{-1}
D-T pulsings	8.235×10^{-1}
Tritium flush-outs	1.716×10^{-2}

TABLE 7-3

TORUS AND VACUUM SYSTEM CHARACTERISTICS FOR INITIAL TRITIUM OPERATIONS

System Portion	Internal Surface cm ² S	Thickness cm L	Volume cm ³ SL	Steel Mass g	Dimensionless Time Values, $D\theta/L^2$ For			Contained Tritium For Saturation At 1.655×10^{-3} torr Ci
					$\epsilon =$ 2.5920×10^5 sec	$\omega =$ 1.0022×10^6 sec	$\epsilon + \omega =$ 1.2614×10^6 sec	
Torus Bellows	6.407×10^6	0.102	6.535×10^5	5.149×10^6	2.3239×10^{-4}	8.9858×10^{-4}	1.1310×10^{-3}	56.4
Torus Body	8.276×10^5	0.675	5.586×10^5	4.401×10^6	5.3065×10^{-6}	2.0519×10^{-5}	2.5825×10^{-5}	48.2
Reinforcing Rings	1.101×10^5	7.62	8.390×10^5	6.610×10^6	4.1640×10^{-8}	1.6101×10^{-7}	2.0265×10^{-7}	72.4
Diagnostics	1.350×10^6	0.388	5.238×10^5	4.127×10^6	1.6060×10^{-5}	6.2100×10^{-5}	7.8160×10^{-5}	45.2
Margin For Parts, Ducts, Etc.	1.739×10^6	0.388	6.747×10^5	5.316×10^6	1.6060×10^{-5}	6.2100×10^{-5}	7.8160×10^{-5}	58.2
Totals	1.043×10^7		3.250×10^6	2.560×10^7				280.4

TABLE 7-4
VALUES OF TRANSPORT SERIES FOR RELEVANT DIMENSIONLESS TIMES
Applicable Dimensionless Times Are As Listed In Table 7-3

Series Designation	Magnitude Of Series For Indicated System Portion			
	Torus Bellows	Torus Body	Reinforcing Rings	Diagnostics & Margin
$s_1(\epsilon)$	1.8004883×10^1	1.2195873×10^2	1.3819243×10^3	6.9891179×10^1
$s_1(\omega)$	8.9109272	6.1776071×10^1	7.0252811×10^2	3.5297217×10^1
$s_1(\epsilon + \omega)$	7.8882145	5.5010362×10^1	6.2614991×10^2	3.1408175×10^1
$s_2(\epsilon)$	$-5.0000000 \times 10^{-1}$	$-5.0000000 \times 10^{-1}$	$-5.0000000 \times 10^{-1}$	$-5.0000000 \times 10^{-1}$
$s_2(\omega)$	$-5.0000000 \times 10^{-1}$	$-5.0000000 \times 10^{-1}$	$-5.0000000 \times 10^{-1}$	$-5.0000000 \times 10^{-1}$
$s_2(\epsilon + \omega)$	$-5.0000000 \times 10^{-1}$	$-5.0000000 \times 10^{-1}$	$-5.0000000 \times 10^{-1}$	$-5.0000000 \times 10^{-1}$
$s_3(\epsilon)$	1.5613116	1.6321305	1.6448182 *	1.6226537
$s_3(\omega)$	1.4824527	1.6211138	1.6444860 *	1.6015333
$s_3(\epsilon + \omega)$	1.4640631	1.6167642	1.6443701 *	1.5962462
$s_4(\epsilon)$	$-8.2132023 \times 10^{-1}$	$-8.2244085 \times 10^{-1}$ *	$-8.2246683 \times 10^{-1}$ *	$-8.2238778 \times 10^{-1}$ *
$s_4(\omega)$	$-8.1803274 \times 10^{-1}$	$-8.2236601 \times 10^{-1}$	$-8.2246624 \times 10^{-1}$ *	$-8.2216058 \times 10^{-1}$
$s_4(\epsilon + \omega)$	$-8.1688592 \times 10^{-1}$	$-8.2233960 \times 10^{-1}$	$-8.2246603 \times 10^{-1}$ *	$-8.2208133 \times 10^{-1}$

The $s(\)$ abbreviations and the time quantities have the following meanings:

$$s_1(\theta) = \sum_{n=1}^{\infty} e^{-(n\pi/L)^2 D\theta}$$

$$\epsilon = 2.5920 \times 10^5 \text{ sec}$$

$$s_2(\theta) = \sum_{n=1}^{\infty} (-1)^n e^{-(n\pi/L)^2 D\theta}$$

$$\omega = 1.0022 \times 10^6 \text{ sec}$$

$$s_3(\theta) = \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-(n\pi/L)^2 D\theta}$$

$$\epsilon + \omega = 1.2614 \times 10^6 \text{ sec}$$

$$s_3(0) = \pi^2/6$$

$$s_4(0) = -\pi^2/12$$

$$s_4(\theta) = \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-(n\pi/L)^2 D\theta}$$

* Determined by linear interpolation, based on values of $s_3(0)$, $s_4(\theta)$, and $s_3(\theta)$ and $s_4(\theta)$ for $D\theta/L^2$ magnitudes of 5.3065×10^{-6} and 1.6060×10^{-5} respectively.

TABLE 7-5

SUMMARY OF TRITIUM DIFFUSION CALCULATIONS FOR FIRST EXPOSURE

Item	Torus Bellows	Torus Body	Reinforcing Rings	Diagnostics	Margin	Total
Section Thickness, L , cm	0.102	0.675	7.62	0.388	0.388	1.043×10^7
Section Surface, S , cm^2	6.407×10^6	8.276×10^5	1.101×10^5	1.350×10^6	1.739×10^6	
AIR SIDE						
Diffusion Current, G (0, ϵ)						
STP $\text{cm}^3/\text{cm}^2 \text{ sec}$	0.000	0.000	0.000	0.000	0.000	
Specific Diffusion Quantity, Q (0, ϵ)						
STP cm^3/cm^2	0.000	0.000	0.000	0.000	0.000	
Diffusion Quantity, SQ (0, ϵ)						
STP cm^3	0.000	0.000	0.000	0.000	0.000	0.000
VACUUM SIDE						
Diffusion Current, G (L , ϵ)						
STP $\text{cm}^3/\text{cm}^2 \text{ sec}$	2.263×10^{-13}	2.263×10^{-13}	2.263×10^{-13}	2.263×10^{-13}	2.263×10^{-13}	
$\mu\text{Ci}/\text{cm}^2 \text{ sec}$	5.840×10^{-7}	5.840×10^{-7}	5.840×10^{-7}	5.840×10^{-7}	5.840×10^{-7}	
Specific Diffusion Quantity, Q (L , ϵ)						
STP cm^3/cm^2	1.172×10^{-7}	1.173×10^{-7}	1.198×10^{-8}	1.176×10^{-7}	1.176×10^{-7}	
$\mu\text{Ci}/\text{cm}^2$	3.024×10^{-1}	3.028×10^{-1}	3.093×10^{-2}	3.034×10^{-1}	3.034×10^{-1}	
Diffusion Quantity, SQ (L , ϵ)						
STP cm^3	7.506×10^{-1}	9.711×10^{-2}	1.320×10^{-3}	1.587×10^{-1}	2.044×10^{-1}	
Ci	1.937	2.506×10^{-1}	3.406×10^{-3}	4.096×10^{-1}	5.276×10^{-1}	3.128
SECTION TRITIUM CONTENT						
Initial Content, $S \Gamma_0$						
STP cm^3	0.000	0.000	0.000	0.000	0.000	
Ci	0.000	0.000	0.000	0.000	0.000	0.000
Amount Diffused In, $\Delta \Gamma_e$						
STP cm^3/cm^2	1.172×10^{-7}	1.173×10^{-7}	1.198×10^{-8}	1.176×10^{-7}	1.176×10^{-6}	
$\mu\text{Ci}/\text{cm}^2$	3.024×10^{-1}	2.506×10^{-1}	3.093×10^{-2}	3.034×10^{-1}	3.034×10^{-1}	
Final Content, $S(\Gamma_0 + \Delta \Gamma_e)$						
STP cm^3	7.506×10^{-1}	9.711×10^{-2}	1.320×10^{-3}	1.587×10^{-1}	2.044×10^{-1}	
Ci	1.937	2.506×10^{-1}	$3/406 \times 10^{-3}$	4.096×10^{-1}	5.276×10^{-1}	3.128

TABLE 7-6

SUMMARY OF TRITIUM DIFFUSION CALCULATIONS FOR FIRST OUTAGE

Item	Torus Bellows	Torus Body	Reinforcing Rings	Diagnostics	Margin	Total
Section Thickness, L, cm	0.102	0.675	7.62	0.388	0.388	1.043×10^7
Section Surface, S, cm ²	6.407×10^6	8.276×10^5	1.101×10^5	1.350×10^6	1.739×10^6	
AIR SIDE						
Diffusion Current, G(0,ω) STP cm ³ /cm ² sec	0.000	0.000	0.000	0.000	0.000	0.000
Specific Diffusion Quantity, Q(0,ω) STP cm ³ /cm ²	0.000	0.000	0.000	0.000	0.000	
Diffusion Quantity, SQ(0,ω) STP cm ³	0.000	0.000	0.000	0.000	0.000	
VACUUM SIDE						
Diffusion Current, G(L,ω) STP cm ³ /cm ² sec	1.251×10^{-14}	1.250×10^{-14}	1.250×10^{-14}	$1,250 \times 10^{-14}$	1.250×10^{-14}	2.368
μCi/cm ² sec	3.228×10^{-8}	3.227×10^{-8}	3.227×10^{-8}	3.227×10^{-8}	3.227×10^{-8}	
Specific Diffusion Quantity, Q(L,ω) STP cm ³ /cm ²	9.016×10^{-3}	7.732×10^{-8}	2.788×10^{-9}	8.934×10^{-8}	8.934×10^{-8}	
μCi/cm ²	2.326×10^{-1}	1.995×10^{-1}	7.195×10^{-3}	2.306×10^{-1}	2.306×10^{-1}	
Diffusion Quantity, SQ(L,ω) STP cm ³	5.776×10^{-1}	6.399×10^{-2}	3.069×10^{-4}	1.206×10^{-1}	1.554×10^{-1}	2.368
Ci	1.490	1.651×10^{-1}	7.921×10^{-4}	3.113×10^{-1}	4.009×10^{-1}	
SECTION TRITIUM CONTENT						
Initial Content, S(Γ ₀ ÷ ΔΓ _e) STP cm ³	7.506×10^{-1}	9.711×10^{-2}	1.320×10^{-3}	1.587×10^{-1}	2.044×10^{-1}	3.128
Ci	1.937	2.506×10^{-1}	3.406×10^{-3}	4.096×10^{-1}	5.276×10^{-1}	
Amount Diffused Out, S ΔΓ _ω STP cm ³	5.776×10^{-1}	6.399×10^{-2}	3.069×10^{-4}	1.206×10^{-1}	1.554×10^{-1}	2.368
Ci	1.490	1.651×10^{-1}	7.921×10^{-4}	3.113×10^{-1}	4.009×10^{-1}	
Final Content, S(Γ ₀ + ΔΓ _e - ΔΓ _ω) STP cm ³	1.730×10^{-1}	3.312×10^{-2}	1.320×10^{-3}	3.809×10^{-2}	4.906×10^{-2}	0.760
Ci	4.465×10^{-1}	8.548×10^{-2}	3.406×10^{-3}	9.829×10^{-2}	1.266×10^{-1}	

comprises 61.4 percent of the total internal surface of the vacuum vessel.

- The 3.128 Ci of tritium diffused into the steel sections during the exposure corresponds to 1.1 percent of the steady state total tritium content (~ 280 Ci) that would result from infinite time exposure of the steel to the vacuum-side reference tritium pressure of 1.655×10^{-3} torr.
- At the end of the first exposure period the concentration gradients at the vacuum side and air side are 3.43×10^{-2} and 0 STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel cm}$ respectively. These drop to 1.34×10^{-3} and 0 STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel cm}$ respectively at the conclusion of the 11.6 day first outage period. These are in contrast to the 6.54×10^{-4} STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel cm}$ concentration gradient encountered under steady state conditions for the bellows section.

In view of the zero estimated tritium release through the air side of the steel sections for the first tritium operations, the question arises -- how much tritium can be expected to diffuse through the thinnest steel section (bellows) under continuous testing with reference full power D-T pulses? This question is dealt with briefly in the following discussion.

For continuous D-T pulsing the applicable tritium mean partial pressure (see Table 7-1) is 2.504×10^{-3} torr, whereupon the corresponding tritium equilibrium concentration (C^*) is 8.225×10^{-5} STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel}$. Utilization of this C^* in equation 58b for various exposure times (θ) generates the cumulative tritium release, $SQ(0, \theta)$, over the time interval θ . The results of such a computation are listed in Table 7-7.

The numbers displayed in Table 7-7 highlight several important features regarding tritium releases to the environment based on classical diffusion concepts applied to a "tight" system composed of metal sections: (a) for each metal thickness there is a substantial "lag-time"

TABLE 7-7
 COMULATIVE TRITIUM DIFFUSED THROUGH BELLOWS SECTIONS
 FOR CONTINUED D-T PULSING OPERATIONS

Consecutive Operating Days	$\frac{D \theta}{L^2}$	$s_4(\theta)$	$SQ(0, \theta)$ μCi
10	7.7463×10^{-4}	$-8.1864437 \times 10^{-1}$	0.00
50	3.8732×10^{-3}	$-8.0335371 \times 10^{-1}$	0.00
100	7.7463×10^{-3}	$-7.8424038 \times 10^{-1}$	0.00
200	1.5493×10^{-2}	$-7.4601363 \times 10^{-1}$	1.81×10^{-3}
300	2.3239×10^{-2}	$-7.0778865 \times 10^{-1}$	7.77×10^{-1}
400	3.0985×10^{-2}	$-6.6959326 \times 10^{-1}$	1.70×10^1
600	4.6478×10^{-2}	$-5.9393383 \times 10^{-1}$	4.32×10^2
800	6.1971×10^{-2}	$-5.2126750 \times 10^{-1}$	2.41×10^3
1,000	7.7463×10^{-2}	$-4.5392125 \times 10^{-1}$	7.18×10^3

before tritium begins to penetrate to the air-side; (b) even for long operating times the cumulative tritium release from the air-side is very low for practical ranges of metal thicknesses. These numbers additionally substantiate the fact that the estimated tritium releases for TFTR based on quasi-steady state permeation calculations are ultra-conservative.

The tritium annual release to the environment for the reference operating mode based on the quasi-steady state mode (25 D-T full power pulse operating days with 40 D-T pulses per sequence) was previously shown to be 661.3 m Ci/year (see operating Mode G, Table 4-4). This result stemmed from an averaging procedure that treated the tritium build-up, D-T operation, and tritium flush-out campaigns separately. A slightly different annual tritium release is calculated for a quasi-steady state model based on the "smeared" approach used to determine C^* , and a 75 day period per year for operations when tritium is present in the torus gas and surface adsorbed material. The details of such a calculation are summarized in Table 7-8.

The disparity between the two estimated annual releases, 661.3 versus 751.2 mCi, is due to differences in the averaging procedures used.

As shown in Table 7-3, the maximum contained tritium in the torus steel sections at steady state conditions based on the smeared C^* value is 280.4 Ci, with a linear concentration distribution over each of the section thicknesses.

Just as the diffused-in tritium content of the steels vary with time, the adsorbed layer tritium content also changes during the different operating phases. This variation which is due to alterations of the tritium mole fraction in the total molecule population, is shown in Table 7-9.

7.4 CLOSING REMARKS REGARDING TRITIUM DIFFUSION TRANSIENTS

The foregoing considerations of tritium diffusion through the stainless steel sections of the

TABLE 7-8

ANNUAL TRITIUM RELEASE BASED ON C^{*} SMEARED STEADY STATE MODEL

<u>Item</u>	<u>Air-Side $\partial C / \partial x$ STP $\text{cm}^3 \text{T}_2 / \text{cm}^3 \text{ steel cm}$</u>	<u>Air-Side DS $\partial C / \partial x$ STP $\text{cm}^3 \text{T}_2 / \text{sec}$</u>	<u>Permeation mCi/year</u>
Bellows Section	6.56×10^{-4}	3.92×10^{-8}	655.2
Torus Body	9.91×10^{-5}	7.65×10^{-10}	12.8
Reinforcing Rings	8.78×10^{-6}	9.01×10^{-12}	0.2
Diagnostics	1.72×10^{-4}	2.17×10^{-9}	36.3
Margin	1.72×10^{-4}	2.80×10^{-9}	46.7
Total		4.49×10^{-8}	751.2

TABLE 7-9

TRITIUM CONTAINED IN SURFACE ADSORBED MONOLAYERS

System Portion	Surface cm ²	Mean Curies of Adsorbed Tritium During Operation Phase			
		Tritium Build-Ups	D-T Pulsings	Tritium Flush-outs	Overall Operation
Torus Bellows	6.407×10^6	279.5	430.8	9.0	239.8
Torus Body	8.276×10^5	36.1	55.6	1.2	31.0
Reinforcing Rings	1.101×10^5	4.8	7.4	0.1	4.1
Diagnostics	1.350×10^6	58.9	90.8	1.9	50.5
Margin For Ports, Ducts, Etc.	1.739×10^6	75.9	116.9	2.4	65.1
Totals	1.043×10^7	455.0	701.5	14.6	390.5

TFTR torus indicate that very low tritium releases are involved. This is a consequence of the very low diffusivity that applies for the relatively low temperatures encountered, as well as by-passing the releases that may occur from leakages at the numerous seals.

The important aspect of the analytical developments described in this section is their potential applicability to other situations and high temperature operations for CTR machines that follow TFTR on the road toward design of practical fusion power reactors, rather than their restricted use in the TFTR program.

The tools generated in this section to treat tritium transport transients constitute the first step of a proposed broader development task, described in greater detail in the TFTR Conceptual Design Final Report ⁽²³⁾. The main immediate objective of this proposed task is the development of a model and versatile computer code for accurate determination of tritium transport through TFTR device walls such as the torus, tritium generator, vacuum system pumps and ducting, ports, and others in combination with expected seal leakages, closely simulating the wide range of transient conditions anticipated in the operation of the facility. The principal shorter range incentives for this development include the benefit of tritium transport and release predictions for the actual TFTR geometries, capability to cope rapidly and more economically with the problems of defining tritium releases accompanying a wide range of plasma scenarios during the preliminary and detail design phases, speeding up the design work on some of the components of the tritium handling system, and better delineation of tritium related problems involved in the facility maintenance operations. The longer range incentives include development of design technology applicable to power generating fusion reactors.

23. "Preliminary Research and Development Activity Plans (RDAC)", Volume VII of TFTR Conceptual Design Final Report, Task 11.0.2.1 - Transient Tritium Transport And Leakage Code (October 1975).

REFERENCES

1. "Solubility of Hydrogen Isotopes in Nickel and Type 347 Stainless Steel", Norval J. Hawkins, KAPL-868 (April 13, 1953).
2. "Diffusion Studies I. The Permeability of Type 347 Stainless Steel to Hydrogen and Tritium", D. Randall and O. N. Salmon, KAPL-904 (August 24, 1953).
3. "Solubility and Distribution of Tritium in Annealed and Cold Worked 304 Stainless Steel in the 100 to 300°C Temperature Range", G. W. Powell, J. D. Braun, K. D. Chaney and G. L. Downs, Corrosion NACE 26:223-228 (1970).
4. "The Diffusivity of Tritium in 304 Stainless Steel in the Temperature Range 25 to 222°C", K. F. Chaney and G. W. Powell (Mound Laboratory), Metallurgical Transactions 1:2536-2537 (1970).
5. "Tritium Diffusion in 304 and 316 Stainless Steels in the Temperature Range 25 to 222°C", J. H. Austin and T. S. Elleman (North Carolina State University), Journal of Nuclear Materials, 43:110-125 (1972).
6. "Grain Boundary Diffusion of Tritium in 304 and 316 Stainless Steel", R. D. Calder, T. S. Elleman and K. Verghese, Journal of Nuclear Materials 46:46-52 (1973), North Carolina State University.
7. "Tritium Absorption in 304L Stainless Steel", M. R. Louthan, Jr., J. A. Donovan and G. R. Caskey, Jr., DP-MS-74-25 (October 1974).
8. "Tritium Properties And Related Quantities Used in the TFTR Conceptual Design", Harold J. Garber, WFPS-TME-004 (September 1975).
9. "Diffusion In Solids", P. G. Shewmon, McGraw Hill Book Co. (1963) p. 164-187.
10. "High Speed Photographic Studies of the Equilibrium and Stability of the ATC Tokamak", R. A. Jacobsen, Matt - 1038 (April 1974).
11. Personal Communication, W. Lange, Westinghouse R & D Center.
12. "Vacuum And Wall Problems in Precursor Reactor Tokamaks", S. A. Cohen (Princeton Plasma Physics Laboratory). Paper Prepared for 22nd National Vacuum Symposium (Philadelphia, Pa. - October 30, 1975) And Submitted for Publication in Journal of Vacuum Science and Technology.
13. "TFTR Vacuum System Considerations", W. J. Lange, J. G. Gorman, D. Green, and D. A. Sink, WFPS-TME-021 (November 1975).

14. "The Vacuum System for the Tokamak Fusion Test Reactor (TFTR)", W. J. Lange, D. Green, and D. H. Sink. Paper Prepared for Sixth IEEE Symposium on Engineering Problems of Fusion Reactors (San Diego, California - November 18-21, 1975).
15. "Fundamentals of Vacuum Science and Technology", Gerhard Lewin, McGraw Hill Book Co. (1965) p. 24-35, 69-76.
16. "Reduction of Stainless Steel Outgassing in Ultra High Vacuum", R. Calder and G. Lewin, British Journal of Applied Physics, 18:1459-1472 (1967).
17. "Diffusion in and Through Solids", R. M. Barrer, Cambridge University Press (1951), p. 13-16.
18. "The Mathematics of Diffusion", J. Crank, Oxford University Press (1957), p. 45-47.
19. "Diffusion Coefficient, Solubility, And Permeability For Helium in Glass", W. A. Rogers, R. S. Buritz and D. Alpert, Journal of Applied Physics, 25:868-875 (1954).
20. "Solution of a Diffusion Problem", T. Holstein, Research Report 60-94411-9 - D, Westinghouse R & D Laboratories (December 20, 1951).
21. "Methods of Mathematical Physics", Volume I, R. Courant and D. Hilbert, Interscience Publishers Inc. (1953), p. 75-76.
22. "Conduction of Heat in Solids", H. S. Carslaw and J. C. Jaeger, Oxford University Press (1947), p. 78.
23. "Preliminary Research and Development Activity Plans (RDAC)", Volume VII of TFTR Conceptual Design Final Report, Task 11.D.2.1 - Transient Tritium Transport and Leakage Code (October 1975).