Project: PS-TGT-14-001 Hall A Tritium Target

Tittle: Estimated pressure in tritium cell and permeation rate

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Code(s) of Record:

Reference Codes and Sources:

- Losowski et. al. Leak testing of Conflat-type flanges under internal pressure (2004)
- Holt et. al. Tritium permeability of the Al target cell (2012)
- DOE Handbook of Tritium Handling and Safe Storage
- Swagelok MS-01-22 Bellows Sealed Valves
- TGT-CALC-103-001 and 003
- R. Lasser: Tritium and Helium-3 in Metals
- Gibala et. al.: Hydrogen embrittlement and stress corrosion cracking

Description:

General target cell calculations for tritium quantity, pressure in cell, permeation, and fugacity from beam disassociation.

Reference Drawing(s):

TGT-103-1000-0013 Cell assembly with shipping covers

Units and definitions:

$Ci := 3.7 \cdot 10^{10} \cdot Bq$ one Curie

$M_{He} := 4 \cdot \frac{gm}{mol}$ molar mass of He

$M_{H2} := 2 \cdot \frac{gm}{mol}$ molar mass of protium H2

$eV := 1.602 \cdot 10^{-19} \cdot J$ electron volt

$MeV := 10^{6} \cdot eV$

General properties of tritium:

$t_{0.5} := 12.32 \cdot yr = \left(3.888 \cdot 10^{8}\right)\ s$ Half life of T2

$\tau := \frac{t_{0.5}}{\ln(2)} = \left(5.609 \cdot 10^{8}\right)\ s$ mean lifetime

$\lambda := \frac{1}{\tau} = \left(1.783 \cdot 10^{-9}\right)\ \frac{1}{s}$ decay const

$M_{T2} := 6\ \frac{gm}{mol}$ Molar mass of T2

$t_{day} := 1 \cdot day$ time = 1 day

$R_{day} := 1 - e^{-\lambda \cdot t_{day}} = 0.015\%$ Decay rate per day

General properties of aluminum 7075

$M_{AL} := 26.98 \cdot \frac{gm}{mol}$ molar mass of Aluminum

$\rho_{AL} := 2.7 \cdot \frac{gm}{cm^{3}}$ Density of Al

Dimensions of the cell

Volume estimate for the cell including fill valve:

$D_1 := 0.5 \cdot in$ bore of main body

$L_1 := 9.52 \cdot in$ length of main body

$V_1 := \pi \cdot \frac{D_1^{\ 2}}{4} \cdot L_1 + \frac{4}{3} \pi \cdot \left(\frac{D_1}{2}\right)^3$ volume in main body

$D_{et} := 0.775 \cdot in$ entrance window bore in main body

$D_{fill} := 0.125 \cdot in$ ID of fill tube section in main body

$L_{fill} := 1.063 \cdot in$ length of fill tube on main body

$L_{et} := 2.83 \cdot in$ entrance window bore in main body

$D_{win} := 0.75 \cdot in$ OD of entrance window

$V_2 := \pi \cdot \frac{D_{fill}^{\ 2}}{4} \cdot L_{fill} = \left(2.138 \cdot 10^{-4}\right) L$ vol of active length of main body

$V_3 := \frac{\pi}{4} \cdot \left(D_{et}^{\ 2} - D_{win}^{\ 2}\right) \cdot L_{et} = 0.001\ L$ volume in re-entrant window bore

$V_{in} := V_1 + V_2 + V_3 = 0.033\ L$ total volume in main body

$L_{stem} := \left(\frac{1.06}{2} + 1.595\right) \cdot in$ eff length of valve stem

$D_{stem} := 0.125 \cdot in$ ID of stem

$V_{stem} := \frac{\pi}{4} \cdot L_{stem} \cdot D_{stem}^{\ 2}$ Volume of stem total volume in cell:

$$V_{cell} := V_{in} + V_{stem} = 0.034\ L$$

This will have to be measured for a more accurate result

Area:

The surface areas of the thin sections of the cell will be required to determine the permeation through the cell. These are determined via the CAD model.

$$A_{main} := 2 \cdot 3.331 \cdot in^2 + 0.438 \cdot in^2 = 0.005\ m^2$$ Main body

$$A_{ent} := 0.196 \cdot in^2 = \left(1.265 \cdot 10^{-4}\right)\ m^2$$ Entrance window

$$A_{tube} := L_{et} \cdot \pi \cdot D_{win} = 0.004\ m^2$$ area of ent window tube

$$A_{cell} := A_{main} + A_{ent} + A_{tube} = 0.009\ m^2$$ surface area of cell wetted

Cell Pressure:

To estimate the cell pressure at room temp, we assume a fill of 1090 Ci of T2 at 100% purity.

$N_{act} := 1090 \cdot Ci = (4.033 \cdot 10^{13})\ Bq$ total target activity

$N_T := \frac{N_{act}}{\lambda} = 2.262 \cdot 10^{22}$ total number of T atoms

$n_{T2} := \frac{N_T}{2 \cdot N_A} = 0.019\ mol$ mols of T2

$m_{T2} := n_{T2} \cdot M_{T2} = 0.113\ gm$ total mass of T2

$\rho_{T2} := \frac{m_{T2}}{V_{in}} = (3.383 \cdot 10^{-3})\ \frac{gm}{cm^3}$ target density

$L_{T2} := \rho_{T2} \cdot 25 \cdot cm = 0.085\ \frac{gm}{cm^2}$ nuclear target length

$n_{act} := \frac{N_{act}}{n_{T2}} = (2.147 \cdot 10^{15})\ \frac{Bq}{mol}$ activity of T2 per mol

$T_{room} := 295 \cdot K$ assumed room temp

$T_{op} := 50 \cdot K$ assumed operating temp of gas

$T_{op} := 150 \cdot K$ assumed operating temp of cell at beam

$z_{T2}(P) := 1 + P \cdot 8.32 \cdot \frac{10^{-7}}{torr}$ compressibility

$Z := z_{T2}(200 \cdot psi) = 1.009$ assumed compressibility of T2

$P_{cell} := \frac{n_{T2} \cdot Z \cdot T_{room} \cdot R}{V_{cell}} = 199.766\ psi$ Total absolute pressure in cell at room temp

$P_{op} := \frac{T_{op}}{T_{room}} \cdot P_{cell} = 101.576\ psi$ normal operating pressure

At STP we have

$$T_{stp} := 273.15 \cdot K$$

$$P_{stp} := 760 \cdot torr$$

$$V_{stp} := \frac{n_{T2} \cdot R \cdot T_{stp}}{P_{stp}} = 0.421\ L$$

Stored energy in the cell: pressure and chemical

$$E_{pres} := P_{cell} \cdot V_{cell} = 46.463\ J$$ pressure energy

$$H_{H2O} := 242000 \cdot \frac{J}{mol}$$ heat of formation H2O

$$E_{HTO} := H_{H2O} \cdot n_{T2} = \left(4.545 \cdot 10^{3}\right)\ J$$ stored chem energy in cell

$$E_{tot} := E_{HTO} + E_{pres} = \left(4.592 \cdot 10^{3}\right)\ J$$ total energy

$$TNT := \frac{E_{tot} \cdot lbm}{1488617 \cdot ft \cdot lbf} = 0.001\ kg$$ equiv energy in lb of TNT

$$R_s := 50 \cdot \frac{ft}{lb^{\frac{1}{3}}}$$ consequence factor

$$R := R_s \cdot TNT^{\frac{1}{3}} = 2.004\ m$$ Safe keep out zone for no bio effet at all

Permeation:

Diffusion rate from the cell at room temp shall be determined from the estimated hydrogen permeation rate and scaled by the square root of the mass ratio.

$t_{main} := 0.018 \cdot in$ cell wall thickness

$t_{ent} := 0.01 \cdot in$ ent window thick

$t_{tube} := 0.125 \cdot in$ wall thick ent window tube

$P_{atm} := 14.7 \cdot psi$ atm pressure

$D_{7075} := 6 \cdot 10^{-11} \cdot \frac{m^2}{s}$ Diff coef conservative

$C_{norm} := 1 \cdot 10^{-9}$ conservative estimated solubility of H in Al alloy at 25C and 1 atm.

$\chi_{AL} := \frac{\rho_{AL}}{M_{AL}} = \left(1.001 \cdot 10^{5}\right) \frac{mol}{m^3}$ molar density of Al

$\Delta H := 1500 \cdot \frac{J}{mol}$ assumed heat of solution for H in AL 7075

$C_0 := \frac{C_{norm}}{e^{\frac{-\Delta H}{R \cdot T_{room}}}} = 1.843 \cdot 10^{-9}$ Coef

$C_{150} := C_0 \cdot \sqrt{\frac{P_{op}}{P_{atm}}} \cdot e^{\frac{-\Delta H}{R \cdot T_{op}}}$ Solubility H2 in Al7075 at op conditions

$C_{room} := C_0 \cdot \sqrt{\frac{P_{cell}}{P_{atm}}} \cdot e^{\frac{-\Delta H}{R \cdot T_{room}}}$ solubility H2 in Al 7075 at room T

Hydrogen permeation rates through various parts of cell at room temp

$$Q_1 := \chi_{AL} \cdot C_{room} \cdot \frac{D_{7075}}{t_{main}} \cdot A_{main} = \left(2.218 \cdot 10^{-13}\right) \frac{mol}{s}$$

$$Q_2 := \chi_{AL} \cdot C_{room} \cdot \frac{D_{7075}}{t_{ent}} \cdot A_{ent} = \left(1.102 \cdot 10^{-14}\right) \frac{mol}{s}$$

$$Q_3 := \chi_{AL} \cdot C_{room} \cdot \frac{D_{7075}}{t_{tube}} \cdot A_{tube} = \left(2.999 \cdot 10^{-14}\right) \frac{mol}{s}$$

The leak rate through the two CF flanges is estimated from the leak rate for He which is scaled for H2. Note that these are conservatively very high.

$$L_{He} := 2 \cdot 10^{-10} \cdot atm \cdot \frac{cm^3}{s}$$

$$L_{T2} := L_{He} \cdot \sqrt{\frac{M_{He}}{M_{H2}}} = \left(2.828 \cdot 10^{-10}\right) atm \cdot \frac{cm^3}{s}$$

$$Q_4 := L_{T2} \cdot \frac{1}{T_{room} \cdot R} = \left(1.168 \cdot 10^{-14}\right) \frac{mol}{s}$$

The leak rate through the valve stem and seal is listed by Swagelok

$$L_{He} := 4 \cdot 10^{-9} \cdot atm \cdot \frac{cm^3}{s}$$

$$L_{T2} := L_{He} \cdot \sqrt{\frac{M_{He}}{M_{H2}}} = \left(5.657 \cdot 10^{-9}\right) atm \cdot \frac{cm^3}{s}$$

$$Q_5 := L_{T2} \cdot \frac{1}{T_{room} \cdot R} = \left(2.337 \cdot 10^{-13}\right) \frac{mol}{s}$$

The total leak rate is scaled from the estimated leak rate for H2 for T2

$$R_{T2} := \sqrt{\frac{M_{H2}}{M_{T2}}} = 0.577$$ scale factor

$$Q_T := \frac{(Q_1 + Q_2 + Q_3 + 2 \cdot Q_4 + Q_5)}{\sqrt{3}} = \left(3.001 \cdot 10^{-13}\right) \frac{mol}{s}$$

$$TT := Q_T \cdot 1 \cdot yr = \left(9.471 \cdot 10^{-6}\right) mol$$

The total activity released in one year is then conservatively estimated at:

$$N_{act} := TT \cdot n_{act} = 0.55 \; Ci$$

Note that many of the above assumptions are very conservative and the true leakage is expected to be much less. None the less the valve represents the dominant leak and the possibility of pinch welding should be considered.

Fugacity of tritium gas in cell during beam operations:

The beam will dissociate the T2 to T+T which will recombine on the walls of the cell.

$T_{cell} := 150 \cdot K$	assumed temp of cell wall
$T_{gas} := 50\ K$	assumed temp of gas
$m_T := 5.006 \cdot 10^{-27} \cdot kg$	mass of triton
$dE_T := 2.83 \cdot W$	beam power in T2 from collision loss TGT-CALC-103-003
$E_{ion} := 13.595 \cdot eV$	ionization energy
$E_{dis} := 4.591 \cdot eV$	Dissociation energy
$n_{dis} := \dfrac{dE_T}{E_{ion} + E_{dis}} = \left(9.714 \cdot 10^{17}\right) \dfrac{1}{s}$	rate of dissociation atom/sec
$N_{dis} := n_{dis} \cdot 1 \cdot s$	number dis in 1 s
$n_{bounce} := \dfrac{1}{4} \cdot \dfrac{N_{dis}}{V_{cell}} \cdot \sqrt{3 \cdot k \cdot \dfrac{T_{gas}}{m_T}}$	kinetic theory wall bounce #/ (area *s) for all species
$N_{bounce} := n_{bounce} \cdot A_{cell} = \left(4.171 \cdot 10^{22}\right) \dfrac{1}{s}$	total bounces
$N_{BR} := 10000$	number of atom bounces to recombine on ave
$n_{rec} := \dfrac{N_{bounce}}{N_{dis} \cdot N_{BR}} = 4.294\ \dfrac{1}{s}$	recombination rate per atom
$\tau := \dfrac{1}{n_{rec}} = 0.233\ s$	mean lifetime for T atom

$N_{trit} := \tau \cdot n_{dis} = 2.262 \cdot 10^{17}$ total T atoms in cell with beam on

$R_T := \frac{N_{trit}}{N_T} = 10 \cdot 10^{-6}$ fraction of T atoms

Under normal conditions we assume the probabilty to dissociate T2 is 1 ppm.

$R_{norm} := 10^{-6}$ ratio of number of T atoms in cell no beam

There is an estimated 10 times more atomic T when beam is then when it is off

$$\frac{R_T}{R_{norm}} = 10$$

this implies that the ratio of T atoms to aluminum atoms may be a factor of 10 larger for beam conditions. The higher concentration/diffusion rate may be considered to result from an effective pressure (temperature) or fugacity. This fugacity is determined below:

solubility is 20x higher

$$C_H := \frac{R_T}{R_{norm}} \cdot C_{150} = 1.455 \cdot 10^{-8}$$

$$P_{eff} := \left(\frac{C_H}{C_0 \cdot e^{\frac{-\Delta H}{R \cdot T_{room}}}} \right)^2 \cdot P_{atm} = \left(3.114 \cdot 10^3\right) \, psi$$

A test in compliance with ASTM E399 shall be performed by SRSTE/SRNL with pressures in excess of 1000 psi. Samples shall be exposed to 4,8,12 months of T2 at room temp and more than 3000 psi. This exceeds the fugacity available by beam on conditions.

Concentration of He3 in aluminum:

The above analysis mayh raise concerns regarding the amount of He3 trapped in the aluminum alloy. A study at SRS indicates that the threshold concentration for blistering is $C_b := 0.0045$ He/Al.

$C_H = 1.455 \cdot 10^{-8}$ our cond beam on Tritiu atoms

$C_{room} = 3.686 \cdot 10^{-9}$ our cond room temp tritium atoms

our conditions are ~ 6 orders of magnitude lower even if we assume all T atoms convert to He immediately

$$\frac{C_b}{C_{room}} = 1.221 \cdot 10^{6}$$

Estimated Error in Fill

The exact quantity of tritium in the cell is important to the target lentgh determination. The cell is filled at SRS. The fill quantity shall be determined from the real gas law.

$Z := 1.01$ compressibility of T2 at temp/pressure

$T := 295 \cdot K$ assmed fill temp

$P := P_{cell}$ assumed fill pressure

$V := V_{cell}$ assumed fill volume

$n := \frac{P \cdot V}{Z \cdot R \cdot T} = 0.019\ mol$ expected fill quantity

$\delta T := 0.025 \cdot K$ reported error on temp

$\delta P := 0.2 \cdot psi$ reported error on pressure

$\delta V := 0.5 \cdot cm^3$ estimated error on volume

$$\delta n := \sqrt{\left(\frac{V}{R \cdot T \cdot Z} \cdot \delta P\right)^2 + \left(\frac{P}{R \cdot T \cdot Z} \cdot \delta V\right)^2 + \left(\frac{P \cdot V}{R \cdot Z \cdot T^2} \cdot \delta T\right)^2} = \left(2.786 \cdot 10^{-4}\right)\ mol$$

$\frac{\delta n}{n} = 0.015$ estimated error in fill quantity