Project: Hall A Tritium Target

Tittle: Determination of solid and fluid target thickness from measurements

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Author: Dave Meekins

Reference:
NIST RefProp
TGT-RPT-17-002
DOE STD-1129-2015
Huang and Chen, Cryogenics 46 (2006) 833-839

Reference Drawing(s):
TGT-103-1006-0000

Description:
Determination of solid and fluid target thickness from measurements. Reads data from thickness data spreadsheet (thick-data) which also has the cell thickness data.

Solid Targets:

The area was measured by tool makers microscope. The sides of each foil are assumed to be straight but not parallel. The straightness is checked on the microscope with an uncertainty reflected in the error on the coordinate. Foil mass is determined with Denver Instruments balance. Calibration is checked at the start and finish of each series of measurements. Coordinate dimensions are mm.

$\delta m := 0.0003 \cdot gm$ uncertainty on mass

$\delta x := 0.0005 \cdot in$ uncertainty on coordinate

25 cm dummy #1

$DataX := \text{READEXCEL}(\text{".\Thick−data.xlsx"}, \text{"SOLID!A6:B9"}) \cdot mm$

$$DataX = \begin{bmatrix} 0 & 0 \\ -12.704 & 0.198 \\ -13.006 & -17.566 \\ -0.304 & -17.744 \end{bmatrix} mm$$

$DataM := \text{READEXCEL}(\text{".\Thick−data.xlsx"}, \text{"SOLID!B3:B3"})$

$m := DataM_{0,0} \cdot gm$

$x1 := DataX_{0,0}$ $x3 := DataX_{2,0}$

$y1 := DataX_{0,1}$ $y3 := DataX_{2,1}$

$x2 := DataX_{1,0}$ $x4 := DataX_{3,0}$

$y2 := DataX_{1,1}$ $y4 := DataX_{3,1}$

$$A := \frac{1}{2} \cdot \left| \left((x1 \cdot y2 - y1 \cdot x2) + (x2 \cdot y3 - y2 \cdot x3) + (x3 \cdot y4 - y3 \cdot x4) + (x4 \cdot y1 - y4 \cdot x1) \right) \right|$$

$$\delta A := \delta x \cdot \sqrt{(x1 - x3)^2 + (x2 - x4)^2 + (y1 - y3)^2 + (y2 - y4)^2}$$

$$\rho t := \frac{m}{A} = 0.3495 \ \frac{gm}{cm^2}$$

$$\delta \rho t := \sqrt{\left(\frac{1}{A} \cdot \delta m\right)^2 + \left(\frac{m}{A^2} \cdot \delta A\right)^2} = \left(6.219 \cdot 10^{-4}\right) \frac{gm}{cm^2}$$

25 cm dummy #2

$DataX := \text{READEXCEL}(\text{".\Thick−data.xlsx"}, \text{"SOLID!D6:E9"}) \cdot mm$

$$DataX = \begin{bmatrix} 0 & 0 \\ 1.011 & -17.756 \\ 13.685 & -17.055 \\ 12.673 & 0.69 \end{bmatrix} mm$$

$DataM := \text{READEXCEL}(\text{".\Thick−data.xlsx"}, \text{"SOLID!E3:E3"})$

$m := DataM_{0,0} \cdot gm = 0.789\ gm$

$x1 := DataX_{0,0}$ $x3 := DataX_{2,0}$

$y1 := DataX_{0,1}$ $y3 := DataX_{2,1}$

$x2 := DataX_{1,0}$ $x4 := DataX_{3,0}$

$y2 := DataX_{1,1}$ $y4 := DataX_{3,1}$

$$A := \frac{1}{2} \cdot \left| \left((x1 \cdot y2 - y1 \cdot x2) + (x2 \cdot y3 - y2 \cdot x3) + (x3 \cdot y4 - y3 \cdot x4) + (x4 \cdot y1 - y4 \cdot x1) \right) \right|$$

$$\delta A := \delta x \cdot \sqrt{(x1 - x3)^2 + (x2 - x4)^2 + (y1 - y3)^2 + (y2 - y4)^2}$$

$$\rho t := \frac{m}{A} = 0.3495\ \frac{gm}{cm^2}$$

$$\delta \rho t := \sqrt{\left(\frac{1}{A} \cdot \delta m\right)^2 + \left(\frac{m}{A^2} \cdot \delta A\right)^2} = \left(6.22 \cdot 10^{-4}\right) \frac{gm}{cm^2}$$

Carbon

$DataX := \text{READEXCEL}(\text{".\Thick−data.xlsx"}, \text{"SOLID!A16:B19"}) \cdot mm$

$$DataX = \begin{bmatrix} 0 & 0 \\ -0.438 & 12.678 \\ -13.11 & 12.253 \\ -12.656 & -0.375 \end{bmatrix} mm$$

$DataM := \text{READEXCEL}(\text{".\Thick−data.xlsx"}, \text{"SOLID!B13:B13"})$

$m := DataM_{0,0} \cdot gm$

$x1 := DataX_{0,0}$ $x3 := DataX_{2,0}$

$y1 := DataX_{0,1}$ $y3 := DataX_{2,1}$

$x2 := DataX_{1,0}$ $x4 := DataX_{3,0}$

$y2 := DataX_{1,1}$ $y4 := DataX_{3,1}$

$$A := \frac{1}{2} \cdot \left| \left((x1 \cdot y2 - y1 \cdot x2) + (x2 \cdot y3 - y2 \cdot x3) + (x3 \cdot y4 - y3 \cdot x4) + (x4 \cdot y1 - y4 \cdot x1) \right) \right|$$

$$\delta A := \delta x \cdot \sqrt{(x1 - x3)^2 + (x2 - x4)^2 + (y1 - y3)^2 + (y2 - y4)^2}$$

$$\rho t := \frac{m}{A} = 0.0883 \ \frac{gm}{cm^2}$$

$$\delta \rho t := \sqrt{\left(\frac{1}{A} \cdot \delta m\right)^2 + \left(\frac{m}{A^2} \cdot \delta A\right)^2} = \left(2.576 \cdot 10^{-4}\right) \frac{gm}{cm^2}$$

Titanium

$DataX := \text{READEXCEL}(\text{".\Thick-data.xlsx"}, \text{"SOLID!D16:E19"}) \cdot mm$

$$DataX = \begin{bmatrix} 0 & 0 \\ -12.702 & 0.218 \\ -12.472 & 12.895 \\ 0.208 & 12.687 \end{bmatrix} mm$$

$DataM := \text{READEXCEL}(\text{".\Thick-data.xlsx"}, \text{"SOLID!E13:E13"})$

$m := DataM_{0,0} \cdot gm = 0.657\ gm$

$x1 := DataX_{0,0}$ $x3 := DataX_{2,0}$

$y1 := DataX_{0,1}$ $y3 := DataX_{2,1}$

$x2 := DataX_{1,0}$ $x4 := DataX_{3,0}$

$y2 := DataX_{1,1}$ $y4 := DataX_{3,1}$

$$A := \frac{1}{2} \cdot \left| \left((x1 \cdot y2 - y1 \cdot x2) + (x2 \cdot y3 - y2 \cdot x3) + (x3 \cdot y4 - y3 \cdot x4) + (x4 \cdot y1 - y4 \cdot x1) \right) \right|$$

$$\delta A := \delta x \cdot \sqrt{(x1 - x3)^2 + (x2 - x4)^2 + (y1 - y3)^2 + (y2 - y4)^2}$$

$$\rho t := \frac{m}{A} = 0.4081\ \frac{gm}{cm^2}$$

$$\delta \rho t := \sqrt{\left(\frac{1}{A} \cdot \delta m\right)^2 + \left(\frac{m}{A^2} \cdot \delta A\right)^2} = \left(8.379 \cdot 10^{-4}\right) \frac{gm}{cm^2}$$

Thickness of gas cells:

The cell wall thicknesses have been reported in TGT-RPT-17-007 and are not recorded here. The density of gas at room temperature is determined from the temperature and pressure measured for each fill. The cell length is 25 cm +/- 0.5 mm.

The tritium cells (both fills) were loaded at SRS/SRTE. The initial reports for the density of tritium in the cells were incorrect due to a communication error in the cell volume where 30 cubic centimeters was assumed at SRS. The actual volume of the cells is 33.3 cm^3 . The correct density is reported below.

Tritium Cell #1:

This cell was filled at SRS on 10/23/2017 with the following parameters:

$V_{cell} := 33.28 \cdot cm^3$ Cell volume measured at JLAB

$\delta V_{cell} := 0.3 \cdot cm^3$ uncertainty in cell volume

$T_{fill} := 23.1\ °C$ Fill temperature

$\delta T_{fill} := 0.05 \cdot K$ Uncertainty in fill temp

$P_{fill} := 203 \cdot psi$ Fill pressure in psia

$\delta P_{fill} := 0.6 \cdot psi$ Uncertainty in fill Pressure

$M := 6.032 \cdot \frac{gm}{mol}$ Molar mass of T2

$z := 1 + \frac{\left(P_{fill} \cdot 0.000832\right)}{1 \cdot torr \cdot 1000} = 1.009$ Compressibility of tritium at 295K temperature

$m_{fill} := \frac{M \cdot P_{fill} \cdot V_{cell}}{R \cdot T_{fill} \cdot z} = 0.113\ gm$ mass of fill from SRS

The uncertainty in the mass is then

$$\delta m := M \cdot \left(\left(\frac{\delta P_{fill} \cdot V_{cell}}{R \cdot T_{fill} \cdot z} \right)^2 + \left(\frac{P_{fill} \cdot \delta V_{cell}}{R \cdot T_{fill} \cdot z} \right)^2 + \left(\frac{P_{fill} \cdot V_{cell}}{R \cdot {T_{fill}}^2 \cdot z} \cdot \delta T_{fill} \right)^2 \right)^{\frac{1}{2}} = 1.073\ mg$$

$t_{cell} := 25 \cdot cm$ target length of cell

$\delta t := 0.05 \cdot cm$ uncertainty in length

$$\rho_{cell} := \frac{m_{fill}}{V_{cell}} = 3.398 \ \frac{mg}{cm^3}$$ density of gas in cell at fill

$$\rho_{fill} := \frac{M \cdot P_{fill}}{R \cdot T_{fill} \cdot z} = 3.3979 \ \frac{mg}{cm^3}$$ density of fill from SRS data

$$\delta\rho_{fill} := \left(\left(\frac{M \cdot \delta P_{fill}}{R \cdot T_{fill} \cdot z} \right)^2 + \left(\frac{M \cdot P_{fill}}{R \cdot T_{fill}^{\ 2} \cdot z} \cdot \delta T_{fill} \right)^2 \right)^{\frac{1}{2}} = 0.01 \ \frac{mg}{cm^3}$$ uncertainty in density

$$T := \frac{m_{fill} \cdot t_{cell}}{V_{cell}} = 84.947 \ \frac{mg}{cm^2}$$ target length ρt

$$\delta T := \left(\left(\delta m \cdot \frac{t_{cell}}{V_{cell}} \right)^2 + \left(\delta t \cdot \frac{m_{fill}}{V_{cell}} \right)^2 \right)^{\frac{1}{2}} = 0.824 \ \frac{mg}{cm^2}$$ uncertainty in target length

Fill data from 10/23/17:
Below is an email from C. Clamp (SRNS engineer) (12/7/2020)

SRS Serial Number: JLAB1-001
Mass Spec Results (mol%), Excludes Waters which are measured in the gas stream during loading
Total T: 99.891%
Total D: 0.047%
Total H (protium): 0.0%
He-3: 0.059%
N2: 0.002%
CO2: 0.0%
(No other contaminants detected)

Fill Date: 10/23/2017

Waters in Gas Stream: 0.1517 ppm (1.517E-5 mol%)
Glovebox Temperature: 23.1°C
Fill Pressure: 203 psia

PVT Calculation Results
Total T: 0.102 Grams
Total D: 3.20E-5 Grams
Total H (protium): 0.0 Grams
He-3: 3.01E-5 Grams
N2: 9.47E-6 Grams
CO2: 0.0 Grams

Tritium Cell #2:

This cell was filled at SRS on 08/24/2018 with the following parameters:

$V_{cell} := 33.28 \cdot cm^3$ Cell volume measured at JLAB

$\delta V_{cell} := 0.3 \cdot cm^3$ uncertainty in cell volume

$T_{fill} := 20.65\ °C$ Fill temperature

$\delta T_{fill} := 0.05 \cdot K$ Uncertainty in fill temp

$P_{fill} := 202 \cdot psi$ Fill pressure

$\delta P_{fill} := 0.6 \cdot psi$ Uncertainty in fill Pressure

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

$z := 1 + \frac{\left(P_{fill} \cdot 0.000832\right)}{1 \cdot torr \cdot 1000}$ Compressibility of tritium at 295K temperature

$m_{fill} := \frac{M \cdot P_{fill} \cdot V_{cell}}{R \cdot T_{fill} \cdot z} = 0.113\ gm$ mass of fill from SRS

The uncertainty in the mass is then

$$\delta m := M \cdot \left(\left(\frac{\delta P_{fill} \cdot V_{cell}}{R \cdot T_{fill} \cdot z} \right)^2 + \left(\frac{P_{fill} \cdot \delta V_{cell}}{R \cdot T_{fill} \cdot z} \right)^2 + \left(\frac{P_{fill} \cdot V_{cell}}{R \cdot {T_{fill}}^2 \cdot z} \cdot \delta T_{fill} \right)^2 \right)^{\frac{1}{2}} = 1.071\ mg$$

$t_{cell} := 25 \cdot cm$ target length of cell

$\delta t := 0.05 \cdot cm$ uncertainty in length

$$\rho_{cell} := \frac{m_{fill}}{V_{cell}} = 3.391 \ \frac{mg}{cm^3}$$ density of gas in cell at fill

$$\rho_{fill} := \frac{M \cdot P_{fill}}{R \cdot T_{fill} \cdot z} = 3.391 \ \frac{mg}{cm^3}$$ mass of fill from SRS

$$\delta\rho_{fill} := \left(\left(\frac{M \cdot \delta P_{fill}}{R \cdot T_{fill}} \right)^2 + \left(\frac{M \cdot P_{fill}}{R \cdot T_{fill}^2} \cdot \delta T_{fill} \right)^2 \right)^{\frac{1}{2}} = 0.01 \ \frac{mg}{cm^3}$$ uncertainty in density

$$T := \frac{m_{fill} \cdot t_{cell}}{V_{cell}} = 84.785 \ \frac{mg}{cm^2}$$ target length ρt

$$\delta T := \left(\left(\delta m \cdot \frac{t_{cell}}{V_{cell}} \right)^2 + \left(\delta t \cdot \frac{m_{fill}}{V_{cell}} \right)^2 \right)^{\frac{1}{2}} = 0.823 \ \frac{mg}{cm^2}$$ uncertainty in target length

Below is from SRS/SRTE fill data report:

Mass Spec Results (mol%), Excludes Waters which are measured in the gas stream during loading

Total T: 99.9285%
Total D: 0.037%
Total H (protium): 0.0045%
He-3: 0.028%
N2: 0.002% (Mass 28 assumed as N2 from glovebox atmosphere and not CO since no CO source in facility and CO2% is small)
CO2: 0.0005%
(No other contaminants detected)
Fill Date: 08/24/2018
Volume: 30 cc (assumed)
Waters in Gas Stream: 0.10 ppm (1.0E-7 mol%)
Glovebox Temperature: 20.65°C
Delta T between Glovebox and Loading Gas: 0°C (assumed to be negligible since very low tritium grams and at least 90 minutes allowed for thermal equilibration)
Fill Pressure: 202 psia
PVT Calculation Results Based on Above Inputs
Total T: 0.102 Grams
Total D: 2.53E-5 Grams
Total H (protium): 1.54E-6 Grams
He-3: 1.43E-5 Grams
N2: 9.51E-6 Grams
CO2: 3.73E-6 Grams

Below is a plot from the eleastic run:
There is about 1.6% H2 contamination in the T2 cell

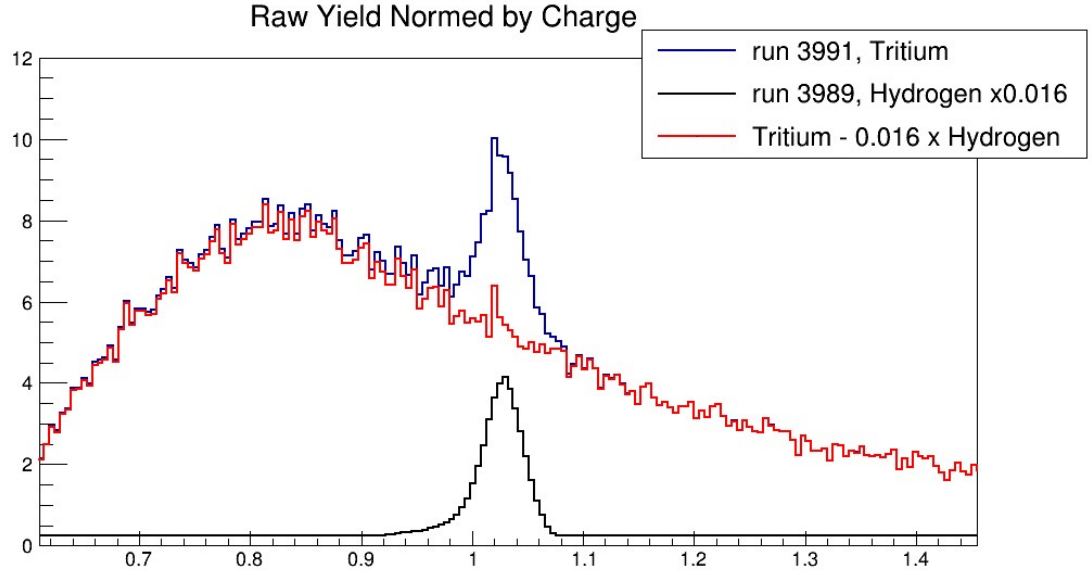

Figure from Shujie Li

Hydrogen cell:

This cell was filled at JLAB. NIST tables have been used to determined the density and uncertainty

$\rho := 2.832 \cdot \frac{kg}{m^3}$ density in H2 cell

$\delta\rho := 0.011 \cdot \frac{kg}{m^3}$ uncertainty in density

$t_{cell} := 25 \cdot cm$ target length of cell

$\delta t := 0.1 \cdot cm$ uncertainty in length

$T := \rho \cdot t_{cell} = 70.8 \ \frac{mg}{cm^2}$ H2 target thickness

$\delta T := \left(\left(\rho \cdot \delta t \right)^2 + \left(\delta\rho \cdot t_{cell} \right)^2 \right)^{\frac{1}{2}} = 0.395 \ \frac{mg}{cm^2}$ Uncertainty in thickness

Deuterium cell:

This cell was filled at JLAB. NIST tables have been used to determined the density and uncertainty

$\rho := 5.686 \cdot \frac{mg}{cm^3}$ density in D2 cell

$\delta\rho := 0.0218 \cdot \frac{mg}{cm^3}$ uncertainty in density

$t_{cell} := 25 \cdot cm$ target length of cell

$\delta t := 0.1 \cdot cm$ uncertainty in length

$T := \rho \cdot t_{cell} = 142.15 \ \frac{mg}{cm^2}$ D2 target thickness

$\delta T := \left(\left(\rho \cdot \delta t \right)^2 + \left(\delta\rho \cdot t_{cell} \right)^2 \right)^{\frac{1}{2}} = 0.788 \ \frac{mg}{cm^2}$ Uncertainty in thickness

He-3 cell:

The cell was filled at JLAB with He-3 99.999%.

$M := 3 \cdot \frac{gm}{mol}$ Molar mass of He3

$\tau := 21.3\ °C = 294.45\ K$ fill temperature

$\delta\tau := 0.1\ K$ error on fill temp

$z := 1.0084$ compressibility

$P := 252.7 \cdot psi$ Fill pressure absolute

$\delta P := 2.5 \cdot psi$ Error in fill pressure

$\rho := \frac{P \cdot M}{R \cdot \tau \cdot z} = 2.117\ \frac{mg}{cm^3}$ density of He-3

$\delta\rho := \left(\left(\delta P \cdot \frac{M}{R \cdot \tau \cdot z} \right)^2 + \left(\delta\tau \cdot \frac{P \cdot M}{R \cdot \tau^2 \cdot z} \right)^2 \right)^{\frac{1}{2}} = 0.021\ \frac{mg}{cm^3}$ uncertainty on density

$T := \rho \cdot t_{cell} = 52.9306\ \frac{mg}{cm^2}$ total thickness of He-3

$\delta T := \left(\left(\delta\rho \cdot t_{cell} \right)^2 + \left(\rho \cdot \delta t \right)^2 \right)^{\frac{1}{2}} = 0.565\ \frac{mg}{cm^2}$ uncertainty in thickness

Argon cell:

The cell was filled at JLAB with natural argon

$M := 39.95 \cdot \frac{gm}{mol}$ Molar mass

$\tau := 291 \cdot K$ fill temperature

$\delta\tau := 0.1\ K$ error on fill temp

$z := 0.97686$ compressibility

$P := 514.7 \cdot psi$ Fill pressure absolute

$\delta P := 0.0025 \cdot 1000 \cdot psi$ Error in fill pressure

$\rho := \frac{P \cdot M}{R \cdot \tau \cdot z} = 59.983\ \frac{mg}{cm^3}$ density of Argon

$\delta\rho := \left(\left(\delta P \cdot \frac{M}{R \cdot \tau \cdot z}\right)^2 + \left(\delta\tau \cdot \frac{P \cdot M}{R \cdot \tau^2 \cdot z}\right)^2\right)^{\frac{1}{2}} = 0.292\ \frac{mg}{cm^3}$ uncertainty on density

$T := \rho \cdot t_{cell} = \left(1.4996 \cdot 10^3\right)\ \frac{mg}{cm^2}$ total thickness of argon

$\delta T := \left(\left(\delta\rho \cdot t_{cell}\right)^2 + \left(\rho \cdot \delta t\right)^2\right)^{\frac{1}{2}} = 9.45\ \frac{mg}{cm^2}$ uncertainty in thickness

Using the Redlich-Kwong equation of state for the He3 cell:

$T := 21.3\ °C = 294.45\ K$ fill temperature

$P := 252.7 \cdot psi = \left(1.742 \cdot 10^{6}\right)\ Pa$ Fill pressure absolute

$T_c := 3.3157 \cdot K$ crit temp of He3

$p_c := 114604 \cdot Pa$ Crit pressure of He3

$M := 3.016 \cdot \frac{gm}{mol} = 0.003\ \frac{kg}{mol}$ Molar mass

$t := \frac{T}{T_c} = 88.805$ ratio of temp to crit temp

$\lambda := \frac{P}{p_c} = 15.203$ ratio of pressure to crit pressure

Relich-Kwong is typically valid when

$\lambda < \frac{t}{2} = 1$ test ratio

which is true in this case

$a := 0.42748 \cdot \frac{R^2 \cdot T_c^{2.5}}{p_c} = 0.005\ \frac{J \cdot K^{0.5} \cdot m^3}{mol^2}$ gas constant a

$b := 0.08664 \cdot \frac{R \cdot T_c}{p_c} = \left(2.084 \cdot 10^{-5}\right)\ \frac{m^3}{mol}$ gas constant b

NOTE: For the solver to work the equation must be made dimensionless:

$\rho := 2$

$T_c := 3.3157$

$p_c := 114604$

$a := 0.005$

$b := 2.084 \cdot 10^{-5}$

$M := 0.003016$

$R := 8.314$

$T := 294.45$

$P := 1.742 \cdot 10^{6}$

$$x := P = \frac{R \cdot T}{y \cdot M - b} - \frac{a}{\sqrt{T} \cdot (M \cdot y) \cdot (M \cdot y + b)} \xrightarrow{assume, y > 0, solve, y} 0.47282502047184673238$$

$$\rho := \frac{1}{x} \cdot \frac{mg}{cm^3} = 2.115 \ \frac{kg}{m^3}$$