Status of IFE Tritium Inventory

A. Schwendt, A. Nobile, W. Steckle
Los Alamos National Laboratory

D. Colombant, J. Sethian
Naval Research Laboratory

D. T. Goodin, N. Alexander, G. E. Besenbruch
General Atomics

Livermore National Laboratory
November 13th and 14th, 2001

Goal of this work is to evaluate the tritium inventory of a target filling facility

Previous Work and Conclusions

- **Developed model to evaluate the theoretical minimum tritium inventory**
- **Used model to determine methods of reducing inventory:**
  - **Increased temperature of the fill process**
  - **Reduction of void volume**
  - **Minimization of DT-ice beta-layering time**
  - **Increased foam density**
- **Updated model as parameters change (permeabilities, buckle pressures, etc)**
- **Studies provide guidance into development of IFE plants, target design, and continued R&D (ex. Reduction of beta-layering time)**

Goal of this work is to evaluate the tritium inventory of a target filling facility

Today….

- **Theoretical Minimum Tritium Inventory Model:**
  - **Analytical solution to the equations**
  - **Update calculations with experimental data on foams**

    ⇒ **Glass transition temperature - limits fill temperature**

    ⇒ **Young's Modulus**
  - **Evaluate affect of foam density on tritium inventory and target gain (Collaborative effort with NRL)**

- **Implement "real" engineering assumptions into modeling effort**

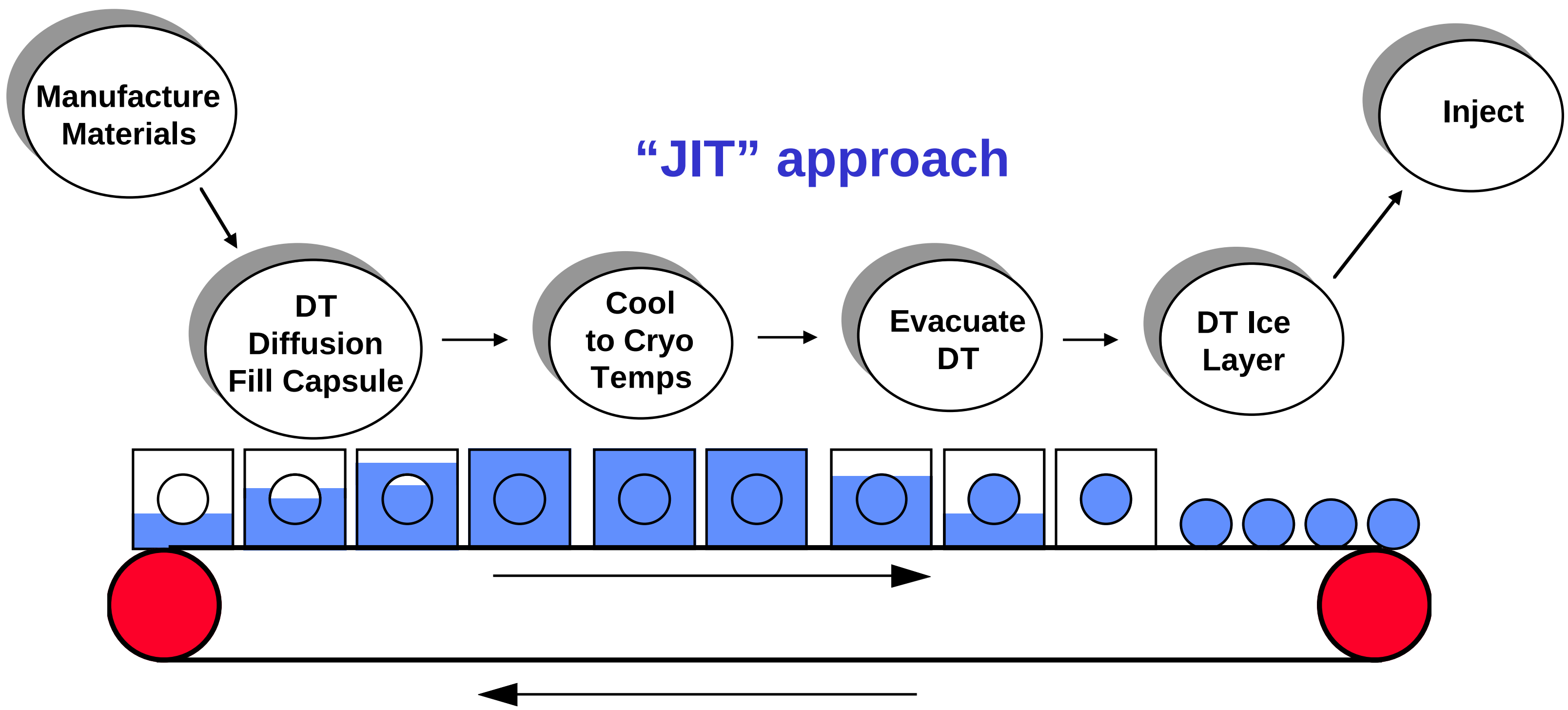
    ⇒ **batch process**

GENERAL ATOMICS

Los Alamos NATIONAL LABORATORY

We are evaluating the minimum tritium inventory required for IFE plants

Fabrication of Direct Drive Targets



Targets are processed at the rate necessary for injection
Benefit of model: eliminates engineering assumptions

GENERAL ATOMICS

Los Alamos NATIONAL LABORATORY

Analytical solution to the equations of theoretical minimum tritium inventory

Total inventory is sum of inventories of each step of the process (fill, cool, etc.)
Inventory for the cool, evacuation, and layering steps is straight forward.
For the filling...

First, determine fill time of a non-ideal gas:

Rate of permeation is proportional to concentration gradient:

$$\frac{dn}{dt} = C(N - n)$$

N - concentration outside shell
n - concentration inside shell

n (or N) is related to pressure by the compressibility equation:

$$P = znRT \text{ where } z = 1 + a\frac{P}{T}$$

The applied pressure external to the shell is the internal pressure plus the overpressure:

$$P_{external} = P + \delta P$$

Therefore the concentration outside the shell is given by:

$$N = \frac{P + \delta P}{z(P)RT} \text{ where } z = 1 + a\frac{P + \delta P}{T}$$

GENERAL ATOMICS

Los Alamos NATIONAL LABORATORY

Analytical solution to the equations of theoretical minimum tritium inventory

Insert N(P) into original equation, and apply the chain rule:

$$\frac{dn}{dt} = \frac{dn}{dP}\frac{dP}{dt}$$

Separation of variables and integration from t=0 to t = τ_{fill} yields:

$$\tau_{fill} = \frac{1}{C}\left[\frac{P_{fill}}{\delta P} + \ln(z_{fill})\right]$$

τ_{fill} - fill time

z_{fill} - z at final fill P and T

P_{fill} - final pressure inside target

Determine C by comparison to “ideal” fill time:

$$\boxed{\tau_{fill} = \frac{w_p r}{3RTK_p}\left[\frac{P_{fill}}{\delta P} + \ln(z_{fill})\right]}$$

w_p - thickness of permeation layer

r - target radius

K_p - permeability

GENERAL ATOMICS

Los Alamos NATIONAL LABORATORY

Analytical solution to the equations of theoretical minimum tritium inventory

The inventory of the fill step is the sum of the inventory internal and external to the target:

$$g_{fill} = g_{in} + g_{ext}$$

To determine the inventory inside the target (g_{in}) integrate the density over all the targets in the fill step of the process (consistent with theo. Min. Tritium Inventory model)

$$g_{in} = N_{fill} V_{in} \int_{n=0}^{N_{fill}} \rho_{in}(n)\, dn$$

Assume a linear density profile:

$$\rho_{in} = \frac{\rho(P_{fill}) - \rho_0}{N_{fill}} n + \rho_0 \text{ where } \rho_0 = 0$$

Integration gives

$$g_{in} = \tfrac{1}{2} V_{in} N_{fill} \rho(P_{fill})$$

N_{fill} = reprate x fill time
V_{in} - volume inside target
ρ_{in} - gas density inside target
n - target#
ρ_{in} - gas density inside target
ρ_0 - initial density inside target
$\rho(P_{fill})$ - density at final fill pressure (final gas density)
$\rho(\delta P)$ - density at overpressure

Similar treatment to the region external to the target (assuming that initial gas density is due the applied overpressure) gives:

$$g_{ext} = \tfrac{1}{2} V_{ext} N_{fill} \left[\rho(P_{fill} + \delta P) + \rho(\delta P)\right]$$

Analytical solution to the equations of theoretical minimum tritium inventory

Densities are a function of pressure, and are given by:

$$\rho = \frac{MW\,P}{zRT} \longrightarrow \rho(\delta P) = \frac{MW\,\delta P}{\left(1 + a\frac{\delta P}{T}\right)RT} \qquad \rho(P_{fill} + \delta P) = \frac{MW\left(P_{fill} + \delta P\right)}{\left(1 + a\frac{P_{fill} + \delta P}{T}\right)RT}$$

Define external volume (void space) with respect to inner volume:

$$V_{ext} = \alpha V_{in}$$

Putting everything together:

$$g_{fill} = \frac{V_{in}\upsilon w_p r_p\, \mathrm{MW}}{6R^2T^2K_p}\left(\frac{P_{fill}}{\delta P} + \ln(z_{fill})\right)\left(\frac{\alpha\delta P}{1 + a\frac{\delta P}{T}} + \frac{\alpha(\delta P + P_{fill})}{1 + a\frac{\delta P + P_{fill}}{T}} + \frac{P_{fill}}{1 + a\frac{P_{fill}}{T}}\right)$$

For the direct drive targets, $\delta P << P_{fill}$ and $\ln(z_{fill}) << P_{fill}/\delta P$. Therefore,

$$\boxed{g_{fill} = \frac{V_{in}\upsilon w_p r_p\, \mathrm{MW}(\alpha + 1)}{6K_p z_{fill}\,\delta P}\left(\frac{P_{fill}}{RT_{fill}}\right)^2}$$

Analytical solution to the equations of theoretical minimum tritium inventory

The overpressure, δP, is a function of the mechanical properties of the supporting layer. For the direct drive target designs, the foam layer is considered the supporting material.

$$\delta P = f\, P_{buckle} = f \frac{2E}{\sqrt{3(1-\nu^2)}} \left(\frac{w_s}{r_s} \right)^2$$

$$\text{for foams} \quad E = E_{polymer} \left(\frac{\rho_{foam}}{\rho_{polymer}} \right)^2$$

f - fraction - “safety factor”
w_s - thickness of supporting layer
ν - Poisson’s ratio (foams = 1/3)
r_s - radius of target

Foam strength sensitive to foam density

Strong effect on inventories

Next, need experimental data…..

GENERAL ATOMICS

Los Alamos NATIONAL LABORATORY

Experimental data on foam mechanical properties improves confidence in calculations

HIPE foam, unfilled (W. Steckle):

Foam density = 152 mg/cc
Young's Modulus = 7.285 x 10^7 Pa

Use as reference data:

$$\frac{E_{foam\_reference}}{\rho^2_{foam\_reference}} = \text{constant} = \frac{E_{polymer}}{\rho^2_{polymer}}$$

Now we can calculate foam modulus for varying foam densities and use to determine buckle pressures:

"IDEAL"

$$P_{buckle} = \frac{2E_{foam}}{\sqrt{3(1-\nu^2)}}\left(\frac{w_s}{r_s}\right)^2$$

"REAL"*

$$P_{buckle} = 0.365E_{foam}\left(\frac{w_s}{r_s}\right)^2$$

Also determined Tg range begins at 120°C ⟶ LIMITS FILL TEMP!

*** Roark and Young, Formulas For Stress and Strain, 1982**

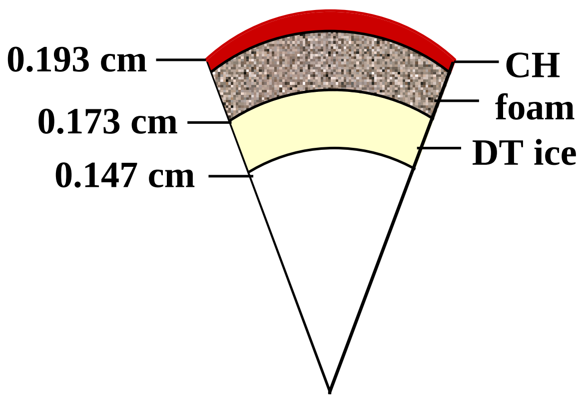
GENERAL ATOMICS

Los Alamos NATIONAL LABORATORY

With the designers, we selected a base case target and process parameters for our studies.

Theoretical minimum tritium inventory for varying foam density

Select base case with target designer
(D. Colombant, NRL)



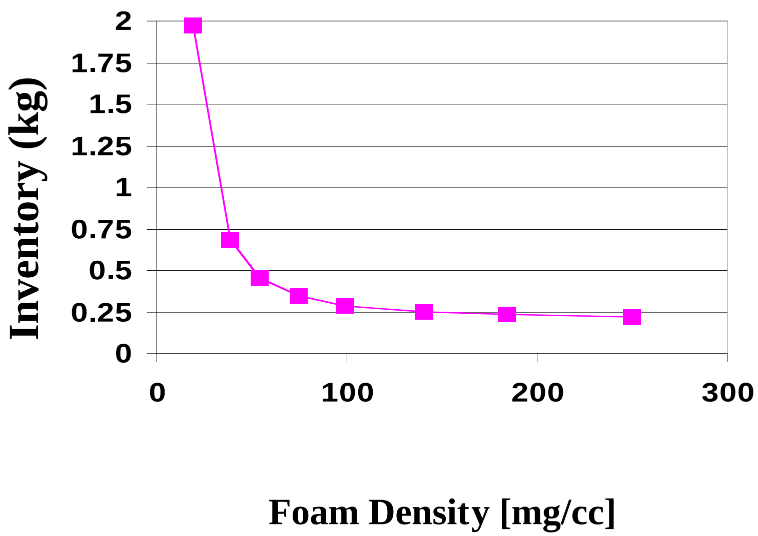
- **7 shots per second**
- **Void fraction – 10%**
- **Fill Temp – 100°C**
- **Cool time - 1/2 hr**
- **Evac time - 1 hr**
- **DT ice layer time - 2 hr**
- **Fill overpressures are 75% of buckle pressure**

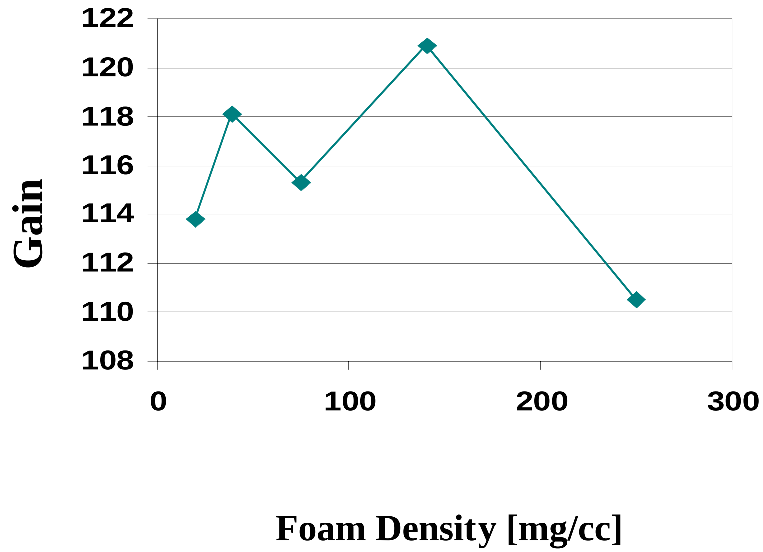
- Vary foam density from 10 mg/cc to 250 mg/cc.
- Keep dimensions and layer thicknesses constant
- Determine inventories (will decrease with density)
- Determine effect on target gain - ANY TRADEOFFS?

GENERAL ATOMICS

Los Alamos NATIONAL LABORATORY

Tritium inventories and target gains have been evaluated for varying foam density





As expected, foam density has a significant impact on tritium inventories.

Impact on gain is not as significant. A trend is difficult to determine since the variations with density are within the error of calculations.

Conclusion: Increased foam density improves tritium inventory without loosing significant gain. However, there is an upper limit to the density…. fill time calculations are based on foam layer not contributing to permeation layer.

GENERAL ATOMICS

Los Alamos NATIONAL LABORATORY

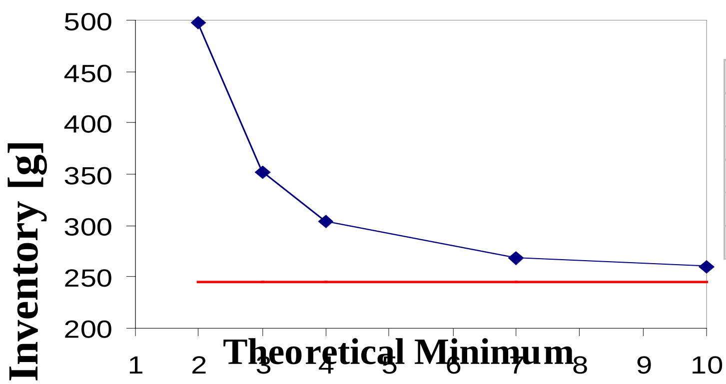
Beginning to implement real engineering assumptions into model: from a continuous to batch process

Theoretical minimum tritium inventory model equivalent to 1 target per batch

Batch process: defined by frequency of batches or time between batches

B = # of batches in process at any given time (includes source batch for injection)

L = lag time between batches $L = \frac{1}{B-1}\tau$ **Where τ is the time required to complete the process**



B [# of batches]

B	# tagets	L [hr]
2	113,400	4.5
3	56,700	2.25
4	37,800	1.5
7	18,900	0.75
10	12,600	0.5

Based on 141 mg/cc foam
Fill time: 1hr

Inventory of batch process approaches theoretical minimum as the number of batches increases

GENERAL ATOMICS

Los Alamos NATIONAL LABORATORY

Significant progress has been made in determining scenarios that reduce IFE plant tritium inventories

- **Theoretical Minimum Tritium Inventory Model:**
  - **Analytical solution to the equations**

    Allows us to clearly determine affect of target design parameters and process parameters on tritium inventory
  - **Updated calculations with experimental data on foams**

    Gives more confidence to calculations
  - **Evaluated affect of foam density on tritium inventory and target gain (Collaborative effort with NRL)**

    Increased foam density decreases tritium inventory and does not significantly affect gain (within the error of the yield calculations)
- **Implement "real" engineering assumptions into modeling effort**

  Tritium inventory approaches the theoretical minimum as the batch frequency increases.