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Conceptual Design of Low Pressure, 300° K Fill System for Ignition Target Capsules with Micron Size Fill Tubes

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Summary

A conceptual design for a low pressure, room temperature, fill system suitable for ignition target capsules is described. The fill system relies on the use of a 5 -10 micron diameter fill tube connecting directly the target capsule to a DT fuel reservoir. The design uses a small reservoir to store the DT fuel at room temperature within the target assembly. A model of the design is developed and used to calculate reservoir size, layer thickness control, and control sensitivity. A procedure to fill the target in-situ after cooling the assembly to cryogenic temperatures using temperature control of the reservoir is also described. The effects of He3 generation and fuel contamination are also discussed.

Introduction

There are two primary types of fuel capsules proposed for use as indirect drive targets for the National Ignition Facility (NIF), plastic and beryllium capsules. Plastic capsules, are intended to be diffusion filled, but do not have sufficient tensile strength^a to support the room temperature gas fill pressure required to form a minimum 80 micron thick solid fuel layer. Thus, it is anticipated that the targets will be fully assembled before being exposed to the high pressures required to diffuse the fuel into the target capsules. The pressurization cycle will expose the whole target assembly to the high pressure DT environment, and to the potential damage caused by the Tritium decay radiation. After filling, the hohlraum assembly must be cooled to cryogenic temperatures to reduce the fill pressure below the capsule's burst pressure, and to decrease the capsule material permeability before removing the fill gas from the high-pressure vessel. This process requires complex dedicated equipment: cryostats, high-pressure fill system, and a fill vessel capable of operating at cryogenic temperatures as well as sophisticated process control. Additionally, once the capsules are filled, they must be kept at cryogenic temperatures while they are transported from the filling station to the layering and diagnostic area, and on to the target chamber. This pressurization scheme has been successfully demonstrated^b at LLNL using D₂ gas to fill the shell.

Beryllium capsules are not permeable to hydrogen. They may be filled during the capsule fabrication process, such as during the bonding stage^c, for capsules assembled from hemi-shells. This method would require very high pressures depending on the capsule bonding temperature, which is expected to be in the 600° to 800° C range. Otherwise, and specially for capsules made by either PVD, a fill and plug^d procedure is under development. However, the capsules do not yet have demonstrated sufficient strength to support the fill pressure at room temperature, to allow for their assembly into hohlraums after fueling. The current hohlraum assembly techniques depend on the use of epoxy adhesives and plastic support films that need to be processed at or slightly above room temperature.

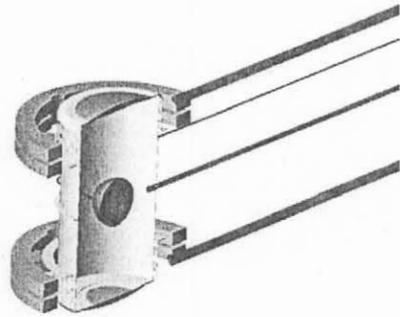


Figure 1. Typical hohlraum target showing fill tube attached to the capsule

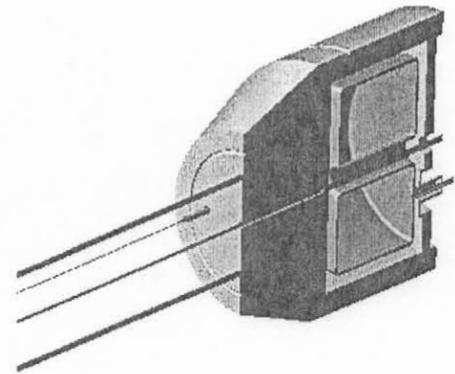


Figure 2. Mark I cryogenic target base modified to include an integral 1.5 cc DT fuel reservoir

Recent modeling of the effects of fill hole and fill tube perturbations in NIF ignition designs have yielded estimates^e of acceptable fill tube diameters in the range of 5 - 10 microns. These sizes, although small, may be practical for ignition target capsule designs because we may be able to adapt commercially available borosilicate micropipettes as fill tubes. Additionally, commercial micropipette pullers are capable of drawing micropipettes to diameters as small as 1 micron. Fill tube based systems have been used for many years in cryogenic target layering experiments, and currently we routinely use 30-micron diameter fill tubes in cryogenic experiments. These fill tube tips are made by heating and pulling 100-micron ID tubes until the diameter is reduced to the desired size. The tips are then cut to the desired length and subsequently inserted into a mechanically drilled hole in the target capsules. Mechanical drilling of plastic target capsules currently limits this technique to 30-micron diameter and 40 - 50 microns depth without step drilling. Smaller diameter holes with high >10 aspect ratios will require LASER^f or particle beam drilling of the target capsules.

We propose to build a prototype fill system, including the hohlraum and a thermally isolated reservoir, to test the feasibility of this design for use in NIF experiments.

Requirements

In a scale-1 indirect-drive target for ignition on the NIF, the target capsule will be a spherical shell ~ 2 mm inside diameter (ID). This shell will have a thickness of $\sim 160 \mu\text{m}$ which forms the ablator and an inner frozen layer of 50:50 atomic % mixture of D-T that is nominally $80 \mu\text{m}$ thick. The volume of the ice layer is $V_i = 0.93 \mu\text{L}$, and the inner volume of the target shell is $V_c = 4.19 \mu\text{L}$. Ignoring the contribution of the DT vapor inside the ice layer, we estimate that the gas density within the target shell due to the ice layer volume at approximately 1/4 solid density. The density of the D-T solid near the triple point is $\rho_s = 19.88 \mu\text{L/mole}$, thus at 273° Kelvin and 1 atm., the amount of DT within the capsule would have a volume of approximately

$$\frac{V_l}{\rho_s} \cdot \frac{22.4 \cdot L}{\text{mole}} = 1.04 \times 10^3 \mu\text{L}$$

for a volumetric increase of approximately one thousand. Of course, if we had a volume of just that size filled to a pressure of one atmosphere we would not be able to condense all the gas within that volume back into the layer because its pressure cannot fall below the saturated vapor pressure of the condensing DT gas just above the triple point. Thus for very low fill rates, where the pressure drop on the fill line can be neglected, the pressure in the reservoir volume will be $P_r = 185.71 \text{ torr}$ during the fuel condensation phase in the target capsule would be the saturated vapor pressure of DT at the capsule temperature $T_c = 20.29 \text{ K}$

Reservoir volume design

The reservoir volume design as depicted in Figure 1, must take into consideration a number of constraints imposed by its operating environment. The reservoir volume control point temperature T_r must be kept low enough to insure that its power dissipation (conductive and radiated) is reasonable; appropriate with its location at the target base, near the tip of the cryostat. A secondary, but perhaps more important constraint on the reservoir control point temperature is that we must insure that the vapor pressure of all potential condensable gasses that may prematurely plug the fill hole is sufficiently low. However, it should be possible to condense or even solidify many potential contaminants by choosing a sufficiently low control point temperature. The contaminant gases with the lowest condensation temperatures are N_2 , 77 K; Ar, 87 K; and O_2 , 90 K. The concentration of these gasses in the fuel mixture should be kept below 100 PPM or 0.1 torr partial pressure, not an unreasonable expectation for high purity bottled gas. Higher molecular weight contaminants such as H_2O , CO_2 and Hydrocarbons will be frozen solid with very low vapor pressures (0.0001 atm.) if the control point temperature $T_r := 75 \text{ K}$ or below.

The cryostat operating temperature will be approximately 10 K. A reasonable combined radiation/conduction heat load from the reservoir volume would be 20 mW. A 1 mL volume with rectangular cross-section would have a surface area of approximately 6 cm^2 . Its blackbody emission would be $\sigma \cdot (T_r)^4 = 0.18 \frac{\text{mW}}{\text{cm}^2}$, which is less than 1.5 mW for the 1 mL volume. A low

emissivity coating would easily reduce the radiated power to less than one mW total, which would leave the bulk of the heat load to accommodate conductive losses.

Ignoring the DT vapor within the fill tube and the capsule, and equating the total DT fuel mass in the reservoir volume V_r at the control temperature $T_r = 75 \text{ K}$ plus the $80 \mu\text{m}$ solid layer fuel mass to the fuel mass of the reservoir volume V_{re} at the fill temperature T_f and fill pressure P_f we have

$$\left(\frac{P_b \cdot V_{re}}{R_o \cdot T_r} + \frac{V_l}{\rho_s} \right) = \frac{V_{re} \cdot P_f}{R_o \cdot T_f} \quad (1)$$

and, solving for the fill pressure P_f as a function of the reservoir volume V_{re} for a nominal fill temperature of $T_f := 300\text{-K}$ we obtain the following relation,

$$P_f(V_{re}) := \left(\frac{P_r}{T_r} + \frac{V_l \cdot R_o}{V_{re} \cdot \rho_s} \right) \cdot T_f \quad (2)$$

For initial fill conditions of $T_f := 300\text{K}$ and for a nominal reservoir volume $V_{re} := 1\text{-mL}$ we calculate the following fill pressure will be required: $P_f(V_{re}) = 2.13\text{ atm}$. This low fill pressure combined with the small reservoir volume required makes an in-situ fill system for target capsules in the NIF practical. The fill line connecting the capsule to the reservoir volume is nominally $L_{ft} = 10\text{ cm}$ long with an internal radius of $r_{ft} = 20\text{ }\mu\text{m}$. Its volume is $V_{ft} = 0.13\text{ }\mu\text{L}$, essentially insignificant compared to a reservoir volume $V_{re} = 1\text{ mL}$ and still much smaller than the capsule volume $V_c = 4.19\text{ }\mu\text{L}$. The capsule volume itself is much smaller than the nominal reservoir volume under consideration, thus the errors introduced by ignoring their additional contribution to the total volume would be less than 0.5%.

Layer thickness control

This reservoir volume design is versatile, and allows large design flexibility. This versatility makes the layer thickness control sensitivity depend not only on the reservoir vessel temperature control, but also on its volume and initial fill pressure. We now solve for the layer volume V_l using equation (1),

$$V_l = V_{re} \cdot \rho_s \cdot \frac{(-P_b \cdot T_f + P_f \cdot T_r)}{R_o \cdot T_r \cdot T_f} \quad (3)$$

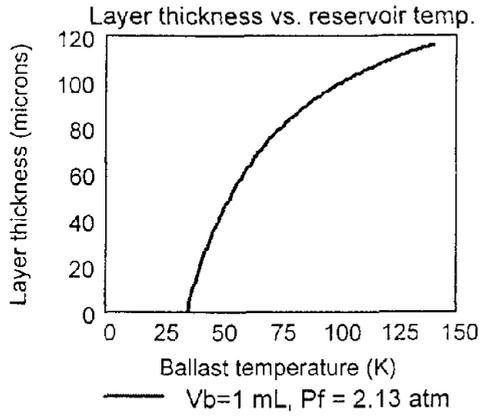
and combined with the layer volume calculation as a function of layer thickness in equation (4),

$$V_l = \frac{4 \cdot \pi}{3} \cdot \left[r_c^3 - (r_c - L_{thk})^3 \right] \quad (4)$$

to determine the uniform layer thickness that would be formed, once the fill process is complete and the capsule temperature is lowered just below the DT triple point, (equation (5) for a given set of initial fill conditions P_b , T_f , reservoir volume V_{re} , and reservoir control temperature T_r .

$$L_{thk} = r_c - \sqrt[3]{r_c^3 - \frac{3 \cdot V_{re} \cdot \rho_s \cdot (-P_b \cdot T_f + P_f \cdot T_r)}{R_o \cdot T_r \cdot T_f}} \quad (5)$$

Now, if the reservoir volume initial fill will be done room temperature $T_f = 300K$, we plot the uniform layer thickness that would form versus the reservoir volume control temperature for the fill pressure previously calculated.

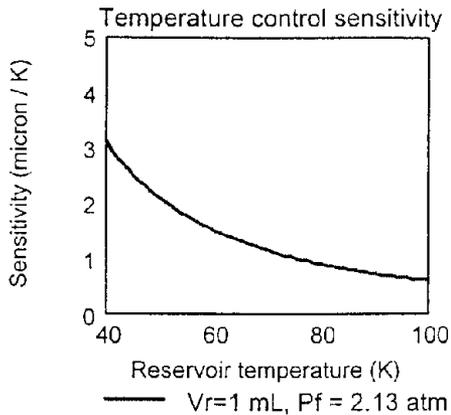


The curve crosses the design point of $80 \mu m$ layer thickness and $T_r = 75K$ reservoir temperature. Liquefaction starts at a lower temperatures (the x intercept), and this effect may be used as a diagnostic for the initial fill pressure, if the first condensation (dew point) can be accurately observed. The slope of the curve also decreases as the reservoir temperature increases, which implies a loss in control sensitivity as the fluid density inside of the reservoir vessel decreases.

Control sensitivity

Taking the partial derivative of the layer thickness L_{thk} equation (5), with respect to the reservoir volume temperature T_r , we obtain the layer thickness sensitivity to the reservoir volume temperature control, equation (6).

$$\frac{\delta L_{thk}}{\delta T_r} = \frac{-1 \cdot \left[\frac{-3}{4} \cdot V_{re} \cdot \rho_s \cdot \frac{P_f}{R_o \cdot T_r \cdot T_f \pi} + \frac{3}{4} \cdot V_{re} \cdot \rho_s \cdot \frac{(-P_b \cdot T_f + P_f \cdot T_r)}{R_o \cdot T_r^2 \cdot T_f \pi} \right]}{3 \cdot \left[r_c^3 - \frac{3}{4} \cdot V_{re} \cdot \rho_s \cdot \frac{(-P_b \cdot T_f + P_f \cdot T_r)}{R_o \cdot T_r \cdot T_f \pi} \right]^{\frac{2}{3}}} \quad (6)$$



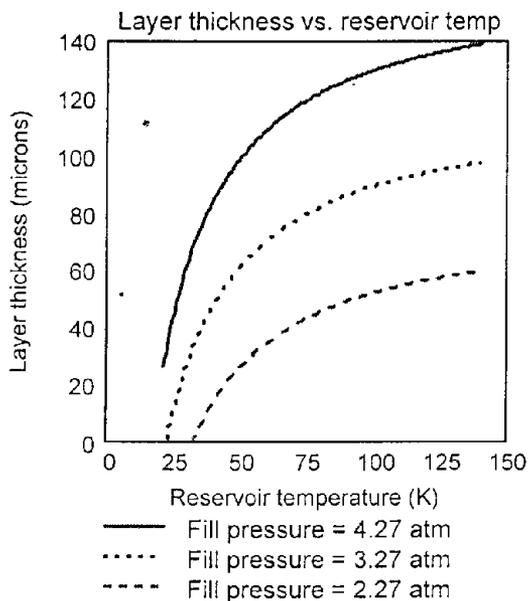
Plotting the derivative value vs. the reservoir volume temperature shows that indeed, the control sensitivity decreases as the reservoir temperature increases. The reservoir control temperature sensitivity should also be proportional to the reservoir volume and to the initial fill pressure, as both contribute to a larger mass of gas under temperature control. The $1 \mu\text{m}/\text{K}$ sensitivity for the $V_{re} = 1 \text{ mL}$ reservoir at the operating temperature of $T_r = 75\text{K}$ is quite adequate for layer thickness control purposes.

Constraint driven design

A more practical design approach would be to first determine the space that would be available for a reservoir volume in the target base and then design the rest of the fill system to accommodate the

space constraints within the target base. Figure (2) shows a solid rendered section of a 1.5 mL reservoir volume inset within the target base design of the Mark 1 cryostat. Of course, there is no room left for other utilities, thus we decrease the reservoir volume by two thirds, to $V_{re} := 0.5 \text{ cc}$.

We now calculate a new nominal fill pressure of $P_f(V_{re}) = 3.27 \text{ atm}$ and plot the layer thickness vs. control temperature for the same. To get a feel for the fill pressure sensitivity we also calculate additional fill pressures at plus/minus one atmosphere from nominal fill pressure.



The nominal layer thickness achieved at the design temperature of $T_r = 75\text{K}$ varies from about $43 \mu\text{m}$ at an initial fill pressure of 2.27 atm, to $120 \mu\text{m}$ when the initial fill pressure increases to 4.27 atm. This would be sufficient to accommodate a wide range of targets, while keeping the room temperature fill pressure very low. Of course, we can decrease the size of the reservoir volume further, but this will require proportionately higher pressures and will make it necessary to reduce the nominal reservoir volume operating temperature to retain the same control sensitivity.

Calculating the layer thickness dependence on the initial fill pressure dL_{thk}/dP_f and evaluating it for, $T_r = 75\text{K}$, $V_{re} = 0.5\text{mL}$, and $P_f(V_{re}) = 3.27\text{atm}$ to obtain

$$\frac{V_{re} \cdot \rho_s}{R_o \cdot T_f \cdot \pi \cdot 4 \cdot \left[r_c^3 - \frac{3}{4} \cdot V_{re} \cdot \rho_s \cdot \frac{(-P_r \cdot T_f + P_f(V_{re}) \cdot T_r)}{R_o \cdot T_r \cdot T_f \cdot \pi} \right]^{\frac{2}{3}}} = 37.96 \frac{\mu\text{m}}{\text{atm}} \quad (7)$$

This high sensitivity to fill pressure will allow us to use a single reservoir design to field targets with a wide range of layer thickness. Preset of the individual target layer thickness control range at the nominal reservoir operating temperature would be determined by the room temperature reservoir fill pressure. Actual layer thickness would still be controlled using the reservoir temperature control

during the capsule fill process. Once the hohlraum assembly is filled to the appropriate pressure in a room temperature fill station, the line connecting the reservoir volume to the fill station will be sealed. To eliminate the need for a bulky valve at the target base, this seal would be made either with a crimping tool^g, or with an ultrasonic tube sealer^h. The target assembly would then be ready for use. A secondary containment vessel will be required during transport to prevent accidental release of DT, and to provide protection for the fragile target assembly. It would then be transported to the target chamber area and attached to an insertion cryostat (still at room temperature) for layering.

Capsule fill procedure

After the target is installed and the cryostat is made ready, cooling would be started. The temperature of the whole assembly would be allowed to cool until the reservoir volume reached the intended capsule fill temperature $T_c = 20.29\text{K}$. At this temperature, the DT vapor would not start condensing yet, because the reservoir volume pressure $P_{f0}(T_c) = 168.25\text{torr}$ is still below the saturated vapor pressure $svP(\text{DT}, T_c) = 185.71\text{torr}$ of the DT at the capsule temperature. At this time, we slowly start increasing the temperature of the reservoir volume; the gas inside it will expand and start flowing into the fill tube towards the capsule. When the overall pressure exceeds the saturated vapor pressure of DT gas at the capsule / hohlraum temperature, the gas will start condensing and liquid will start accumulating. The first cold area that will be exposed to the flowing gas will be the fill tube junction at the hohlraum wall, therefore it is expected that for slow gas flows condensation will occur at this junction. A reasonable method to fill the capsule would be to maintain constant mass flow rate through the fill tube. This method will insure that the fill time is minimized once the maximum practical fill rate is determined experimentally. Assuming that a reasonable capsule fill time of $t_{fill} := 60\text{-min}$ can be achieved, a vapor flow rate of Q_v will be required to flow through the $r_{ft} = 20\mu\text{m}$ radius fill tube spanning the distance from the control volume to the hohlraum wall.

$$Q_v := \frac{V_f \cdot \text{AtWt}_{DT}}{\rho_s \cdot t_{fill}} \quad Q_v = 3.91 \frac{\mu\text{g}}{\text{min}} \quad (8)$$

where the variable $\text{AtWt}_{DT} = 5.03 \frac{\text{gm}}{\text{mole}}$ is the atomic weight of DT. To insure constant mass flow, the flow velocity must increase to compensate for the decrease in reservoir volume gas density as fuel condenses and flows into the capsule. The reservoir volume gas density as a function of fill time will be,

$$\rho_{\text{reservoir}}(t_{fill}) := \frac{\frac{P_f(V_{re})}{T_f} \cdot \frac{V_{re} \cdot \text{AtWt}_{DT}}{R_o} - \int_0^{t_{fill}} Q_v dt}{V_{re}} \quad (9)$$

And the gas flow velocity calculated assuming laminar flow is

$$\text{Vel}_{ft}(t) := \frac{Q_v}{\pi \cdot r_{ft}^2 \cdot \rho_{\text{reservoir}}(t)} \quad (10)$$

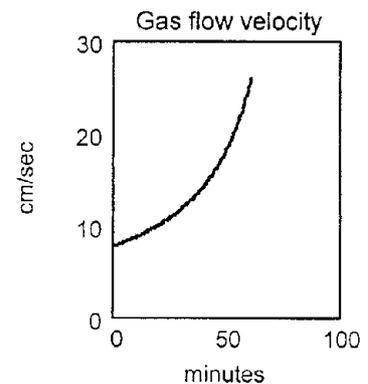
Maximum flow velocity will be achieved when the gas density is lowest towards the end of the fill cycle when the reservoir temperature is highest, thus $\text{Vel}_{ft}(t_{fill}) = 25.96 \frac{\text{cm}}{\text{s}}$.

We next check the vapor flow Reynolds's number

$$\text{Re}_v = \frac{V \cdot d}{\nu_v} \text{ to see if our laminar flow assumption is correct,}$$

where V is the fluid velocity, ν_v is the dynamic viscosity μ/ρ for the vapor at the reservoir temperature T_{re} and d is the fill tube diameter. Substituting the appropriate values and simplifying, we obtain

$$\text{Re}_v(T) := \frac{2 \cdot Q_v}{\pi \cdot r_{ft} \cdot \mu_{dt}(T)} \quad (12)$$



The vapor flow Reynolds' number is $Re_v(20\cdot K) = 1.44$ and $Re_v(100\cdot K) = 0.32$ which indicates that the flow through the fill line will indeed be laminar in the range of interest. Now, assuming that all condensation takes place in the fill tube at the hohlraum junction, we will have to remove the heat of condensation $H_v := 1360\cdot\text{joule}\cdot\text{mole}^{-1}$, as well as the enthalpy from 100 K to 20 K (worst case), and the rotational energy $Rot := 730\cdot\text{J}\cdot\text{mol}^{-1}$ at 100 K. This will be a maximum towards the end of the fill when the reservoir temperature is highest

$$\frac{Q_v \left(H_v + \frac{3}{2} \cdot R_0 \cdot 100 \cdot K + Rot \right)}{AtWt_{DT}} = 43.23 \mu\text{W} \quad (13)$$

This heat flux into the hohlraum wall will be easily handled without changing the local temperature profile of the hohlraum wall by more than a few milikelvin. After the vapor condenses at the hohlraum wall junction, the liquid will flow through the small $r_{tip} = 3 \mu\text{m}$ capillary tip into the capsule. The liquid mass flow rate will be the same as the gas flow rate $Q_l := Q_v$, and its flow velocity will be:

$$Vel_{tip} := \frac{Q_l}{\pi r_{tip}^2 \cdot \rho_L(DT, 20\cdot K)} \quad Vel_{tip} = 10.38 \frac{\text{mm}}{\text{s}} \quad (14)$$

At this velocity, one might expect a jet of liquid hydrogen to form at the exit of the fill tube and splash on the opposite side of the capsule during the fill process. The Reynolds's number for the liquid flow will be

$$Re_l := \frac{Vel_{tip} \cdot 2 \cdot r_{tip}}{v_l(DT, T_c)} \quad Re_l = 0.29 \quad (15)$$

which is also in the laminar flow region and indicates that our initial assumptions are conservative. The pressure drop for the vapor flow across the $L_{ft} = 10\text{cm}$ long, $r_{ft} = 20 \mu\text{m}$ radius fill line will be,

$$\Delta P_V(T_r, t_f) := \frac{32 \cdot \mu_{dt}(T_r) \cdot L_{ft} \cdot \text{Vel}_{ft}(t_f)}{(2r_{ft})^2} \quad \Delta P_V(T_r, t_{fill}) = 19.6 \text{ torr} \quad (16)$$

which is manageable, but a significant addition to the saturated vapor pressure of the fuel during liquefaction. The pressure drop across the fill tube tip $L_{tip} = 3 \text{ mm}$ long and $r_{tip} = 3 \mu\text{m}$ radius from the hohlraum to the capsule will be essentially constant throughout the fill process since the hohlraum and hence the capsule temperature will remain constant.

$$\Delta P_I := \frac{32 \cdot \mu_I(DT, T_c) \cdot L_{tip} \cdot \text{Vel}_{tip}}{(2r_{tip})^2} \quad \Delta P_I = 9.81 \text{ torr} \quad (17)$$

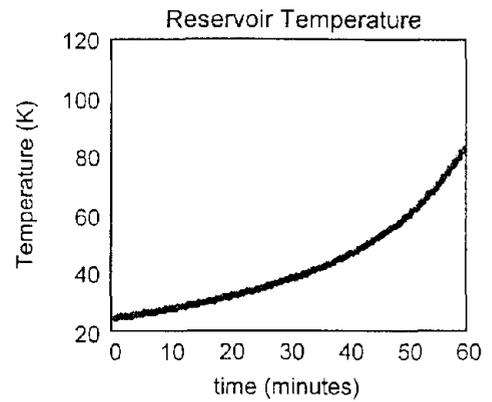
The calculated pressure drop for the tip flow appears low and one may be tempted to consider reducing the tip diameter further. However, for these calculations, it is assumed that the fill tube will remain unobstructed during the duration of the fill process. A further reduction in the tip's effective diameter will have the effect of severely reducing its flow for a fixed pressure head. As previously noted, starting the fill process with a cold reservoir volume $T_r \sim 20.3 \text{ K}$ will help reduce the vapor pressure of potential contaminants N_2 , O_2 that may freeze and obstruct the tip during the fill. For constant laminar flow rate, the pressure head will increase inversely proportional to the fourth power of the effective tip diameter. Since we have limited pressurization capabilities, reduced effective tip diameters will quickly translate into much longer fill times with the attendant increase in the risk of plugging.

Now the combined pressure head must be equal to the pressure of the reservoir vessel during the fill process. Our initial assumption that the reservoir pressure would be equal to the saturated vapor pressure of the fuel would allow the fuel fill to reach its intended level asymptotically. Since we would like the fill process to be completed in a specified amount of time, we will have to account for the additional pressure drops induced by the fluid flow through the connecting conduits. The total pressure head will be

$$P_{head}(T_r) := \text{svP}(DT, T_c) + \Delta P_I + \Delta P_V\left(\frac{T_r + T_c}{2}, t_{fill}\right) \quad P_{head}(T_r) = 208.44 \text{ torr} \quad (18)$$

The required reservoir temperature can now be determined, however since the temperature dependence of the fuel viscosity is interpolated, the temperature solution must be obtained numerically. For any given time up to the maximum fill time, $t_{\text{fill}} = 60 \text{ min}$ a reservoir temperature is calculated. Once the elapsed fill time reaches its maximum, the fuel fill is completed but not yet stable. To prevent gross overfilling the capsule, the reservoir temperature must be quickly re-set to the value calculated for the initial static conditions $T_r = 75 \text{ K}$ and allowed to stabilize for a some time before proceeding. After the fill level stabilizes (this should be only a function of system temperature stability), the temperature of the hohlraum will be lowered slowly below the triple point of DT to plug the fill tube and start the on to the fuel layering phase.

A certain amount of overfill may be desirable to allow the extraction from the capsule of non-condensable gas (He^3) that may have accumulated during the fill process. It should be feasible to expel some of the accumulated He^3 as the reservoir vessel cools and the pressure gradient on the fill line reverses, provided that the fill line is located at the top of the capsule during the fill procedure. However, it is not clear what effect the high surface tension of the liquid fuel will have on this process. Confirmation of this possibility will come from actual experiments with DT fuel.



The He^3 problem

Aging of DT in the control volume may inhibit the capsule pressurization when the He^3 partial pressure becomes higher than the partial pressure of DT at the capsule fill temperature of $T_c = 20.29 \text{ K}$. The He^3 gas will not condense at the capsule fill temperature, thus as the mixed gas reaches the cold fill tube section near the hohlraum wall, the DT gas condenses within the fill tube increasing the He^3 concentration near the condensation point. This process will continue until the Helium concentration is high enough to slow the mixed gas flow by forcing the DT gas to diffuse through, or if the pressure is high enough, force a bubble of He^3 gas through the small fill tube along with the liquid into the capsule. Assuming that the He^3 cannot be removed from the capsule once it goes in, we can estimate the static pressure increase necessary to compensate for the He^3 pressure build-up. The quantity of DT required for the proposed reservoir parameters will be

$$n_{\text{DT}} := \left(\frac{P_f(V_{\text{re}}) \cdot V_{\text{re}}}{T_f R_0} \right) \quad (19)$$

The total mass of DT in the target assembly is $n_{DT} \cdot AtWt_{DT} = 0.33 \text{ mg}$ and with decay constant of $\lambda_T := 1.782 \cdot 10^{-9} \cdot \text{Bq}$ the He^3 partial pressure in the reservoir vessel will increase at a rate of

$$P_{r\text{He}3} := n_{DT} \cdot \lambda_T \cdot \left(\frac{T_f \cdot R_o}{V_{re}} \right) \quad P_{r\text{He}3} = 0.38 \frac{\text{torr}}{\text{day}}$$

The pressure increase within the capsule will be faster due to its smaller volume relative to the DT quantity within the solid layer, but still small enough to be manageable with a small additional increase in the reservoir temperature.

$$P_{c\text{He}3} := \frac{V_I}{\rho_s} \cdot \lambda_T \cdot \left(\frac{T_c \cdot R_o}{V_c - V_I} \right) \quad P_{c\text{He}3} = 2.79 \frac{\text{torr}}{\text{day}}$$

With this rate of pressure increase, it will take

$$\frac{svP(DT, T_c)}{P_{c\text{He}3}} = 66.67 \text{ days}$$

to match the saturated vapor pressure of DT at the triple point. Thus, we will have about a month to perform experiments with the assembly before the He^3 partial pressure in the target capsule becomes too high for the fuel fill to proceed to completion. Although it would be many days before the He^3 partial pressure build-up becomes high enough to interfere with the fill process, the implosion requirements put a much more severe constraint on the He^3 density that can be allowed to accumulate. The target specifications require that the He^3 density at shot time be below 0.05 mg/cc . Once the fill is completed and the fill tube is filled with ice, the rate of

He^3 increase for an 80 micron layer will be $\frac{V_I}{\rho_s} \cdot \lambda_T \cdot \frac{AtWt_{\text{He}3}}{V_c - V_I} = 6.64 \frac{\mu\text{g}}{\text{cc} \cdot \text{day}}$, which will achieve

the maximum density in about 7.5 days from the day the reservoir vessel was filled. This calculation presumes that the He^3 gas produced while in the reservoir vessel will be trapped by the fast fill flows and forced into the capsule during the fill procedure. It may be possible, that after the fill process is completed and the pressure within the capsule and the reservoir vessel equalize, that the partial pressure of He^3 will also equalize. If this can be achieved, then the He^3 density inside the capsule will be determined by the He^3 density within the much larger volume of the reservoir vessel. This will have the effect of decreasing the effective He^3 density before freezing by the ratio of their respective volumes,

$$\frac{V_{re}}{V_c - V_l} = 153$$

and allow the target assembly to remain viable for a considerably longer time. The flow impedance of the tip section of the fill tube to the He³ gas flow will increase the pressure drop required to fill the capsule. After an aging period of $t_{age} := 30 \cdot \text{days}$, the amount of evolved He³ will have increased to $n_{DT} \cdot \lambda_T \cdot \text{AtWt}_{He3} \cdot t_{age} = 0.93 \mu\text{g}$, of which we will have the following amount flow through the fill tube on its way to the capsule during the fill time $t_{fill} = 1 \text{ hr}$.

$$Q_{He} := \frac{V_l \cdot (\lambda_T \cdot \text{AtWt}_{He3} \cdot t_{age})}{\rho_s \cdot t_{fill}} \quad Q_{He} = 0.65 \frac{\mu\text{g}}{\text{hr}} \quad (20)$$

The He³ pressure drop may be calculated separately, because He³ will flow as a gas (in the form of bubbles) at the fill line tip where it is expected that the hydrogen fuel will be flowing as a liquid. The flow velocity for the He³ will be

$$V_{He} := \frac{Q_{He}}{\pi \cdot r_{tip}^2 \cdot He_{\rho}(T_c, P_f(V_{re}))} \quad V_{He} = 0.83 \frac{\text{mm}}{\text{s}} \quad (21)$$

and the pressure drop will be

$$\Delta P_{He} := \frac{32 \cdot \mu_{He}(T_c) \cdot L_{tip} \cdot V_{He}}{(2r_{tip})^2} \quad \Delta P_{He} = 0.06 \text{ torr} \quad (22)$$

which should not present a problem even after several months of aging.

Contamination Issues

The use of tritium in any experiment always entails some risk of accidental contamination, and the best way to reduce the contamination potential is to reduce the amount of tritium at risk. The total amount of DT fuel within the whole assembly for making an 80 μm fuel layer would be $n_{\text{DT}} \cdot \text{AtWt}_{\text{DT}} = 0.33 \text{ mg}$, and this would increase to approximately 0.39 mg for a layer thickness of 100 μm thick. About two thirds of the DT fuel would be condensed within the capsule to form the fuel layer while the rest remains within the reservoir vessel. The total activity for the quantity of tritium required to make a 80 μm layer will be $\lambda_{\text{T}} \cdot N_{\text{A}} \cdot n_{\text{DT}} = 1.93 \text{ Ci}$, which is a very small quantity of DT at risk. The whole assembly would be enclosed within a secondary containment vessel during transport or storage, to insure that no tritium will be released in case of a component failure, or via slow diffusion thru the capsule walls (in the case of plastic capsules).

The permeability of polyimide to deuterium at room temperature is $k_{\text{PI}} := 4.4 \cdot 10^{-16} \frac{\text{mole} \cdot \text{m}}{\text{Pa} \cdot \text{sec} \cdot \text{m}^2}$,

thus for a capsule attached to a much larger reservoir we would have an initial leak rate of

$$k_{\text{PI}} \cdot \frac{4 \cdot \pi \cdot r_{\text{c}}^2}{160 \cdot \mu\text{m}} \cdot P_{\text{f}}(V_{\text{re}}) \cdot \text{AtWt}_{\text{DT}} = 4.98 \frac{\mu\text{g}}{\text{day}}$$

which is rather large. An external PVA coating may be used to lower the permeation rate, but with a hydrogen permeability of around 10^{-18} and a coating thickness of 2 - 4 microns, it will only decrease the leak rate by a factor of 2 to 3, assuming that the coating is uniform (not quite there yet). A more promising technology will be to use a sputter coated glass SiO_2 layer, which has a much lower $\sim 10^{-20}$ hydrogen permeability than PVA, however we will have to test the viability of this coating at cryogenic temperatures.

Conclusion

This memo describes a viable conceptual design for a low pressure, self contained fill system that may be suitable for ignition target capsules. This design offers an alternative to conventional diffusion filled designs, which require cryogenic transport. Specific features of this design which may provide some advantages over the diffusion fill system are (1) a low pressure fill requirement, (2) room temperature handling and transport capability, (3) minimal tritium exposure of hohlraum components during and after the fuel fill procedure, and (4) flexibility to accommodate different fuel layer thickness with a single target fuel reservoir design. The potential disadvantages of this design are (1) the need to have a small fill tube permanently attached to the capsule, and (2) its impact on the capsule ignition symmetry. Also, the small fill tubes make the target assembly (3) fragile and (4) more difficult to fabricate.

Other application areas may also benefit from the compact, self-contained design. Experiments requiring the use of DT could be executed in areas where conventional fill systems with their much larger amounts of "at risk DT" would not be acceptable.

^a J. Sanchez and S. Letts, Polyimide Capsules may Hold High Pressure DT Fuel without Cryogenic Support for the National Ignition Facility Indirect Drive Targets. *Fusion Technology* Vol. 31, July 1997, p 491

^b Sater, et al, D2 test system results (to be published)

^c Margevicius, RW, et. al., *FUSION TECHNOLOGY*; MAR 1999; v.35, no.2, p.106-114

^d Cook, Robert; Surface perturbation caused by melt sealing drilled Be capsules, TAT memo Nov. 20, 2002

^e Steve Haan, WBS4 Review, May 2002

^f RESONETICS *Inc.* www.resonetics.com

^g Commercially available crimp tool, CHA Industries, model CRP-375

^h Ultrasonic tube sealer, American Technology Inc., Ultraseal 20