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# Stability Time of a DT-filled Cryogenic ICF Target in a High Vacuum Environment

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## **Abstract:**

Following the successful pressure loading with DT of a thin-walled plastic inertial fusion target shell (such as those designed for use at the OMEGA facility at the University of Rochester's Laboratory for Laser Energetics (UR/LLE)), continual care must be taken to safeguard the shell from being exposed to unacceptable pressure differentials across its wall. In particular, once the DT has been condensed into a liquid or solid phase and the outside pressure has been reduced, the target must be maintained below some upper cutoff temperature such that the vapor pressure of the DT is below the bursting pressure for the shell. Through the process of  $\beta$ -decay the DT self-heats, but while the shell is in a high vacuum environment ( $P \ll 0.8$  Pa (6 mtorr) for the OMEGA layering sphere) there is only a negligible heat loss mechanism. This will cause the temperature to increase. A calculation has been done to estimate the rate of temperature increase of the loaded target under high vacuum conditions. A functional form for calculating the target's temperature increase given its starting temperature is presented. An overall result is that under high vacuum conditions the DT changes from a solid at 10 K to a liquid at 37 K ( $T_c=39.4$  K) in about 19 minutes. This "holding time" is significantly less if the initial temperature is higher, the initial state is liquid, or the upper allowed temperature is lower. Simplifying assumptions which were made and their impact on interpreting the results of this calculation are discussed.

## 1. Introduction and Initial Assumptions

The success of inertial confinement fusion (ICF) experiments depends on, among other things, the ability to produce target shells conforming to a number of demanding standards. In general, all target designs consist of a spherical shell of solid (cryogenic) DT (a deuterium-tritium mixture) contained within a spherical metal or plastic shell. The amount of DT necessary corresponds to extremely high pressures in the containing target shell when the DT is in the gaseous state at room temperatures. Some of the plastic shells are not strong enough to hold these high pressures, requiring the development of permeation loading and handling schemes in which the filled target shell is protected from dangerous pressure differentials across its wall by maintaining the exterior pressure comparable to the interior pressure while the DT is being frozen. The calculation presented here is concerned with what happens after a DT filled target is successfully cooled: because the DT is self-heated due to the thermal energy released as tritium undergoes beta decay, there must be a continual strong cooling link to the rest of the cryostat to maintain a constant temperature. If the cooling link is removed (e.g. exchange gas is pumped away or a mechanical link is opened) there is a risk that the target shell could self-heat to a temperature at which the internal vapor pressure will cause a failure. We have calculated the rate of temperature increase with time for a target shell with only a negligible cooling link to the rest of the cryostat. While we consider a target shell designed for the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics (UR/LLE) as a specific example, the basic calculation is generalized to obtain a result that will be applicable to DT filled target shells of any design including those for the National Ignition Facility (NIF).

After an OMEGA target shell has been permeation loaded, the initial pressure inside the shell will be high but the pressure outside will also be high, preventing the shell from rupturing. As the permeation cell is cooled, these pressures both decrease as the DT first cools and then condenses. The target is cooled via the DT vapor during this initial cooling. Later, during the beta-layering phase, the target is cooled by  $^4\text{He}$  exchange gas. During the period between these two times, when the excess DT is pumped away before being replaced by  $^4\text{He}$  exchange gas, special attention must be taken to prevent the target from warming to a temperature above some upper temperature bound ( $T_{UB}$ ) at which the saturated vapor pressure of the DT in the target shell is great enough to rupture the shell. The exact value of  $T_{UB}$  will be determined by the strength of the target shell and the vapor pressure curve of condensed DT, but recent data can give an approximate range of values. In experiments at General Atomics, shells

filled (with  $D_2$ ) at room temperature under 16,000 psi were cooled, removed from the pressure cell, then warmed up and allowed to burst. Shells with the thickest walls ( $\sim 10 \mu\text{m}$ ) failed in the range of 49-54 K while the shells with the thinnest walls ( $\sim 3.3 \mu\text{m}$ ) failed in the range of 35-41 K [General Atomics]. The actual OMEGA target shells may be loaded under a higher pressure ( $\approx 20,000$  psi). We note that the estimates for critical temperature and critical pressure of DT are 39.42 K and 1.773 MPa (17.5 Atm.) [Souers p.3].

During the removal of excess DT and perhaps at other stages in the handling of the OMEGA targets (e.g. transfer to the moving cryostat), they will be in an enclosure which is evacuated, possibly to a high vacuum. During these operations, even though all of the surfaces surrounding the shell may be well below  $T_{UB}$ , care must be taken to avoid a catastrophic warmup. Under the assumption that the target mounting components present only a negligible thermal link, the only heat loss mechanisms available for dissipating this power are radiation and conduction through the surrounding vapor. For  $^4\text{He}$  at 20 K, the mean free path is comparable to the radius of the layering sphere (1.27 cm) at a pressure of 0.8 Pa (6 mtorr). This pressure nominally is the pressure at which the conductivity of the exchange gas begins to fall as pressure is further reduced, thus for  $P \ll 0.8$  Pa we make the assumption that the conductivity of the gas is negligible. In considering radiation as a possible mechanism for dissipating the heat produced by  $\beta$ -decay, we note that for a 100- $\mu\text{m}$  wall thickness of DT in an OMEGA target, the thermal power of the decay is approximately 13  $\mu\text{Watts}$  (the thermal power of DT is 0.977 Watts/mole) [Souers pp.206-208]. If we then assume an absolute extreme case emissivity of 1 for both the shell ( $R = 0.5$  mm) and its surroundings we find that for the extreme case of  $T_{\text{shell}} = 40$  K and  $T_{\text{surroundings}} = 10$  K the radiative heat transfer is about 0.4  $\mu\text{Watts}$ . This suggests that we may safely assume that in a case with a lower temperature differential and lower emissivities, the heat transfer via radiation will dissipate only a negligible fraction of the total heating power of the DT.

## **2. Calculation**

By totally neglecting heat dissipation through radiation and the residual exchange gas, we have simplified our model of the system. Even with these simplifications our calculations will have useful results: as discussed above, even a generous estimate of the total radiated power would represent less than a 5% correction to the thermal power input to the target shell and the contribution due to the vapor link can be made vanishingly small. Both of

these assumptions will give a more conservative result as the actual vapor and radiative thermal links will have the effect of slowing the rate of temperature increase of the DT.

We further assume that the heat capacity of the shell is negligible relative to that of the DT. One result of the combined assumptions is that we can do the calculation using the molar heat production due to  $\beta$ -decay and the molar specific heat of DT and arrive at results that are independent of the exact value of the DT filling of the shell. Hence these results will generally hold for any size shell (OMEGA, NIF,....) as long as the amount of DT is such that the heat generation is significantly larger than the amount of radiative transfer to the environment and the heat capacity is significantly larger than that of the enclosing shell. For thick walled shells, the likelihood of shell failure due to DT warming is expected to be much less. However, similar holdtime calculations which account for the shell's heat capacity may still be useful in developing handling procedures that maintain thick shells intact. In the following general derivation the neglected terms are presented in italics. The effects of these terms on the allowed holdtime have been evaluated for the specific case of an OMEGA target shell (with a 10  $\mu\text{m}$  shell wall, 100  $\mu\text{m}$ -thick DT shell, and 1 mm outer diameter) and will be discussed in Section 5.

The calculation is performed by setting the molar thermal power equal to the product of the molar specific heat and the time derivative of the temperature:

$$1. \quad \dot{Q} = c(T) \frac{dT}{dt} \quad (+ \text{vapor exchange term} + \text{shell heat capacity term})$$

This is then integrated to obtain the total time necessary for the temperature to increase from  $T_1$  to  $T_2$ :

$$2. \quad \int dt = \int_{T_1}^{T_2} \frac{c(T)}{\dot{Q}} dT \quad (+ \text{vapor exchange term} + \text{shell heat capacity term})$$

This integral is done separately for both the saturated solid and saturated liquid temperature regimes. At the triple point,  $T_t$  (19.79 K)[Souers p.3], the sample temperature will remain fixed for the time necessary for the solid phase to melt entirely. That time is expressed as:

$$3. \quad t_{\text{melt}} = \frac{L}{\dot{Q}} \quad (+ \text{vapor correction term}) = 223 \text{ seconds}$$

where  $L$  is the molar heat of fusion and  $\dot{Q}$  is the molar thermal power. It should be noted that the melting time expressed in the form of Equation 3 is calculated for an isothermal process and hence is completely independent of the heat capacity of the target shell. This form fails to be exact in that it treats all of the DT as being initially solid whereas there is a non-zero vapor pressure. At the triple point, the density of the solid is 400 times the vapor density [Souers pp.57,80]. Thus if the vapor volume is comparable to or less than the solid volume the form of Equation 3 is a good approximation (for the shell described in section 1 the vapor will pose a ~0.2% correction to the heating power). The form of Equation 3 also ignores the fact that the ternary DT mixture does not have a true 'triple point', but a finite width melting region.

The 'hold time' of a DT sample under high vacuum is then estimated by evaluating Equation 2 using the liquid specific heat from the initial temperature to  $T_{UB}$  if the initial temperature is greater than  $T_t$ . If the initial temperature is less than  $T_t$ , the evaluation of Equation 2 using the solid specific heat from the initial temperature to  $T_t$  and  $t_{melt}$  must be added to the evaluation of Equation 2 using the liquid specific heat from  $T_t$  to  $T_{UB}$ .

### 3. Form of Specific Heat

The specific heat data that was used came from Souers [pp.68, 96]. The data is given there in tabular form for both the saturated solid and liquid phases. It should be noted that Souers designates all of the specific heat data for DT as being "estimated". In order to allow analytic integration we first fit the data to polynomial forms. The data, fits, and fit parameters are given in Figure 1.

### 4. Results

Equation (2) evaluated with the solid specific heat has the form;

$$4. \quad time = -0.98274T - 0.374918T^2 + 0.0472535T^3 - 0.00056T^4 \Big|_{T_1}^{T_2}$$

and evaluation with the liquid specific heat has the form;

$$5. \quad time = 223.729T - 15.8828T^2 + 0.636974T^3 - 0.0125179T^4 + 0.000100765T^5 \Big|_{T_1}^{T_2}$$



Since the polynomial fit for the solid specific heat did not take into account any data points below 10 K Equation 4 should not be used with  $T_1 < 10$  K.

To determine  $t_{\text{melt}}$ , we used the heat of fusion value for DT as tabulated by Souers [pp.112] to be 218 J/mol. The time for melting the solid at  $T_1$  is 223 seconds. The melting of a DT solid in an OMEGA target shell in a high vacuum was observed by Asaki and Hoffer [Asaki and Hoffer] to take "several minutes". This observed melting time was comparable to that predicted in this calculation, however, their target shell had an additional conductive heat link (a fill tube).

The minimum stable holdtime in high vacuum of a DT filled target shell can be estimated using Equations 4 and 5 with the procedure given in Section 2. In Figure 2 we have plotted temperature vs. time for a DT sample that starts as a solid at 10 K and ends as a liquid at 37 K. The total time for this process is seen to be about 19 minutes.

## 5. Refinements of Calculation

The calculation above resulted from several simplifications. We have argued that a number of terms would be negligible, these included effects due to: residual exchange gas conduction, radiative heat loss, the heat capacity of the plastic target shell, the latent heat necessary to convert the condensed phase into the vapor phase as the sample follows the two-phase coexistence curve upon warming, and the heat generated by the DT in the vapor phase at the triple point. The result of including any of these simplifications would be to affect the predicted system holdtime by only a few percent and for all but the last of these the result would be to *increase* the predicted system holdtime. For the specific case of a 100  $\mu\text{m}$  DT wall OMEGA shell, we have demonstrated in Section 1 that the radiative heat loss will only approach 3% of the self heating in the worst case situation. For the same cell specifications we will evaluate here the contributions of the terms neglected in the derivation of Section 2:

*Vapor exchange term* (solid to vapor,  $T < T_1$ ) This term represents the heat necessary to sublime some of the DT as the cell warms along the solid-vapor saturation curve from 10 K to  $T_1$ . To estimate the necessary sublimation density we assume that the vapor has zero density at 10 K relative to its density at  $T_1$  (this assumption is correct to 0.01%) and use the triple point vapor density, the heat of sublimation at the triple point (a slight overestimate at lower temps) [125 mol/m<sup>3</sup> and 1580 J/mol, Souers pp. 57,112] and the volume of the vapor space to

calculate the total heat necessary for sublimation. The total heat necessary is 53  $\mu\text{J}$ , which, with a heating power of 13  $\mu\text{W}$ , would add only 4 seconds to the holdtime.

*Vapor exchange term* (liquid to vapor,  $T > T_1$ ) This term represents the heat necessary to evaporate some of the DT as the cell warms along the DT liquid-vapor saturation curve. The total density of the DT charge in an Omega target is actually 1.4 times the density of the DT critical point. Therefore, at some point above 36 K but below  $T_c$ , the DT liquid falls off the saturation curve. We simplify by evaluating this term at 36 K, because that temperature is already in the range for which failure is likely. By applying the constraint that both the total number of moles of DT and the total volume remain constant, we used the vapor and liquid densities [Souers pp. 57,62] to calculate the decrease through evaporation in moles of liquid as the temperature increased from  $T_1$  to 36 K. The total energy necessary for this evaporation was then overestimated to be the product of total change in the amount of liquid and the latent heat of evaporation at the triple point (the location of the maximal value of this latent heat). The total heat necessary for evaporation is 1.02 mJ, which will add about 78 seconds to the holdtime.

*Vapor correction term* This term accounts for the fact that a finite amount of the DT is in the vapor phase when the sample reaches the triple point. The heating power available to melt the solid comes from all of the DT but the necessary latent heat is proportional only to the amount in the solid phase. For the geometry considered here 0.2% of the DT is in the vapor phase so that the available heating power per mole of DT is 1.002 times that used in the general calculation above. This "extra" heating will cause the solid DT to melt 0.5 seconds *faster*.

*Shell heat capacity term* This term represents the heat necessary to warm the plastic shell as it increases in temperature along with the DT. As with the DT, this heat is properly determined by integrating the temperature dependent heat capacity over the range of temperature increase. However, an upper bound may be simply determined by the product of the maximum heat capacity value attained at any of the temperatures spanned by the range (typically the warmest temperature) and the magnitude of the temperature range (i.e.  $Q = \Delta T \cdot C(T)_{\text{max}}$ ). Assuming a 10  $\mu\text{m}$  thick, 1 mm diameter spherical shell with a density of 0.2 g/cc [Gibson p.1] and the specific heat value for polystyrene at 40 K, [219 J/kg•K, Hartwig p. 254] we calculate that the heat necessary to warm the shell from 10 to 36 K is 18  $\mu\text{J}$ . The contribution of this term to the holdtime will be slightly more than one second.

In the case of an OMEGA target these evaluations indicate that inclusion of the neglected terms would only add about a minute and a half to the allowable high vacuum holdtime. Further they suggest that the general holdtime calculation performed above could be used as a reasonable first estimate for any target cell that has a similar geometry with similar ratios of DT solid volume to DT vapor volume and heat capacity of DT to heat capacity of target. These calculations also point out the relative importance of considering the latent heat as the liquid evaporates along the saturation curve. We have not treated the effects of residual exchange gas pressure but note that the addition of any other heat loss mechanism will increase the safe holdtimes above those calculated here. A detailed calculation of the power loss through the vapor should be performed before using any procedure that relies on the presence of a residual exchange gas to extend a safe holdtime.

## **6. Conclusions**

We have evaluated the self-heating of DT filled target shells in a high vacuum environment and have developed equations that may be used to estimate safe holdtimes. Several assumptions were input into our model, most of which have the result that the calculated safe holdtime is less than or equal to the actual value. The holdtimes of any experimental procedures that require the filled DT target to be in a high vacuum should be kept below the times estimated by this calculation. If any experimental procedures require holdtimes greater than those predicted by this calculation, then a full calculation that includes thermal radiation, shell heat capacity, and thermal conduction through residual vapor should be performed to determine the maximum holdtime allowed (*and thus whether or not the procedure will need to be modified*). This self-heating phenomena has been experimentally observed to occur at a time scale comparable to our predictions.

## **Acknowledgements**

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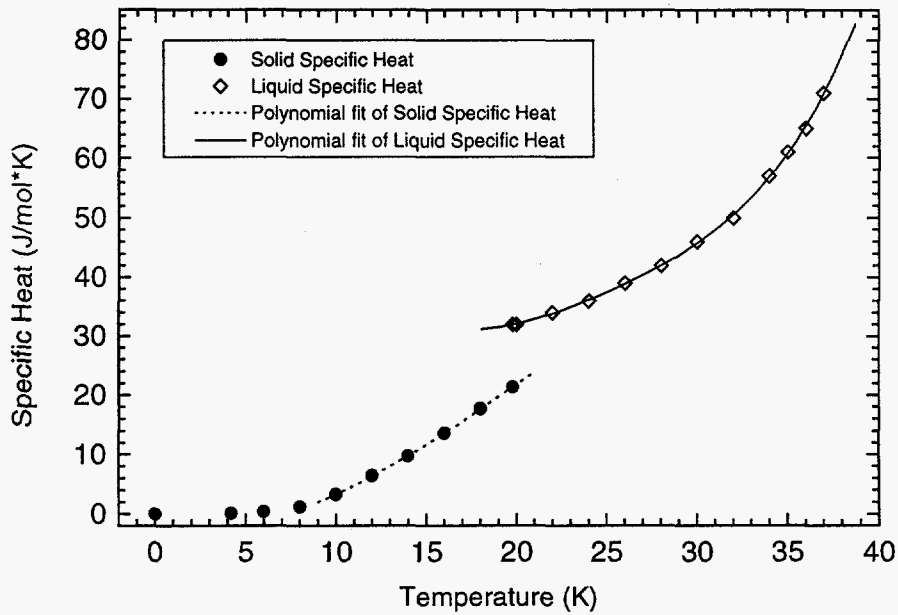
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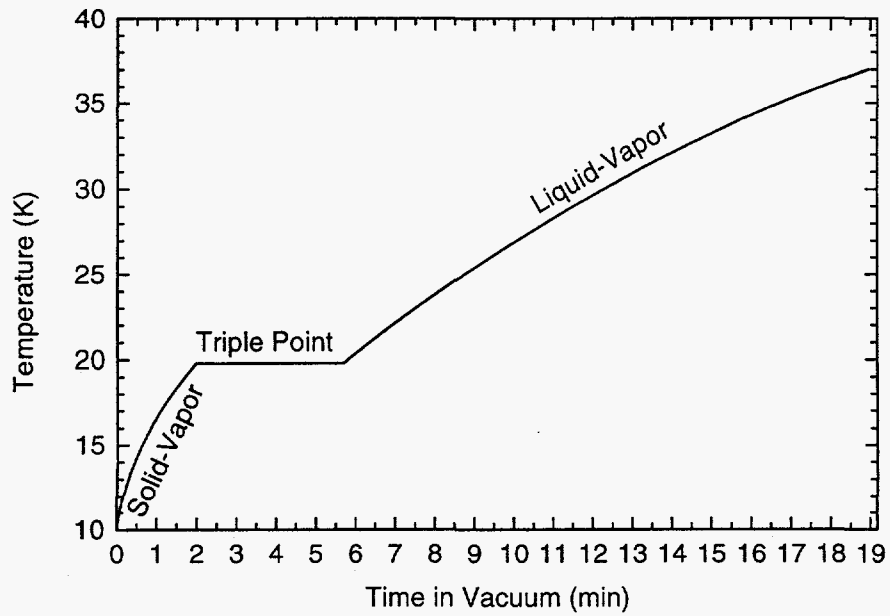
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**Fig. 1.** DT specific heat values (symbols) as tabulated by Souers, the polynomial fits used in this calculation are plotted as curves. The polynomial fits are  $c_s(T)=-0.96014-0.73259T+0.1385T^2-0.00224T^3$  (valid  $10 \text{ K} < T < T_i$ ) and  $c_l(T)=218.58335-31.03505T+1.86697T^2-0.04892T^3+0.000492237T^4$  (valid  $T_i < T < 37 \text{ K}$ ).



**Fig. 2.** Temperature increase with time for DT filled cryogenic ICF Target Shell calculated by the method outlined in Section 2. The regions of two and three phase coexistence that the DT passes through are labeled.