Heating and Thermal Response of Direct-Drive Target During Injection

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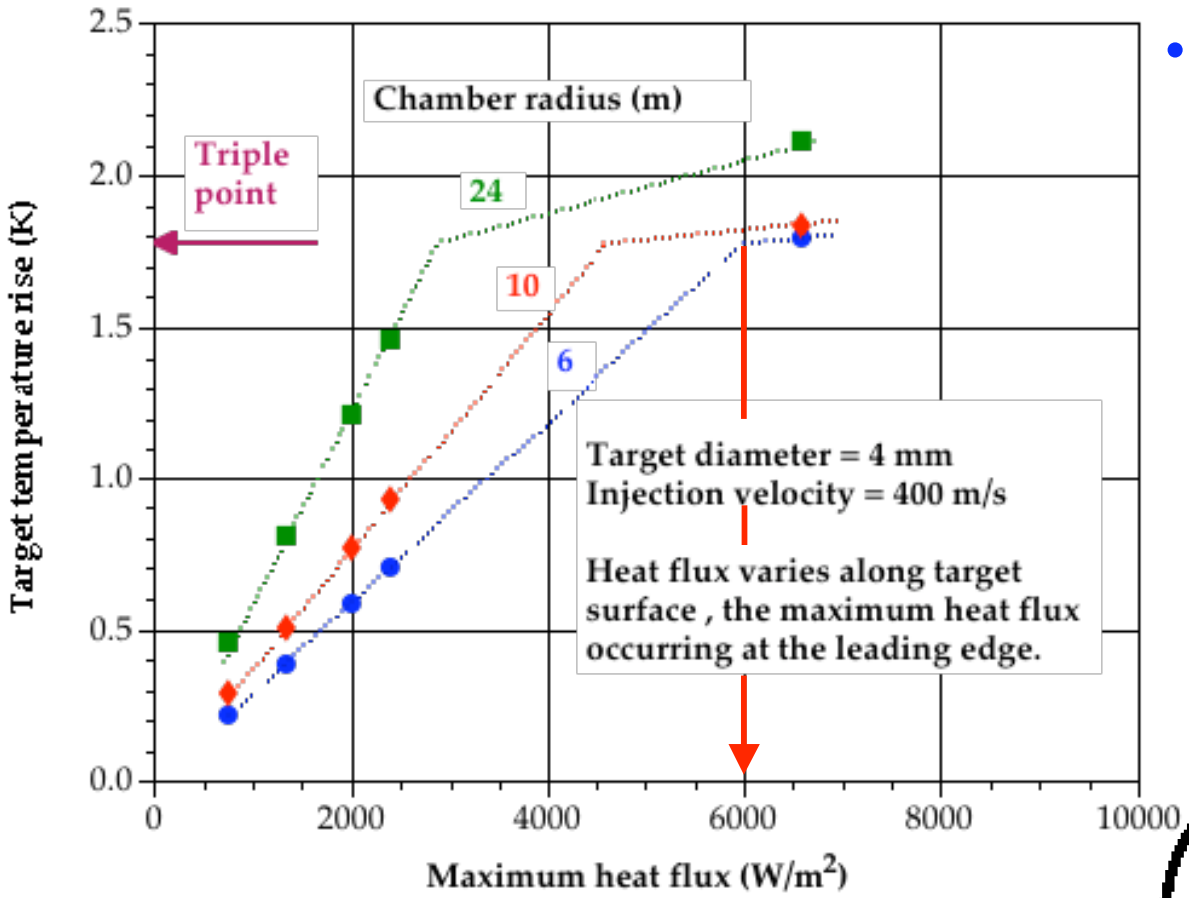
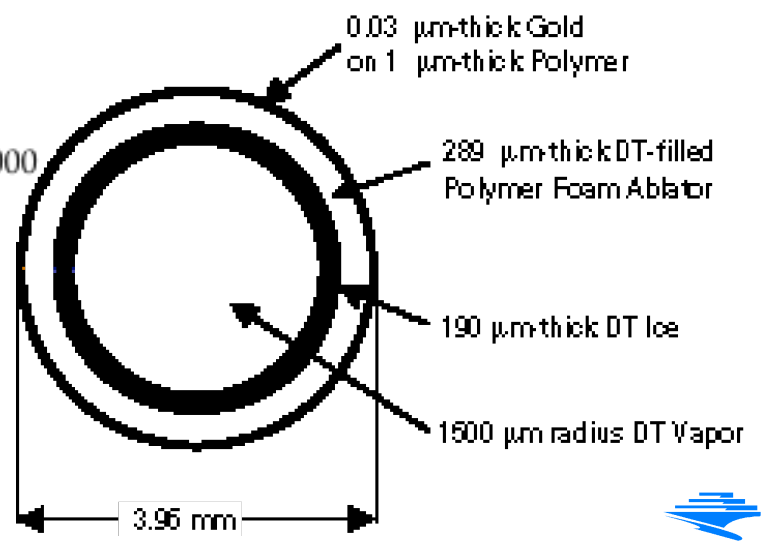
Previous Transient Thermal Analyses Have Shown Very Low Heat Flux Limits for Target Survival Based on Maintaining DT Below its Triple Point



- **Analysis using ANSYS**
  - **Target is not tumbling**
  - **2-D heat flux distribution from DSMC results**
  - **Temperature dependent DT properties including latent heat of fusion at triple point to model phase change**



- **Heat flux to reach triple point only ~ 6000 W/m^2 for a 6-m radius chamber**
- **Major limit on energy transfer from background gas and absorbed radiation from chamber wall**

Heat Loads on Target During Injection

1. Radiation Heat Transfer from Chamber Wall

2. Energy Exchange from Background Gas Needed for Chamber Wall Protection
   - Enthalpy transfer
   - Condensation (latent heat transfer) in the case of gas with boiling point and melting point above target temperature (18K) (e.g. for Xe)
   - Recombination of ions at the surface if plasma conditions remain in the chamber
     - Some uncertainty regarding plasma conditions during injection
     - Would substantially increase heat load on target
     - Not included in these initial calculations to see possibility of operating design window in the "best" of cases
     - Need to be considered in evolving final design and operating conditions

Highly Reflective Target Surface Needed to Minimize Total Absorbed Heat Flux from Chamber Wall

- **Simple estimate given by:**

$$q_{rad}'' = (1 - \rho)\sigma_{S-B} T_w^4$$

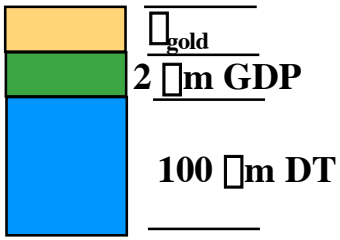
Where T_w is the wall temperature (assumed as a black body), σ_{S-B} is Stefan-Boltzmann constant, and ρ the target surface reflectivity.

- **For very thin (275–375 Å) gold coating, ρ ~96% was assumed**
- **A 1% change in reflectivity --> 25% change in absorbed heat flux**
- **As an illustration:**

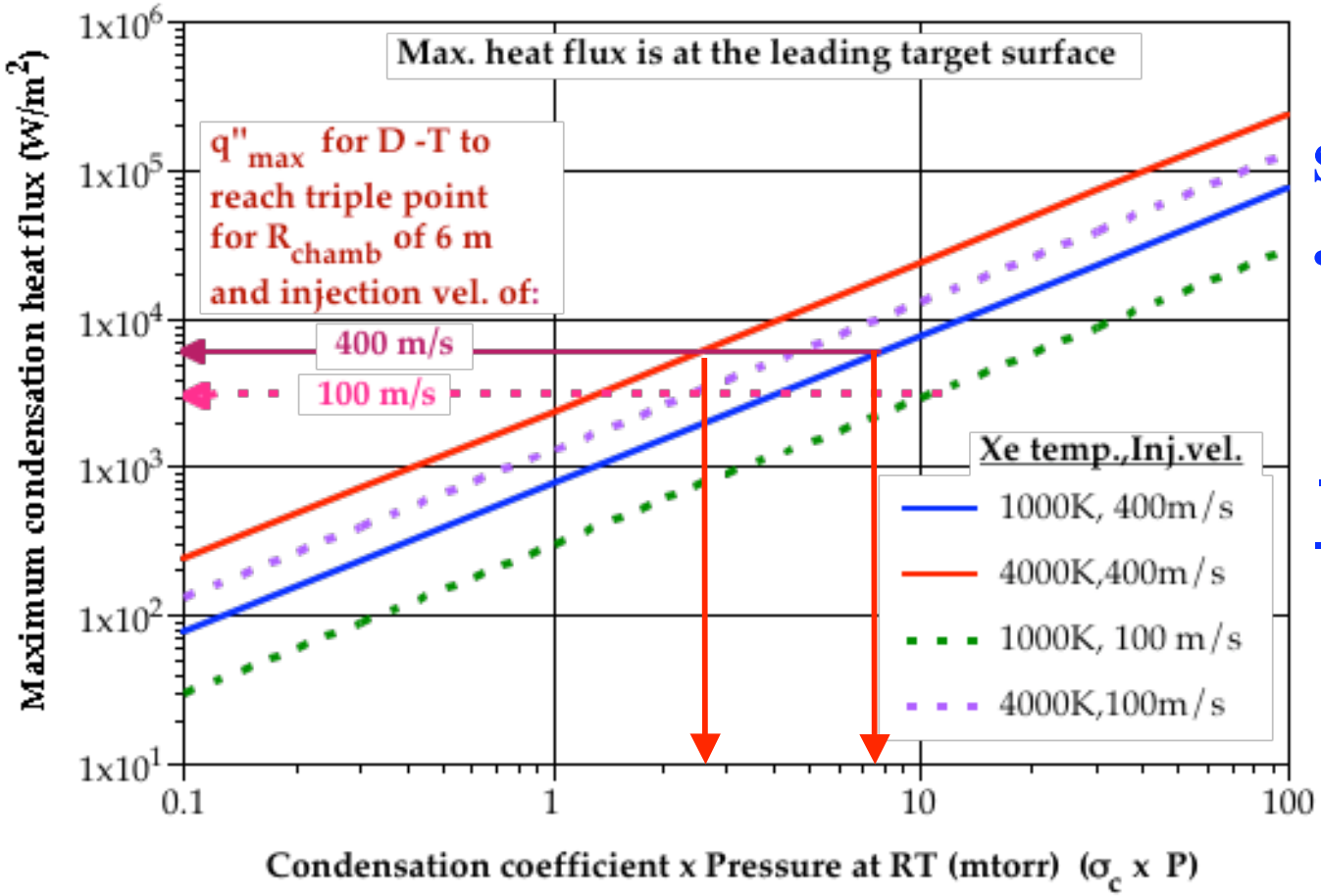
T_w(K):	1000	1275	1500
q_{rad}''(W/m^2):	2300	6000	11,500

- **Effort underway to estimate more accurately radiated energy absorption and reflection based on a multi-layer wave model**
- **Initial results based on spherical and wavelength averaging**

δ_{gold}(Å)	ρ
50	0.622
100	0.806
150	0.879
200	0.915
400	0.963
600	0.973
900	0.976



Condensation from Xe as Background Gas



Similar results for He

- **For 400 m/s injection velocity, q''= 6000 W/m^2 with only:**
  - **1mTorr/4000K He or**
  - **7mTorr/1000K He**

- **For an assumed condensation coefficient of ~1, q''= 6000 W/m^2 with only 2.5mTorr/4000K Xe or 7.5mTorr/1000K Xe for 400 m/s injection velocity**
  - **Minimal wall protection under these Xe densities**

How to Enhance Target Survival?

- **To provide a reasonable design window for gas protection and power core performance:**
  - **Gas pressure up to ~50 mTorr at 1000-4000 K (q_{cond}''= 4 -10 W/cm^2 for Xe)**
  - **Chamber wall temperature ~ 1000-1500 K (q_{rad}''~ 0.2 -1.2 W/cm^2)**
  - **Total q'' to be accommodated by target = 5 -11 W/cm^2 (compared to current case of ~0.6 W/cm^2)**
  - **Need means to increase thermal robustness of target**

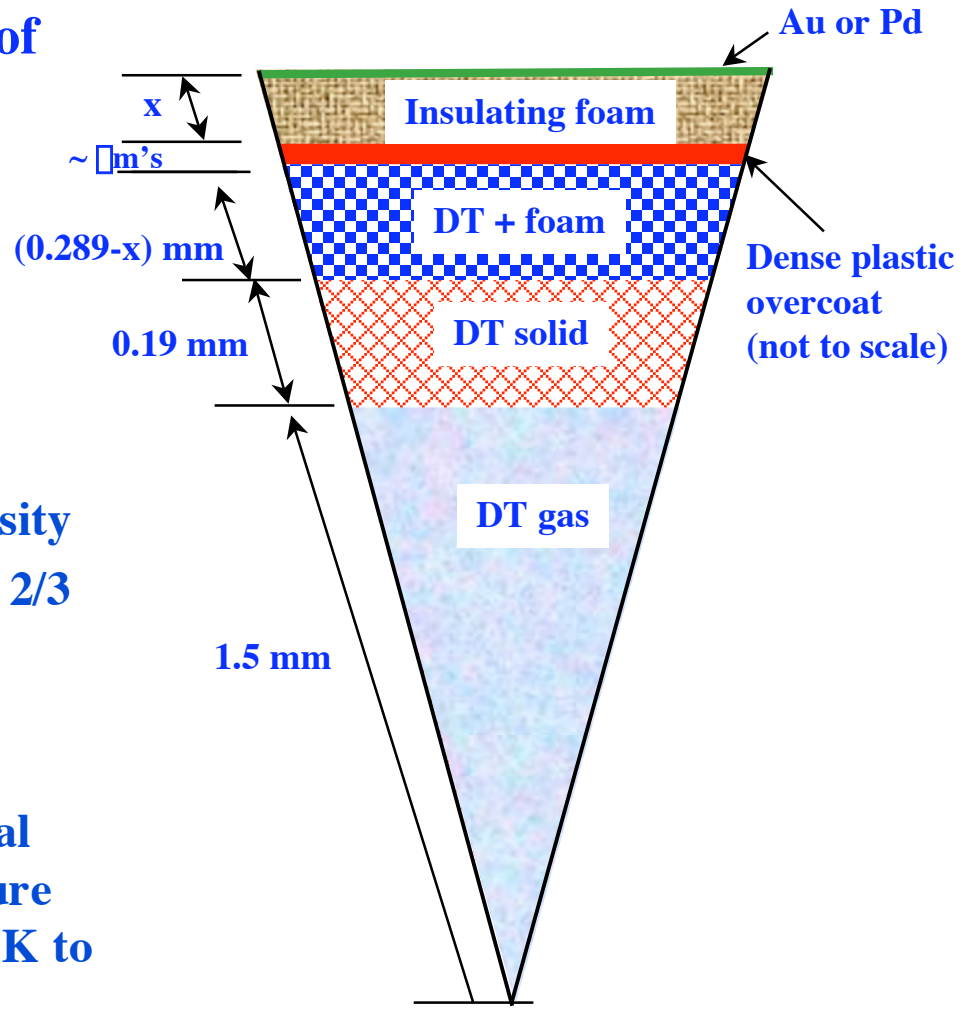
- **Two-prong approach:**
  1. **Design modification to create more thermally robust target**
  2. **Explore possibility of relaxing phase change constraint**

  - **Solution must accommodate target physics requirements as well as injected target integrity requirements**

Add Outer Insulating Foam Layer to Enhance Target Thermal Robustness

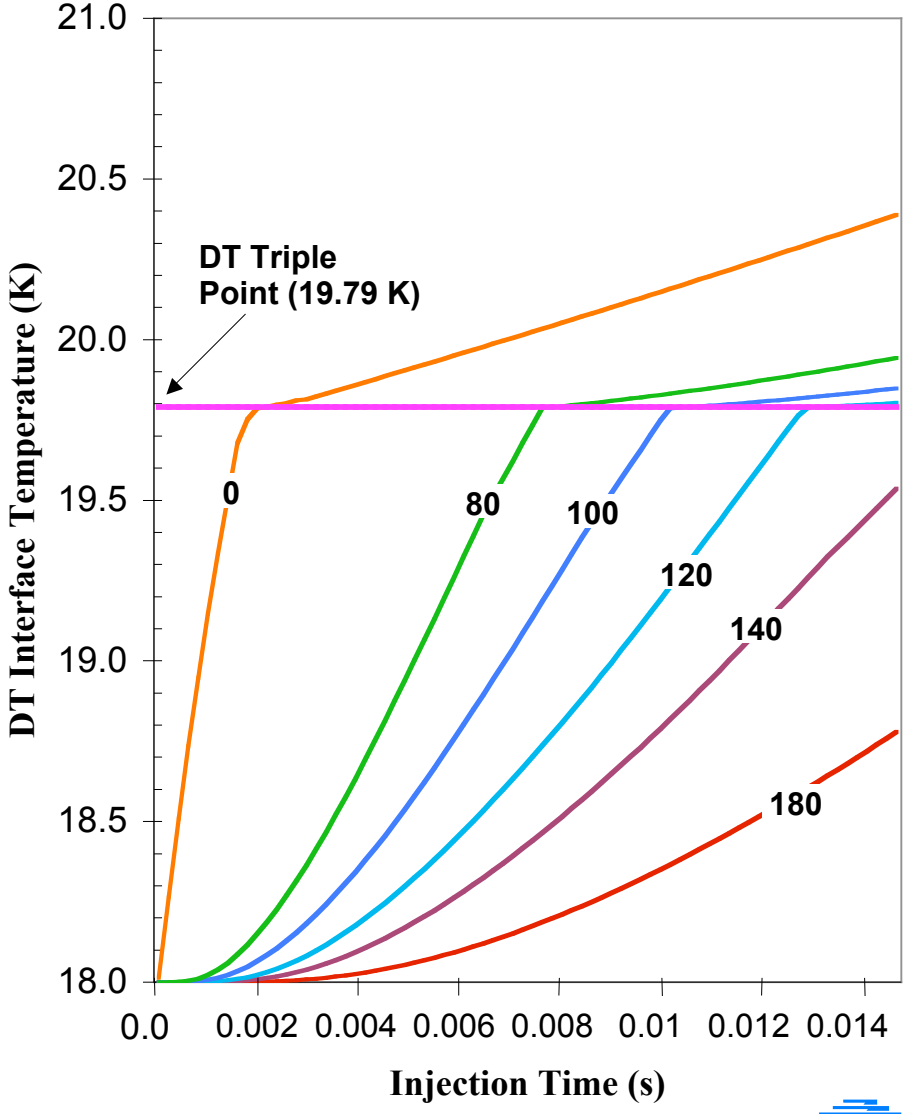
- **Simple assumption: adjust thickness of DT+foam layer accordingly to maintain same overall thickness**
  (consistent with initial S. Obenschain's guidelines)

- **Properties of cryogenic foam based on those of polystyrene**
  - **Density and thermal conductivity adjusted according to foam region porosity**
  - **Thermal conductivity further scaled by 2/3 to account for possible optimization of porous micro-structure to minimize the conductivity.**
  - **As conservative measure, higher thermal conductivity values found in the literature used, ranging from 0.088 W/m-K at 19 K to 0.13 W/m-K at 40 K**
  - **Heat capacity values used range from 100 J/kg-K at 20 K to 225 J/kg-K at 40 K**



Example DT Interface Temperature History for Different Thicknesses(μm)of 25% Dense Outer Foam Region

- Transient analyses performed using ANSYS
  - q'' = 2.2 W/cm^2 for example case (10 mTorr/4000 K Xe)
  - Outer foam region density = 25% (Consistent with J. Sethian's guideline)
- ~130 μm (32 μm of equivalent solid polystyrene) would be sufficient to prevent DT from reaching the triple point after 0.015 s (corresponding to flight time of 400 m/s target in 6 m radius chamber)
- As comparison, DT would reach the triple point after ~0.002 s in the absence of the outer foam layer



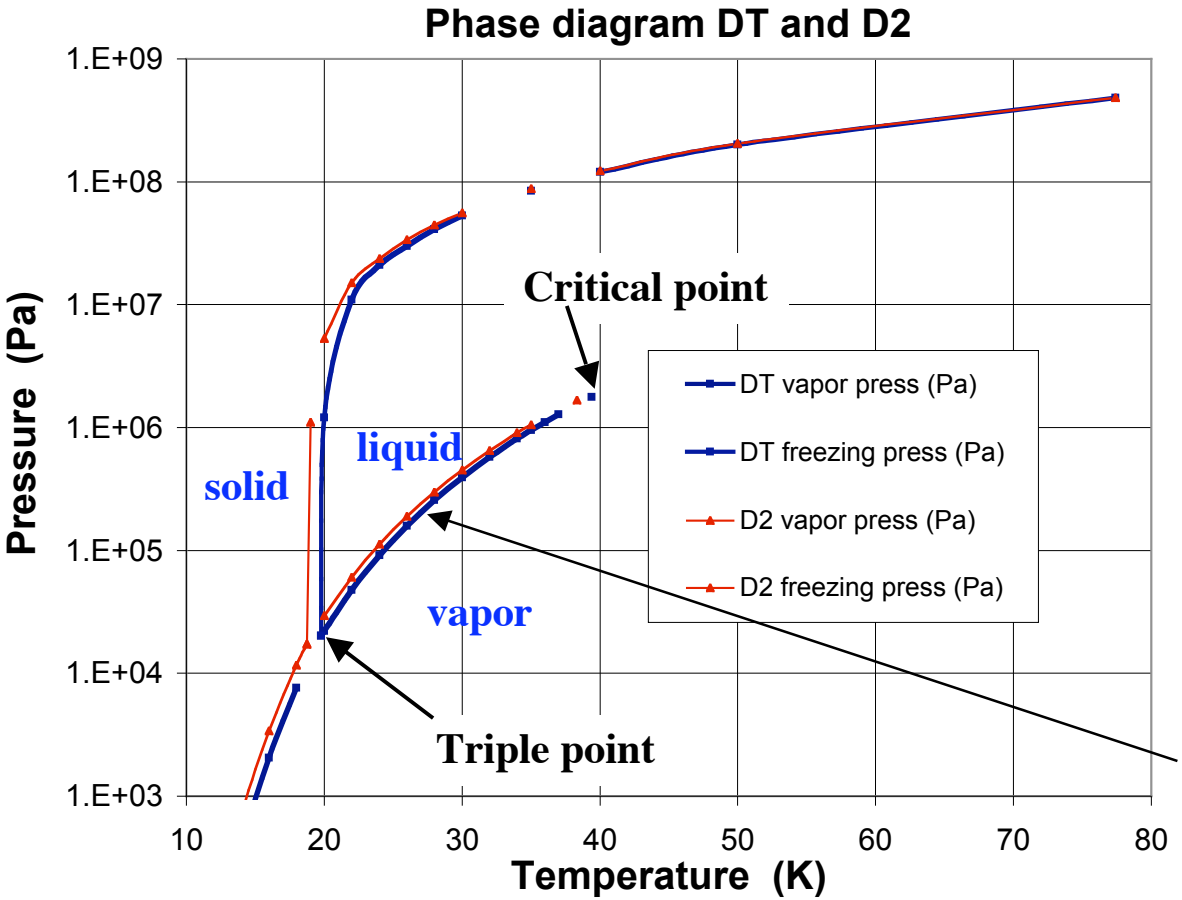
Summary of Thermal Analysis Results on Effectiveness of Insulating Outer Foam Layer

Foam Density	Foam Thickness (μm)	Plastic coating thickness (μm)	Maximum q'' on Target (W/cm^2)	Time for DT to Reach Triple Point (s)
0.25	72	2	1.17	0.010
0.25	72	10	1.17	0.0108
0.25	104	2	1.17	>0.015
0.25	104	2	7.5	0.0068
0.1	72	2	1.17	0.0116
0.1	97	2	1.17	>0.015
0.1	152	2	7.5	0.0147

- **To increase target thermal robustness:**
  - **maximize both thickness and porosity of outer foam layer while**
  - **accommodating target physics and structural integrity requirements.**

Allowing DT Phase Change

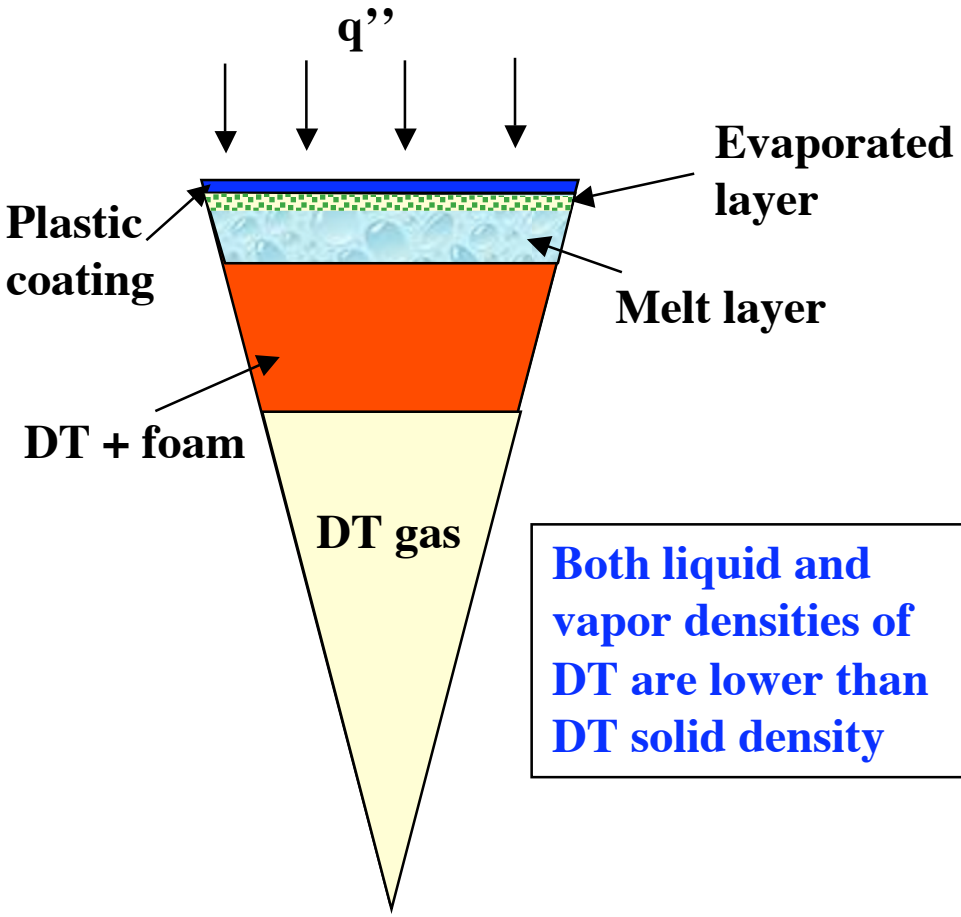
- Formation of DT vapor at DT/foam and plastic overcoat interface depends on bonding
  - For high quality bond, evaporation would only occur through nucleation
    - Homogeneous nucleation very low under typical conditions (~0 for T<26 K and takes off at 34 K)
  - If localized micro-defects are present, heterogeneous nucleation is possible (> ~1 μm)
  - If micro-gap present, surface evaporation is possible (worst case scenario considered here)



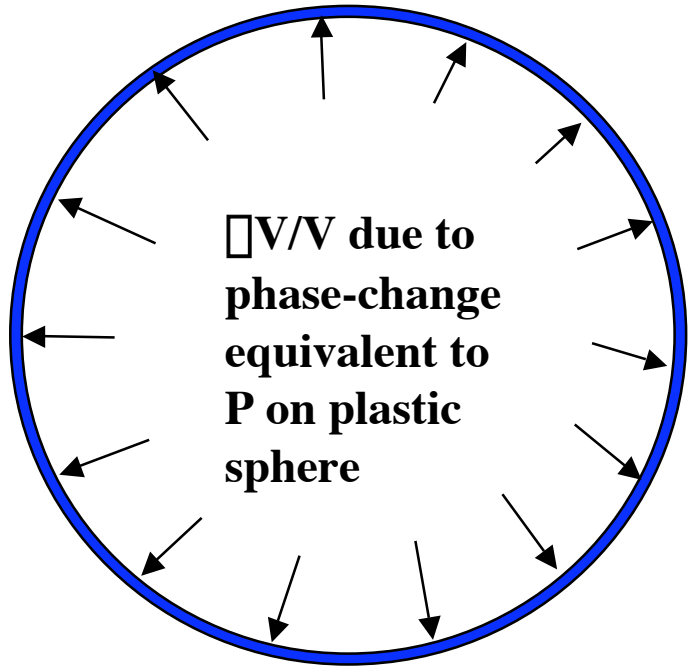
- Amount of DT liquid and vapor based on saturation P-T relationship from phase diagram

$$T_{sat} = 5.2911\ P^{0.1356}$$

Thermo-mechanical Model for Rigid DT



Both liquid and vapor densities of DT are lower than DT solid density



$$\frac{\Delta V}{V_{target}} = \frac{6PR_{int}}{4t_{plastic}E}(1-\nu)$$

$$\Delta V = V_l + V_v - V_s - \Delta V_{th}$$

ΔV=total volumetric change of target
V_s=Equivalent solid volume of phase change region
V_l and V_v=liquid and vapor volumes of phase change region
ΔV_{th}=volumetric thermal expansion of plastic coating

$$\sigma_h = \frac{PR_{int}}{2t_{plastic}}$$

Simple Model Utilizing DT T_{int} and Phase-Change Thickness as a Function of Heat Flux from Transient ANSYS Calculations

- **The initial solid volume, V_s, that has undergone phase change is given by:**

$$V_s = \frac{4}{3}\pi(R_{\text{int}}^3 - (R_{\text{int}} - \Delta_{p-c})^3)$$

- **Assume that a mass fraction x_l of the phase change region, Δ_{p-c}, is liquid and $(1-x_l)$ is vapor:**

$$V_l = V_s \frac{\rho_s}{\rho_l} x_l \qquad V_v = V_s \rho_s (1 - x_l) R_{DT} \frac{T_v}{P}$$

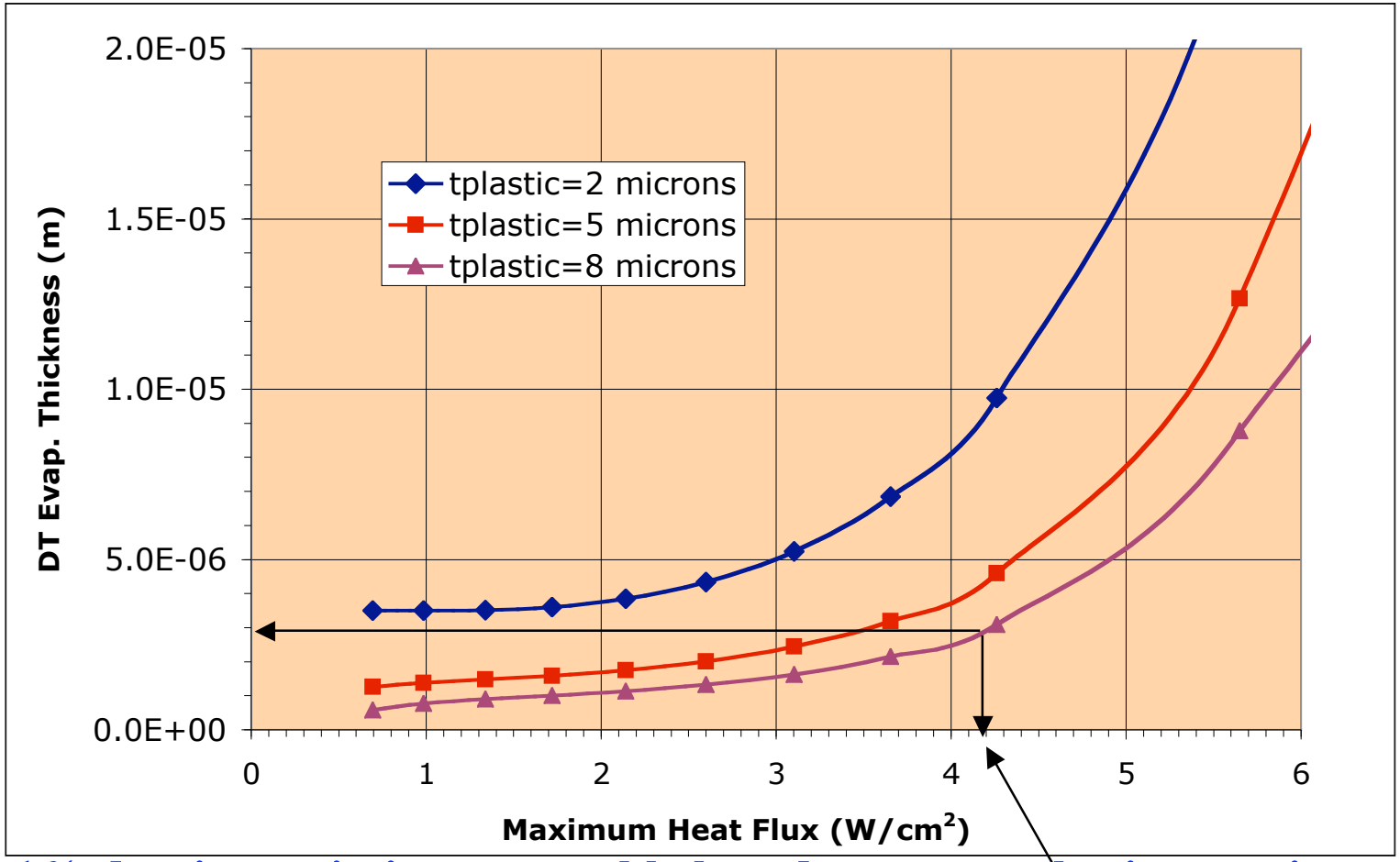
- **The volumetric expansion of the plastic coating is given by:**

$$\Delta V_{th} = \frac{4}{3}\pi R_{\text{int}}^3((1 + \alpha \Delta T_{pl})^3 - 1)$$

- **Substitution in $\Delta V/V$ eqn. leads to a quadratic equation for P:**

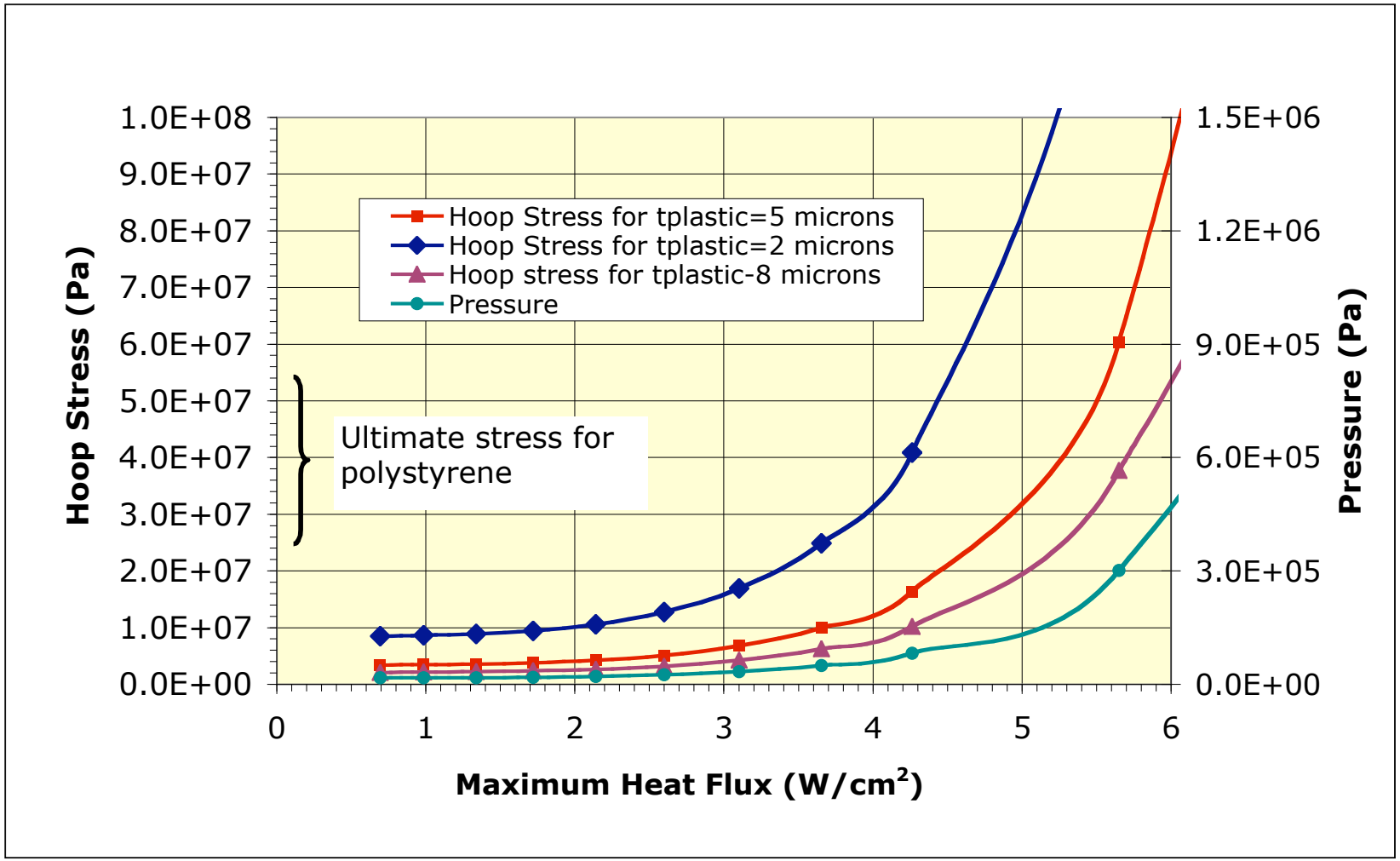
$$\left(\frac{x_l \rho_s}{\rho_l} + \frac{(1 - x_l)\rho_s R_{DT} T_v}{P} - 1\right) V_s - \Delta V_{th} = V_{target} \frac{6 P R_{\text{int}}}{4 t_{plastic} E}(1 - \nu)$$

DT Evaporated Region Thickness as a Function of Maximum Heat Flux for Different Plastic Coating Thicknesses



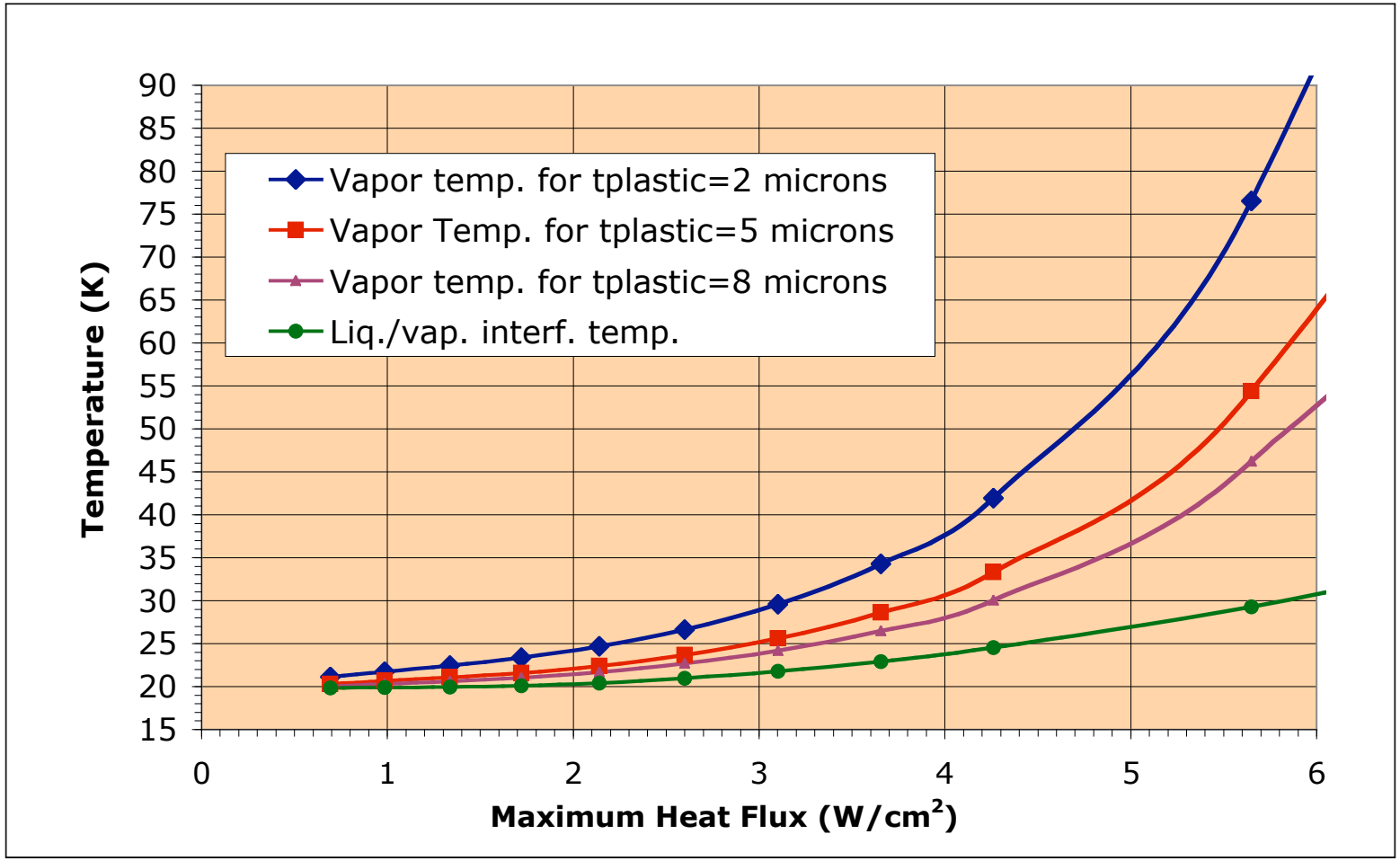
- **Is 1% density variation acceptable based on target physics requirements?**
  - **For the 289 μm foam+DT region--> ~3 μm vapor region**
  - **e.g. for a 8 μm plastic overcoat, the maximum allowable q''~4.2 W/cm²**
- **A thicker plastic coating is preferred to minimize vapor region thickness**

Hoop Stress as a Function of Maximum Heat Flux for Different Plastic Coating Thicknesses



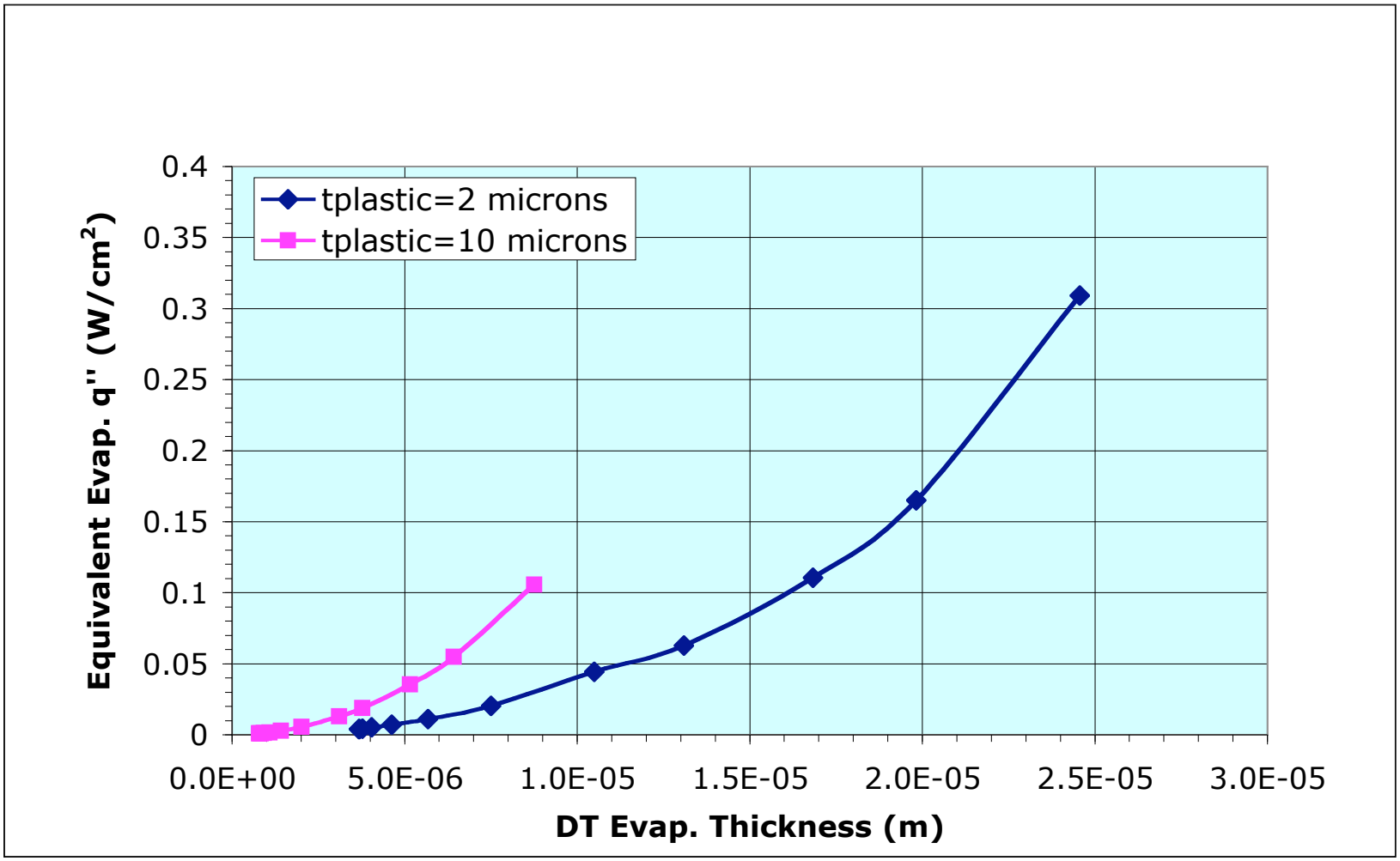
- **A maximum q'' of ~5-5.5 W/cm^2 for a plastic overcoat thickness of 8 μm is allowable based on the ultimate tensile strength of polystyrene**

DT Vapor and Maximum Interface Temperatures as a Function of Maximum Heat Flux



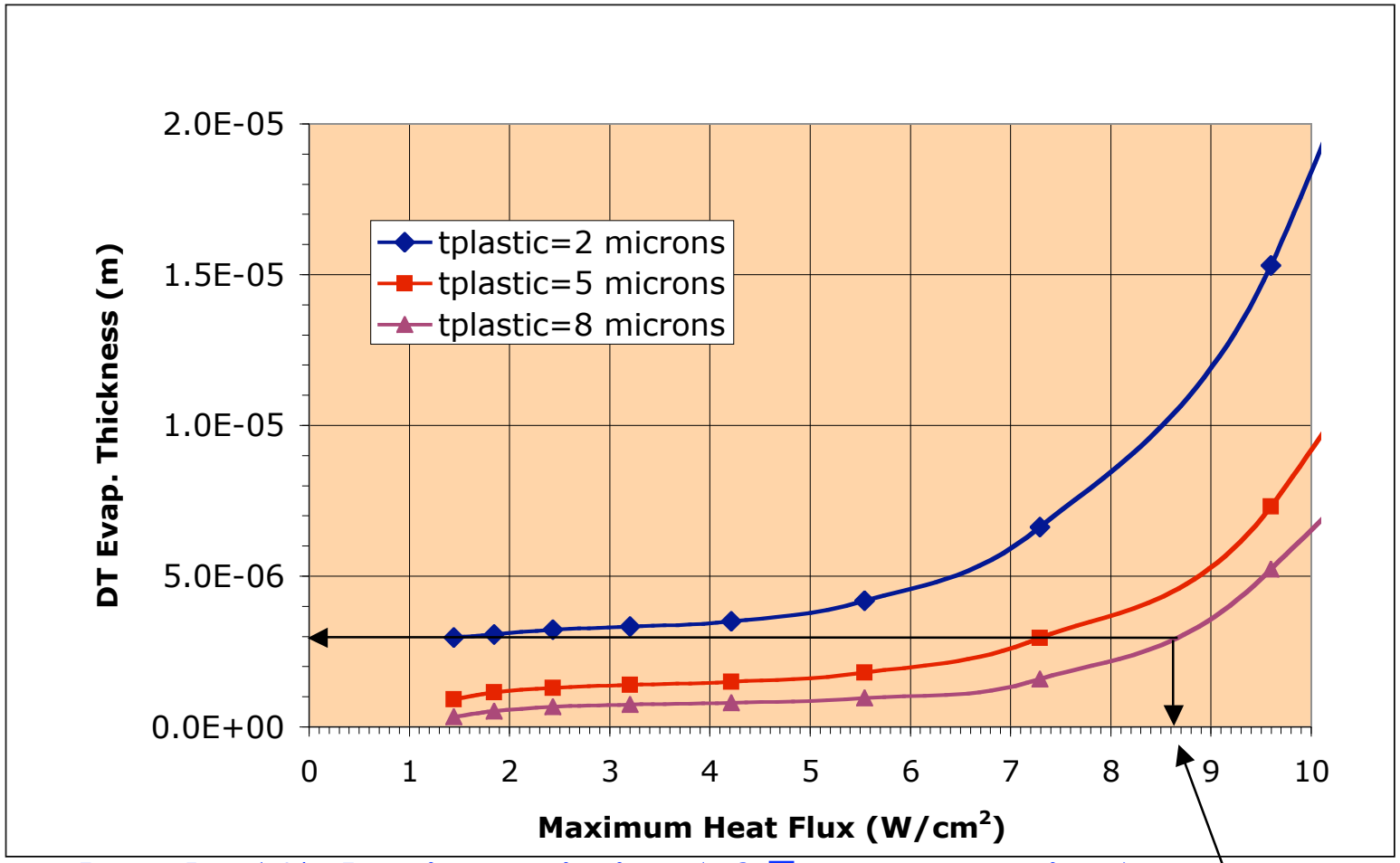
- **Homogeneous nucleation increases dramatically as T--> 34 K, corresponding to q'' > 6 W/cm²**

Equivalent Heat Flux as a Function of DT Evaporated Thickness



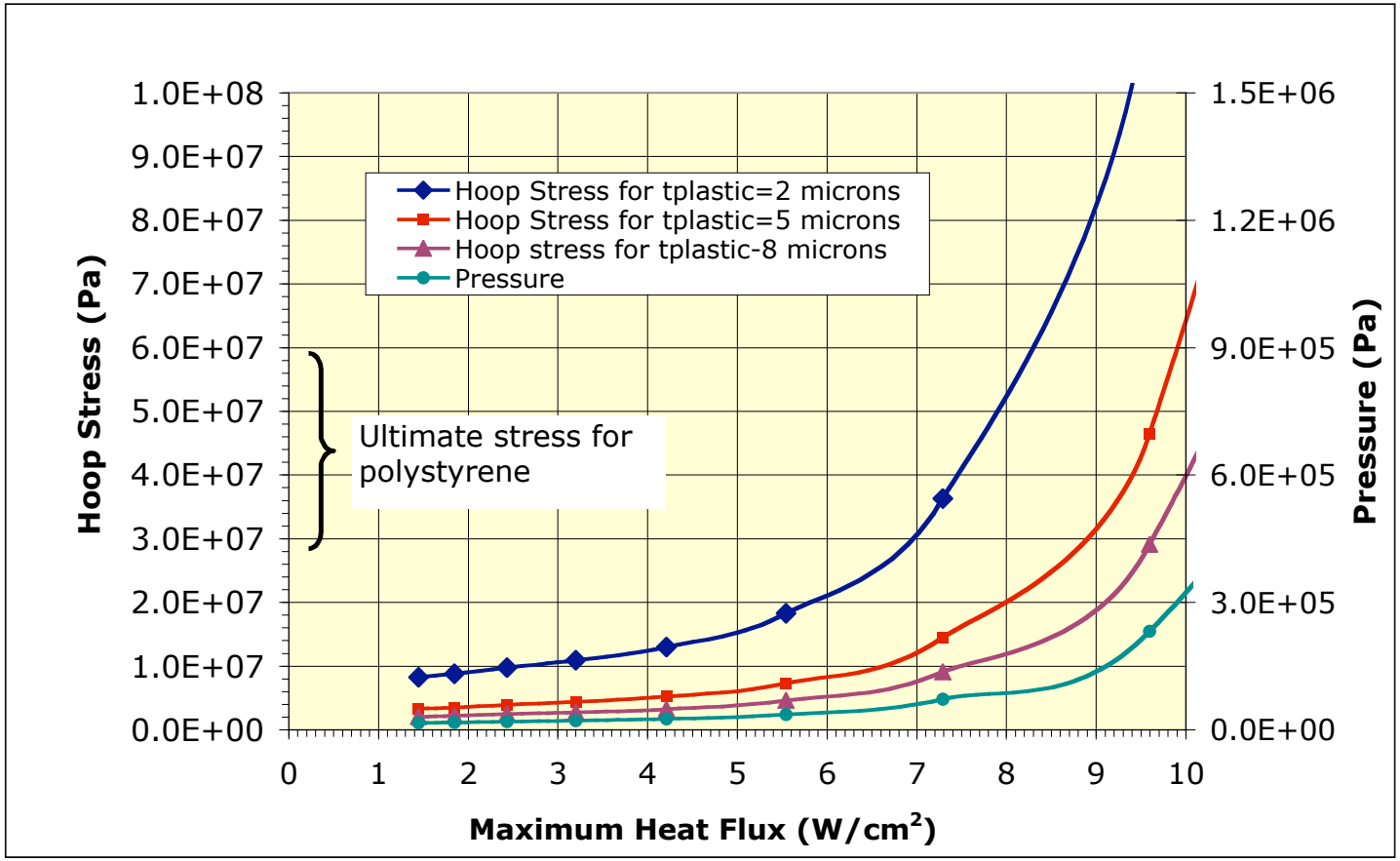
- **Equivalent q'' required to evaporate vapor region is small for vapor region thicknesses ~ 1-10 μm (<< heat flux on target)**

DT Evaporated Thickness as a Function of Maximum Heat Flux for Different Plastic Coating Thicknesses for a Case with a 72-μm 25% Dense Insulating Outer Foam Layer



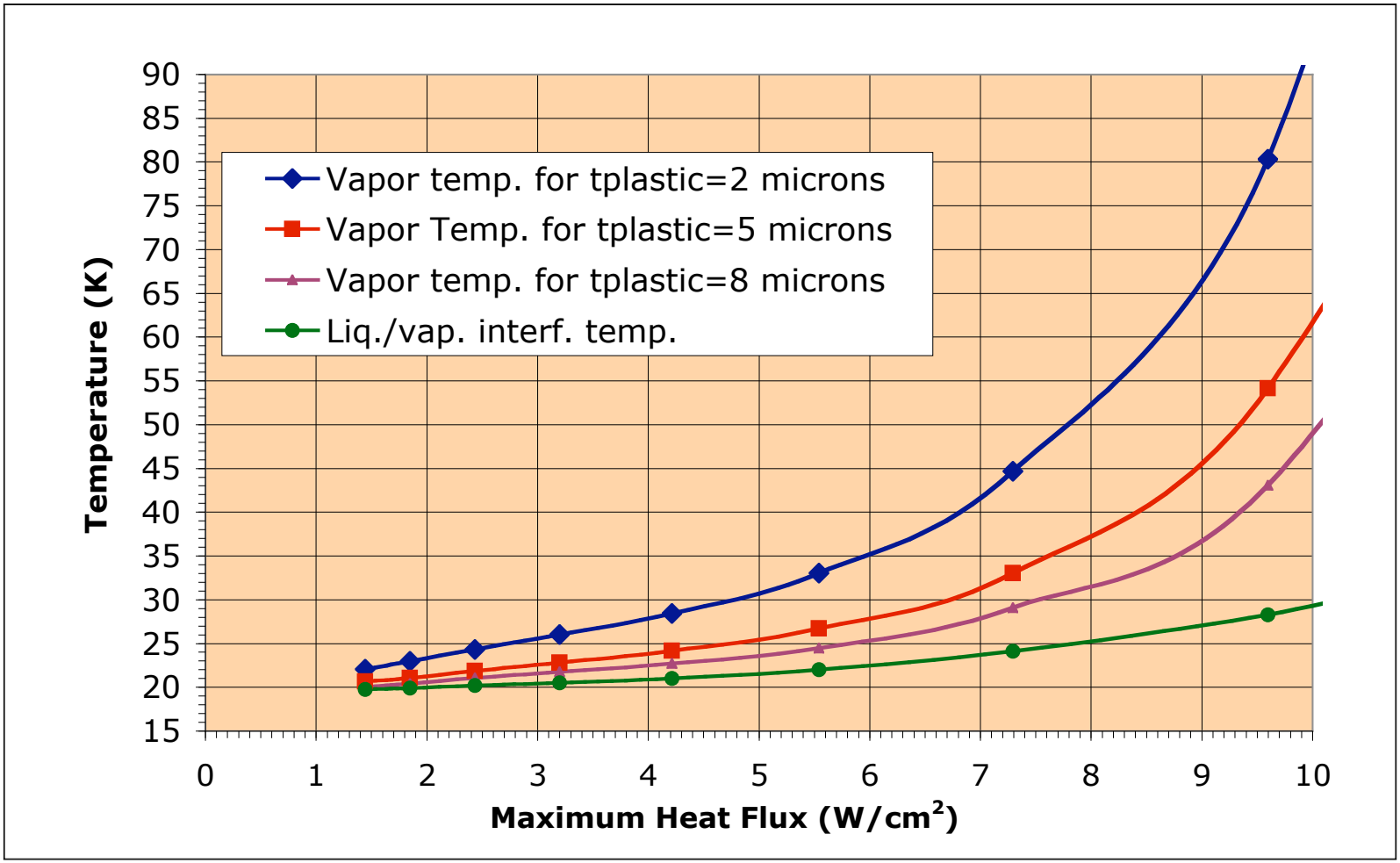
- **Based on the 1% density variation (~3 μm vapor region), the maximum allowable q'' is now ~8.6 W/cm² for a 8 μm plastic overcoat (compared to 4.2 W/cm² for case without insulating foam layer)**

Hoop Stress as a Function of Maximum Heat Flux for Different Plastic Coating Thicknesses with a 72-μm 25% Dense Insulating Outer Foam Layer



- **A maximum q'' of ~9.5 W/cm^2 for a plastic overcoat thickness of 8 μm is allowable based on the ultimate tensile strength of polystyrene**

DT Vapor and Maximum Interface Temperatures as a Function of Maximum Heat Flux for a Case with a 72-μm 25% Dense Insulating Outer Foam Layer



- **DT vapor generation forms an insulating layer that retards heat flux to DT liquid and solid (such transient effect not included in this model)**

Conclusions (I)

- **For a typical target configuration the maximum q'' for DT to reach its triple point is only about 0.6 W/cm^2 for a 6-m radius chamber.**
  - **This would place an unreasonable constraint on background gas density that might be required for wall protection.**
- **Adding an outer foam layer would increase the allowable q''for DT to reach its triple point**
  - **e.g. a 152 μm 10% dense foam layer would increase q'' up to 7.5 W/cm^2**
- **For increased target thermal robustness, it is preferable to have the maximum thickness and porosity outer foam layer which can still accommodate the target physics and structural integrity requirements.**

- **Allowing for vapor formation would relax the target thermal constraint**
  - **A simple thermo-mechanical model was developed to help in better understanding the DT phase change process.**
  - **A thicker plastic overcoat was found preferable to reduce the vapor region thickness**
  - **A ~1% change in DT/foam region density corresponds to ~ 3 μm of vapor region**
  - **If this were acceptable, the maximum allowable q'' is ~4 W/cm^2 for the original target design and ~ 9 W/cm^2 for a target design with 72-μm thick, 25%-dense outer insulating foam layer and an 8-μm thick plastic overcoat**
  - **In both cases, the corresponding hoop stresses in the plastic coating are less than the anticipated ultimate tensile strength.**

Conclusions (II)

- **The results from the simple thermo-mechanical model have helped to highlight benefits of relaxing DT vapor formation constraint and of including design modifications such as an insulating outer layer**

- **However, this model has limitations and a better understanding of the phase change processes would be obtained from a more comprehensive model including interactions of key processes such as:**
  - **Effect of 2-D heat flux variation on vapor gap formation**
  - **Insulating effect of vapor gap formation**
  - **Local effect of latent heat of vaporization effect**
  - **Nucleation boiling based on local conditions**
  - **Structural function of foam fibers depending on foam/plastic overcaot bond quality**
  - **Non-rigid DT ice assumption**

- **This also indicates the need for an experimental effort to better characterize the DT multi-phase behavior at the plastic overcoat interface ideally by using or possibly by simulating the actual materials.**

- **Guidance is needed from the target physics perspective to understand better the constraints and limitations imposed on such actions.**