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Title: The Development and Advantages of Beryllium Capsules for the Natinal Ignition Facility

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The development and advantages of beryllium capsules for the National Ignition Facility

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Capsules with beryllium ablators have long been considered as alternatives to plastic for the National Ignition Facility laser ; now the superior performance of beryllium is becoming well substantiated . Beryllium capsules have the advantages of relative insensitivity to instability growth, low opacity, high tensile strength, and high thermal conductivity. 3-D calculation s with the HYDRA code [NTIS Document No. DE-96004569 (M. M. Marinak *et al.* in UCRL-LR-105821-95-3)]confirm 2-D LASNEX [G. B. Zimmerman and W. L. Kruer, Comments Plasmas Phys. Controlled Thermonucl. Fusion, 2, 51 (2975)] results that particular beryllium capsule designs are several times less sensitive than the CH point design to instability growth from DT ice roughness. These capsule designs contain more ablator mass and leave some beryllium unablated at ignition. By adjusting the level of copper dopant, the unablated mass can increase or decrease, with a corresponding decrease or increase in sensitivity to perturbations . A plastic capsule with the same ablator mass as the beryllium and leaving the same unablated mass also shows this reduced perturbation sensitivity. Beryllium's low opacity permits the creation of 250 eV capsule designs. Its high tensile strength allows it to contain DT fuel at room temperature. Its high thermal conductivity simplifies cryogenic fielding.

I. INTRODUCTION

The use of beryllium to create pressure by X-radiation driven ablation has been explored from the earliest days of the inertial confinement fusion program. Capsules with beryllium ablators have long been considered as alternatives to plastic for the National Ignition Facility laser; now the superior performance of beryllium is becoming well substantiated . Early NIF work considered both beryllium and plastic[1]. In hope of using fabrication techniques similar to those used for Nova capsules, design effort was concentrated on using a bromine and oxygen doped polystyrene ablator (the PT design), placed inside a gold hohlraum as shown in Figure 1[2]. Later , a copper doped beryllium capsule (Be330), which was designed to be similar and placed in the same physical hohlraum using a different laser pulse shape, showed less sensitivity to perturbations on the DT ice surface[3]. In this paper we will elaborate on the reasons for this behavior, some of which were due initially to different design choices, but highlight intrinsic differences. We then focus on the inherent advantages of beryllium, both hydrodynamic and mechanical. These include beryllium's high density, low opacity, high tensile strength, and high thermal conductivity.

Many choices must be made to specify a capsule design. Below we discuss the similarities and differences in these choices between capsules with plastic and beryllium ablators. A plastic ablator has the advantage that it can be diffusion filled with DT, as well as being easily doped with higher Z material to achieve any desired mean opacity. The baseline NIF capsule design has been the PT [3] which uses a bromine (0.25 atom %) and oxygen (5 atom %) doped plastic (CH) ablator (0.95 - 1.11 mm radius) around a frozen DT (0.25 g/cm^3) shell (0.87 - 0.95 mm). The peak drive temperature for this capsule is 300 eV. Saillard [4] presented a modified design (L1000) driven with a peak temperature of 350 eV. Lindl[1] presented a beryllium capsule at 250 eV doped with sodium and bromine. A beryllium capsule[3] (Be330) was designed using copper dopant (0.9 atom %) with the same DT mass and radii, and a slightly smaller outside radius (1.105 mm) as the PT, with an important difference being an 80% higher ablator mass. Dittrich [5] has added polyimide ($C_{22}H_{10}N_2O_4$), and B_4C designs at 300 eV, and beryllium designs at 300 eV (Be300) and at 250 eV with a radially graded copper dopant concentration.

A high Z dopant adds extra opacity needed to adjust the penetration of the radiation front into the ablator, separating , in the rocket model, the payload from the exhaust. By varying the concentration of high Z dopant in the ablator, capsules can be optimized over a wide range of hohlraum temperatures. The choice of atomic dopant is not as critical to a design as the concentration . The original choice of bromine for the plastic dopant has been changed to germanium, because is easier to fabricate. Copper was chosen to dope beryllium because it has the highest solubility of any element in beryllium. By creating an alloy rather than an mixture, the copper should be distributed as uniformly as possible throughout the beryllium, avoiding possible concentration at grain boundaries. Any inhomogeneities could seed later instability growth. However the greater ablator mass of the Be330 capsule required a lower ablator opacity than the PT design. At 200 eV the Be330 Rosseland mean opacity is a factor of 3 less than the PT. At their peak temperatures the Be330 opacity at 330 eV is 1.8 times less than the PT at 300 eV.

An important factor in the success of an ignition capsule is driving it with the proper radiation pulse shape. The first step of a radiation drive is designed to set a desired entropy in the fuel. Thereafter, the pulse is designed to adiabatically compress the capsule until the final pulse, whose time history is governed by limits on the maximum power and energy available from the laser driver. The Be330 discussed here and the PT were designed to place the fuel on the same adiabat, and to drive the fuel to the same final velocities. The NIF laser is designed to have the flexibility and precision to deliver a chosen shape within the limits set by sensitivity studies performed on the PT design[3]. The beryllium design has similar sensitivities.

If the proper radiation pulse is provided, then the capsule sensitivity to radiation drive asymmetries becomes critical. Radiation drive asymmetries are controlled by 1) the static placement of cones of laser beams along the axis of cylindrical hohlraums, and 2) the time dependent adjustment of the relative laser power in each cone. Integrated calculations, which include both the laser driven hohlraum and the capsule demonstrate that we can adequately control drive symmetry for the plastic PT[2], the plastic L1000 [6] and the 330 eV beryllium design (Be330) [3,7]. An integrated 280 eV beryllium design has been calculated based upon a capsule scaled from the Be330 design. The DT fuel mass was kept constant, but the capsule volume was increased to keep the product of ablation pressure and volume constant. An integrated 250 eV design [8] used only 900 kJ of laser energy to explore the lower end of expected NIF laser performance. Table I summarizes all of the integrated beryllium NIF target designs and Figure 2 shows their radiation temperature drive histories.

II. ADVANTAGES OF BERYLLIUM FOR INSTABILITY GROWTH

A. Reduced sensitivity compared to the PT design

Sensitivity to material perturbations (surface roughness, defects, etc.) will be an important issue for NIF capsules, because it is one of the most difficult to control, to calculate, and to determine experimentally. Calculations of such multi-mode perturbations include only the capsule to allow better angular and radial resolution. These methods are described by Hoffman [9] and Marinak [10]. The multi-mode perturbations initialized are based upon mode spectra derived from measurements of ablator and ice surfaces. Random phases are added for individual modes to obtain one possible realization of a surface roughness. NIF size capsules have not yet been built, so we must estimate the expected spectrum of surface roughness based on measurements from existing capsules of various sizes. To obtain a suitable spectrum we extrapolate the DT ice roughness measurements made on a 1 mm radius beryllium cylinder which typically show a 1.2 μm r.m.s. roughness[11]. By imposing the same perturbation spectra on each capsule we can compare their tolerances to surface roughness. Figure 3 shows the resulting degradation of yield as the DT ice surface is roughened. It combines the 2-D calculations [3] with new 3-D results[12]. The 2-D calculations were performed with LASNEX[13] using modes between 12 and 40. These show that the Be330 capsule tolerates rougher (~4 x) DT ice surfaces than the PT capsule. The 3-D calculations were performed with HYDRA [14] using modes 15 to 120 on the PT and Be300 capsules. They confirmed the reduced sensitivity of beryllium capsules to ice perturbations. They also showed that higher modes (60 to 100) are the most important for shell breakup, but the lowest modes, which penetrate the shell, are principally responsible for degrading the yield.

This difference in perturbation growth between the PT and beryllium capsules appears not to be due to the radiation drive, although drive profiles can make a substantial difference in sensitivity to perturbations. For example, the Be330 capsule is 50 times more sensitive to ablator perturbations if the final drive temperature alone is reduced 7% [3]. This may explain why Dittrich [5] found the Be300 design gave 20% the growth from ablator outside surface perturbations as the PT design, while Krauser[3] shows the Be330 to have the same sensitivity as the PT. Surprisingly, Dittrich was able to use the same radiation drive pulse on his design as the PT, whereas the Be330 has the very different pulse seen in Figure 2.

The instability characteristics of the Be330 and the PT capsules appear to be affected significantly by one difference in the design optimization. The beryllium ablator is more massive than the plastic (3.9 Vs 2.2 mg) and carries more payload inward. In fact its payload includes unablated copper doped beryllium about equal in the mass to the DT fuel. The lower PT ablator mass cannot deliver so much high velocity payload, and its dopant was adjusted so that the radiation completely penetrates the plastic at ignition time. The difference in instability characteristics appears to be due to the extra ablator mass that is imploded along with the fuel. Instability calculations show that, after the first shock transits across the inner DT ice surface, a rarefaction carries perturbations and their

Richtmyer -Meshkov flow field outward to the ablation front. There the perturbations grow by the ablative Rayleigh-Taylor instability, move inward with the ablation front, and eventually feed through to disturb the fuel. We refer to the whole phenomena as the feed-out/feed-in process. The extra ablator mass of the beryllium design attenuates the feed-through of these perturbations both outward and inward. At ignition the unablated mass separates the ablation front from the fuel in the Be330 and Be300 capsules, attenuating the perturbations further when compared to the PT.

To confirm this behavior we used the same radiation drive on the Be330 capsule, but adjusted the copper dopant to vary the unablated mass carried in with the fuel. This resulted in only slight increases in implosion velocity with decreasing dopant. At 1.2% copper substantially more mass was carried. At 0.6% the radiation front penetrated the ablator completely, leaving no unablated payload. Figures 4 and 5 compare the trends in perturbation growth in these capsules to the 0.9% copper Be330. These figures schematically show the arbitrarily normalized and angularly weighted r.m.s. perturbation amplitude at the ablator /ice interface (S), where $S^2 = \int (r-\bar{r})^2 \cos\Theta d\Theta$, as a function of the arbitrarily normalized distance the interface has moved. Figure 4 compares capsules with an initial DT ice roughness and shows that late in the implosion the 0.6% Be330 design gives similar interface perturbations to the PT. As the unablated mass progressively increases in the 0.9% and 1.2% designs, the perturbation growth is reduced. Figure 5, based on ablator roughness, shows the same progressive decrease of perturbation growth, but the PT capsule now lies between the 0.9% and 1.2% Be330 designs.

Since the amount of unablated material affects the instability characteristics of the implosion, it is crucial to measure it experimentally. The values of yield weighted rho-r ($\int \rho dr$) of the ablator in the Be330 capsule with three different dopant concentrations (0.6, 0.9, and 1.2% cu) were 0.25, 0.39, and 0.51 g/cm^2. These could be measured using (n,2n) production of ^{62}Cu from the natural ^{63}Cu dopant in the beryllium ablator. This is proportional to the ablator rho-r at the time neutrons are produced, the neutron yield, and the amount of copper collected. The latter two can be measured directly, or at high fluences the collected copper can be eliminated using the ratio of (n,2n) production of ^{61}Cu to ^{62}Cu. Coincident counting of gamma rays allows detection of the ^{62}Cu positron emission with a 9.7 minute half-life, and the ^{61}Cu with a 3.4 hour half-life. For typical targets and yields, a collection fraction of 10^{-6} will yield ample signals. Measurements have already demonstrated 55% collection and 54% detector efficiencies[15]. Thus the intended ablator payload can be measured. If the copper is not thoroughly mixed during the capsule expansion and interaction with the hohlraum, it may be possible to detect angular variation in the pusher rho-r by collecting samples from different locations in the target chamber.

Attempting to understand why beryllium capsule designs were better has led to experiments on the Nova laser to study the radiation-hydrodynamic behavior of the feed-out / feed-in process[16]. Three different types of planar aluminum foil targets are being studied with different feed-out characteristics driven by hohlraum radiation from either a 2.2 or 4.5 ns laser pulse. In all cases the foils have perturbations of 4 μm amplitude and 50 μm wavelength imposed on the side facing away from the radiation drive. Perturbation growth in the aluminum is observed both through, and perpendicular to the perturbations with a variety of monochromatic 4 - 8 keV backlighters. In order to observe the effects of a density discontinuity on the feed-out process, some targets are a composite of an aluminum foil facing the hohlraum, and a 10 μm thick beryllium foil transparent to the backlighter. The thicker targets driven with the 2.2 ns pulse show the evolution of only the Richtmyer-Meshkov instability near the perturbed surface. Thin targets with the 4.5 ns pulse have both the Richtmyer-Meshkov feed-out and Rayleigh-Taylor growth. Generally LASNEX calculations are in agreement with measurements of the fundamental mode growth, giving us confidence in our understanding of the feed out /feed in process.

B. The Advantage of High Initial Density

In order to study how much of the difference between the PT and Be330 performances was intrinsic to beryllium as opposed to plastic and how much was due to imploding unablated material, we designed a plastic capsule ,the Pthick, which had an ablator mass equal to that of the Be330, imploded the same DT mass with the same shock history to the same final velocity and rho-r, and carried the same unablated mass at the Be330. The capsule radii are 0.87, 0.95, 1.199 mm, with a CH ablator doped with 0.02% germanium. Figures 4 and 5 schematically show that its sensitivity to DT ice and ablator roughness is similar to or better than the 0.9 atom % Be330, proving plastic ablator capsules can be designed to carry unablated mass and reduce sensitivity to perturbations. However Figure 6 shows that a 7 ns longer pulse is needed to drive this capsule. Only the early portion of the radiation drive temperature needed to be adjusted to accommodate the Pthick target. The later portions of the pulse, which require the vast majority of the laser power, were identical. The differences arise predominantly in the first and slightly in the second steps. In order to have the same ablator mass, the lower density plastic had to be made thicker than the beryllium. The first shock, required to set the fuel on the same adiabat in both targets, takes longer to traverse the thicker plastic ablator. Thus a fundamental difference between the beryllium and plastic ablators is the higher initial density of beryllium, which leads to a shorter radiation drive pulse.

The consequences of the longer drive may be significant. The NIF laser is currently designed to produce at most a 20 ns pulse. It may not be possible to produce a 27 ns pulse. Only a capsule design was produced for the Pthick. It is 8.5% larger than the Be330, and may require an 8.5% larger hohlraum to deliver adequate symmetry. The longer foot will cause more hohlraum wall motion , also leading to a larger hohlraum and more laser energy to drive the same radiation pulse. We plan to create an integrated design using the Pthick to quantify these issues.

C. The Advantage of Low Specific Heat

The specific heat of fully ionized beryllium is 80.2 MJ/(g-keV), while for polystyrene it is 100 MJ/(g-keV). The difference is simply due to the lower number of particles per unit mass for beryllium (5/9) than for CH (9/13). From tabular equations of state, we find the ratio of the plastic specific heat to beryllium varies from 1.2 to 1.3 over the relevant range of densities and temperatures. For beryllium with 0.9 atom % copper, and CH with 5 atom % O and 0.25% Br, the ratio of fully ionized specific heats changes by only 2%. This means that at a fixed temperature and for the same absorbed energy in an ablator, more beryllium will be ablated than plastic. Following Petschek and Williamson [17] we see that a lower specific heat results in a higher ablation velocity . If we assume a constant specific heat, c_v, no energy in the radiation field, a constant driving temperature, an opacity $\kappa = \kappa_0 \rho^{\alpha} T^{-n}$, and planar geometry, then we can transform the diffusion equation using a similarity variable

$\zeta = A\, x\, t^{-1/2}$, where $A^2 \propto \kappa_0\, c_v\, (n+4)\, \rho^{2+\alpha}\, T_0^{-n-3}$

Thus the radiation field penetrates a distance proportional to $c_v^{-1/2}$, and the velocity of the ablation front, V_a, is proportional to $c_v^{-1/2}$. Consider the hypothetical case of two materials with equal density and opacity (the Rosseland mean opacities of beryllium and polystyrene are set equal with low concentrations of dopants) , but with different heat capacities. The material with the beryllium heat capacity has a 12% higher ablation velocity.

From the Rayleigh-Taylor instability growth rate formula [1] $\gamma = \sqrt{\frac{ka}{1+kl}} - \beta k V_a$, we see that an increase in V_a will decrease the growth rate, especially for large *k*, or short wavelengths. The relative significance of specific heat to instability growth will need to be explored with numerical simulations and design variations.

D. The Advantage of Low Opacity

The inherently low opacity of pure beryllium could be a significant advantage. The lower the capsule ablator opacity, the more energy it can absorb from a hohlraum, and the higher is the ablation velocity. The somewhat lower Rosseland opacity of the Be330 ablator compared to the PT may contribute to some of its improved stability. However, opacities are temperature and density dependent, and cannot be treated this simply. In the equation for opacity $\alpha \approx 0.4$, $n \approx 2$ for beryllium with 0.9 atom % copper, and for the PT's bromine and oxygen doped CH $\alpha \approx 0.5$, $n \approx 3.5$. Since V_a is proportional to $(\kappa_0^{-1} c_v^{-1} \rho^{-a-2} T_0^{n+3})^{1/2}$ confirmation of any comparative advantage in V_a must await much more detailed analysis.

The lower opacity is a definitive advantage for beryllium over other materials if capsules can be designed to use the low opacity. Because opacities decrease with temperature, a low opacity would be an advantage at low drive temperatures (e.g. 250 eV). At a fixed absorbed capsule energy, a lower final drive temperature requires a larger radius and thinner ablator to drive fuel to the same conditions. All the beryllium capsules yet designed for the NIF at 250 eV and higher use a dopant (e.g. copper) to increase the opacity to avoid the rapid radiation penetration of the ablator at the end of the implosion. The Pthick design at 330 eV was at the lower range of possible dopant concentrations and could have performed well without any dopant. A 250 eV capsule with a plastic ablator has been explored (Dittrich, aps), but appears sensitive to instabilities. At a minimum, the low opacity of beryllium allows more control over the ablator opacity, because it can be adjusted to lower values. At greater capsule energies, and consequently for more energetic lasers than the NIF, the advantage of lower opacity should come more into play.

III. MECHANICAL ADVANTAGES OF BERYLLIUM

Two important physical characteristics make beryllium more attractive for an ignition capsule --- its strength and its high thermal conductivity. A disadvantage is that beryllium is opaque to visible and rf radiation, prohibiting optical inspection and RF heating of a DT layer. The yield strength of pure beryllium, which depending on the fabrication method can be as highs as 3.3 kbar, allows the Be330 design to contain its DT fuel at room temperature with a pressure of 346 bar. Cryogenic handling is only required when the DT layer is formed. By contrast the weaker polystyrene of the PT design must always be kept at cryogenic temperatures after it is filled, including during transport from the filling station to the target chamber.

Another important advantage of a beryllium ablator is its high thermal conductivity, 0.015 W/mm-K with copper dopant to the level of 0.9 atom % [18], which is 100 times larger than polystyrene. To create a uniform thickness DT layer inside the capsule, the temperature must be uniform on the inner surface. The ratio temperature variation to thickness variation is equal to the heat production per unit volume in the DT divided by it thermal conductivity times the layer thickness. A 17 μK peak to valley temperature difference on this surface causes a 1 μm variation in a 100 μm thick DT layer. Recent work[19] shows that the ambient heating of the cylindrical hohlraum wall by the target chamber thermal radiation can impose a non-uniform temperature profile on the wall of a cryogenically cooled hohlraum. This outside profile compensates for the non-uniform heat flow from the capsule to the hohlraum wall when the hohlraum is isothermal. If the capsule ablator is plastic with low thermal conductivity, then a temperature gradient of about 25 mK must be maintained between the midplane and the cooling hubs of the hohlraum to create a uniform DT layer and this differential must be controlled to about +/- 0.5 mK. The greater smoothing of a beryllium shell lessens the control requirement to +/- 5 mK, and may even require no active heating, as the ambient target chamber temperature provides all the required heating. This may be a significant advantage in the cryogenic system.

IV. FABRICATION OF BERYLLIUM CAPSULES AND NIF HOHLRAUMS

Two leading candidates for fabricating beryllium capsules are the machining and bonding of hemispheres [20], or sputtering beryllium onto plastic or other shells [21]. One attractive possibility would be to diffusion fill a glass shell, and then coat it with beryllium, producing a seamless capsule. If a glass shell could replace the unablated beryllium in the Be330 design, it might be strong enough to hold DT gas at room temperature. To explore the instability growth of this concept we designed a capsule driven by the Be330 radiation pulse using the same DT fuel, enclosing it in a 10 μm thick SiO_2 shell at a density of 2.205 (fused silica), surrounded by a 0.9% copper doped beryllium ablator with the same total mass (glass + beryllium) as the Be330's density 1.84 g/cm^3 shell but at density of 1.94 g/cm^3 to minimize instability growth and be consistent with the copper dopant. Single mode LASNEX calculations showed somewhat increased sensitivity to ablator roughness and much greater sensitivity to DT ice roughness compared to the Be330 design. Multi-mode calculations show several times more sensitivity to both ice and ablator surface roughness. The cause is perturbation growth at the additional unstable interface between the glass and beryllium. Unless means can be found to control this perturbation growth, a beryllium coated glass capsule may be unacceptably sensitive.

Much recent work has focused on joining machined beryllium hemispheres. Beryllium surfaces can be first machined to about 1 μm surface roughness, and polished and lapped further. One sphere larger than the Be330 has achieved 140 nm roughness. We expect to be able to achieve 10-20 nm surface finishes, but this remains to be demonstrated. Several joining techniques are being investigated, including diffusion bonding, laser welding, and brazing with various metals. An attractive method is isothermal brazing at about 900 C with a thin (0.2 μm) copper layer between the hemispheres. The exact mechanism for the joining by this method remains yet to be definitively demonstrated, however, experimental evidence fairly conclusively points to the following. By raising the temperature above the point where pure copper and copper-rich beryllium alloys melt, but below the point where the copper doped beryllium melts, the copper will diffuse into the surrounding beryllium. The copper migrates from the joint into the bulk material, reducing any variation in composition below detectable limits -- a nearly undetectable seam. Margevicius [22] has recently demonstrated copper brazed beryllium joints in planar samples with strength adequate to hold the Be330 DT pressure at room temperature. Joints have also been formed in a hydrogen atmosphere which suggests that bonding in DT gas is feasible. A major objective during the next year is to produce a bonded and lapped capsule the size of the Be330 design.

Creating an adequate joint is the major hurdle for any bonding technique. At this time we do not know how large a perturbation can be tolerated at the joint between hemispheres. We can expect to be able to construct a sub-micron thick joint. Spatially resolved calculations are beyond the current state of the art. Lagrangian calculations fail after a few nanoseconds when flows become significantly distorted. Eulerian calculations have difficulty with calculating spherical implosions with such a small perturbation. In order to begin to understand the relevant radiation hydrodynamics, experiments have begun studying the radiation ablation of two planar copper doped beryllium foils[23]. In these experiments a scale 1 Nova hohlraum is driven with a 1 ns square laser pulse to a peak radiation temperature of 200 eV. The radiation field drives an ablation front and shock wave through a 155 μm thick planar beryllium foil made from two pieces bonded with a layer of either an aluminum, CH, or C_8H_7Br. A relatively thick 15 μm layer was required for visibility with the limited spatial resolution of Nova diagnostics. Using sidelighting from a 4.7 keV titanium source, we observe the density changes of the shock and ablation fronts as they propagated perpendicular to the joint. Currently the observations show qualitative, but not yet quantitative agreement with LASNEX calculations. The joint tends to create a perturbation that can propagate laterally away from the joint to distances an order of magnitude greater than the joint thickness. Near the aluminum joint the shock front lags compared to its position farther away in the beryllium. Near the CH joint the shock front leads. The brominated polyethylene joint produces intermediate results. Quantitative comparisons with the data await more detailed calculations. By comparing calculations with these and other experiments, we hope to develop the capability of modeling realistically thin joints in convergent geometry with the passage of multiple shocks, and eventually to achieve an understanding and specification of tolerances for NIF capsules.

V. CONCLUSIONS

Capsules with beryllium ablators have the advantages of high density, low opacity, high tensile strength, and high thermal conductivity when compared to those using doped polystyrene (CH) ablators. Computationally, in both 2-D and 3-D, the 330 eV and 300 eV beryllium capsule designs are more tolerant of DT ice perturbations than the PT. This has been viewed as a major advantage for beryllium. It appears due to a combination of intrinsic differences between the materials and differences in the capsule design - a greater ablator mass and unablated material at ignition. By increasing or decreasing this unablated payload, instability sensitivity can be decreased or increased. A doped plastic ablator capsule (Pthick) with the same initial and unablated masses has similar hydrodynamic sensitivities. A fundamental difference is the higher initial density of beryllium. At the same ablator mass, this allows a thinner shell and consequently a shorter foot on the drive pulse. Fundamental to beryllium is its higher density which appears to force a plastic target with comparable sensitivity to instability growth to be physically larger and to require a longer drive pulse. This larger size and longer pulse which pose problems for plastic capsules.

The material property advantages of a high tensile strength and high thermal conductivity capsule are clear. The challenge for beryllium capsule fabrication is how to place the DT inside with the minimum perturbation to the shell. Although attractive, a beryllium coated diffusion filled glass shell appears substantially more sensitive to perturbation growth than a homogeneous ablator. However the effects of a joint in the beryllium shell cannot yet be calculated or measured experimentally. Adequate fabrication of a NIF size beryllium capsule remains a goal.

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Table I. Integrated NIF designs using copper doped beryllium capsules

Design	Yield (MJ)	Laser Energy (MJ)	Hohlraum Scale	Outer radius (μm)	Outer DT radius (μm)	Inner radius (μm)
Be-330	16	1.4	1.0	1105	950	870
Be-300	18	1.4	1.0	1105	950	870
Be-280	13	1.4	1.23	1363	1244	1200
Be-250	6	0.9	1.0	1092	972	917.4

Figure 1. NIF Hohlraum design showing dimensions and materials

Figure 2. Hohlraum radiation temperatures driving different beryllium capsules in integrated designs.

Figure 3. 2-D and 3-D calculation s of capsule yield as DT ice surface roughness is varied.

Figure 4. Normalized surface roughness at the ablator/ice interface for 5 capsule designs as a function of distance moved with an initial perturbation on the inner DT ice surface

Figure 5. Normalized surface roughness at the ablator/ice interface for 5 capsule designs as a function of distance moved with an initial perturbation on the outside, ablator, surface.

Figure 6. Radiation temperatures driving the Be330 and the Pthick capsule designs.

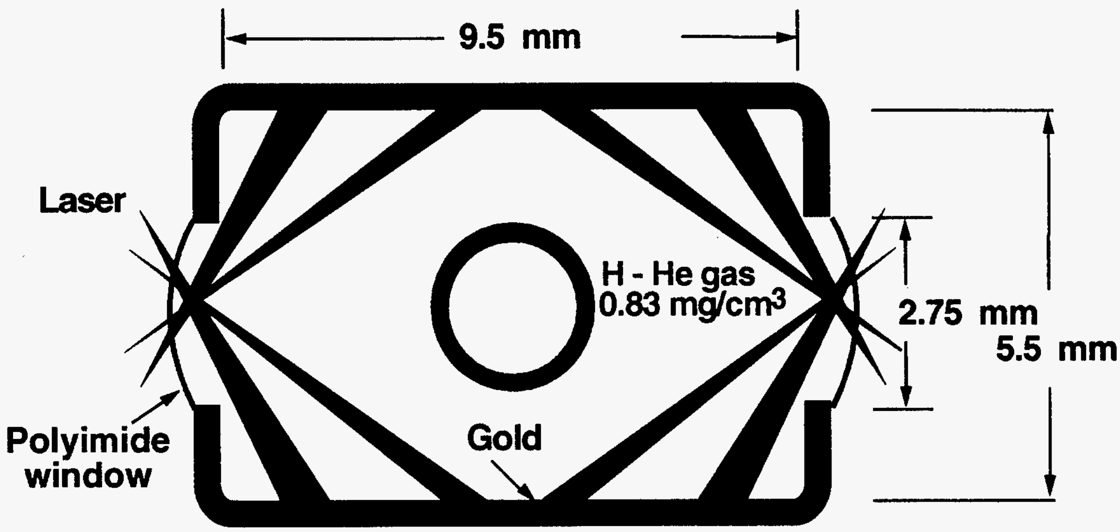

9.5 mm
Laser
H - He gas
0.83 mg/cm3
2.75 mm
5.5 mm
Polyimide
window
Gold

Figure 1

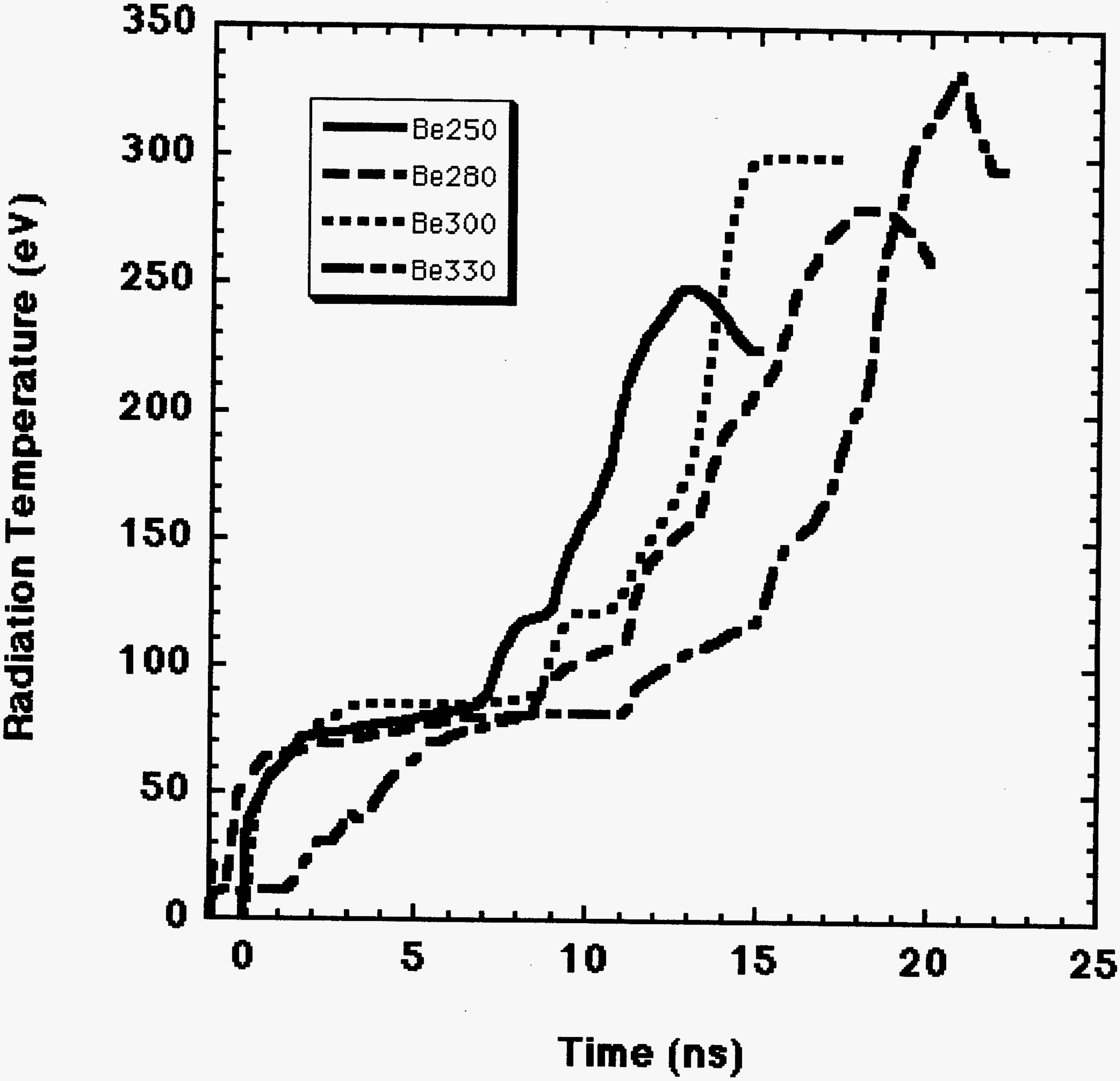
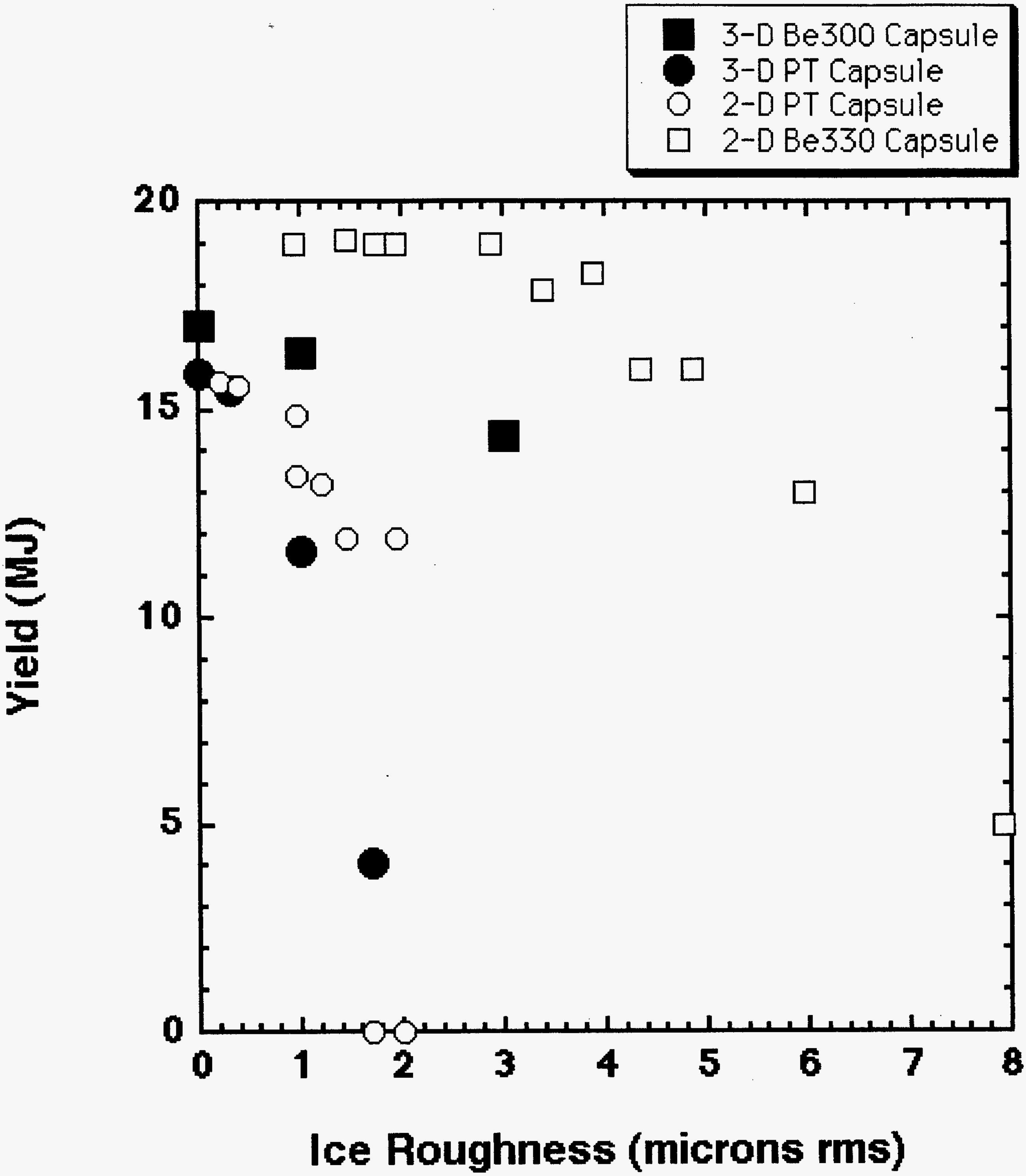
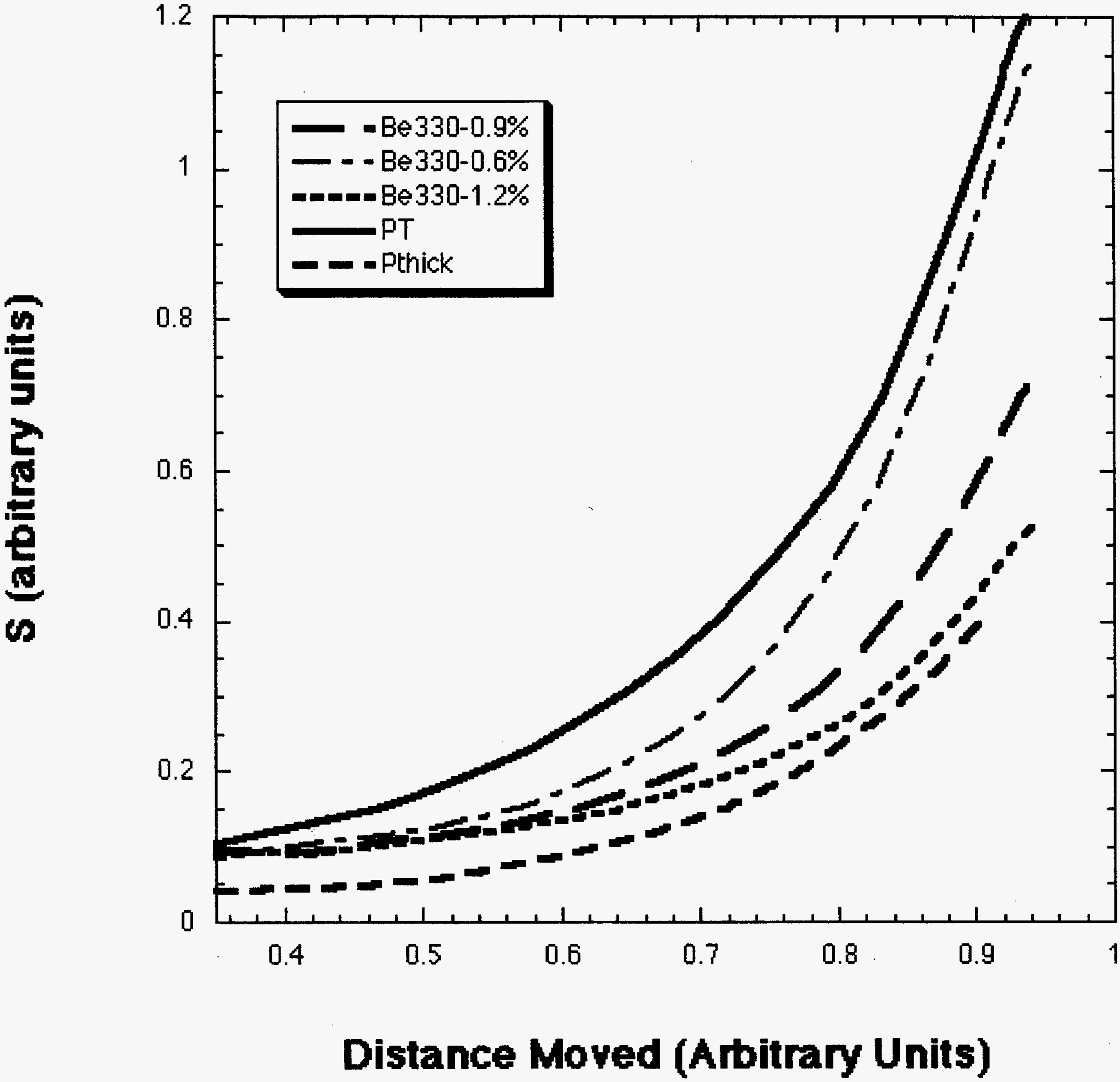

Be250
Be280
Be300
Be330
Radiation Temperature (eV)
Time (ns)
350
300
250
200
150
100
50
0
0
5
10
15
20
25

Figure 2



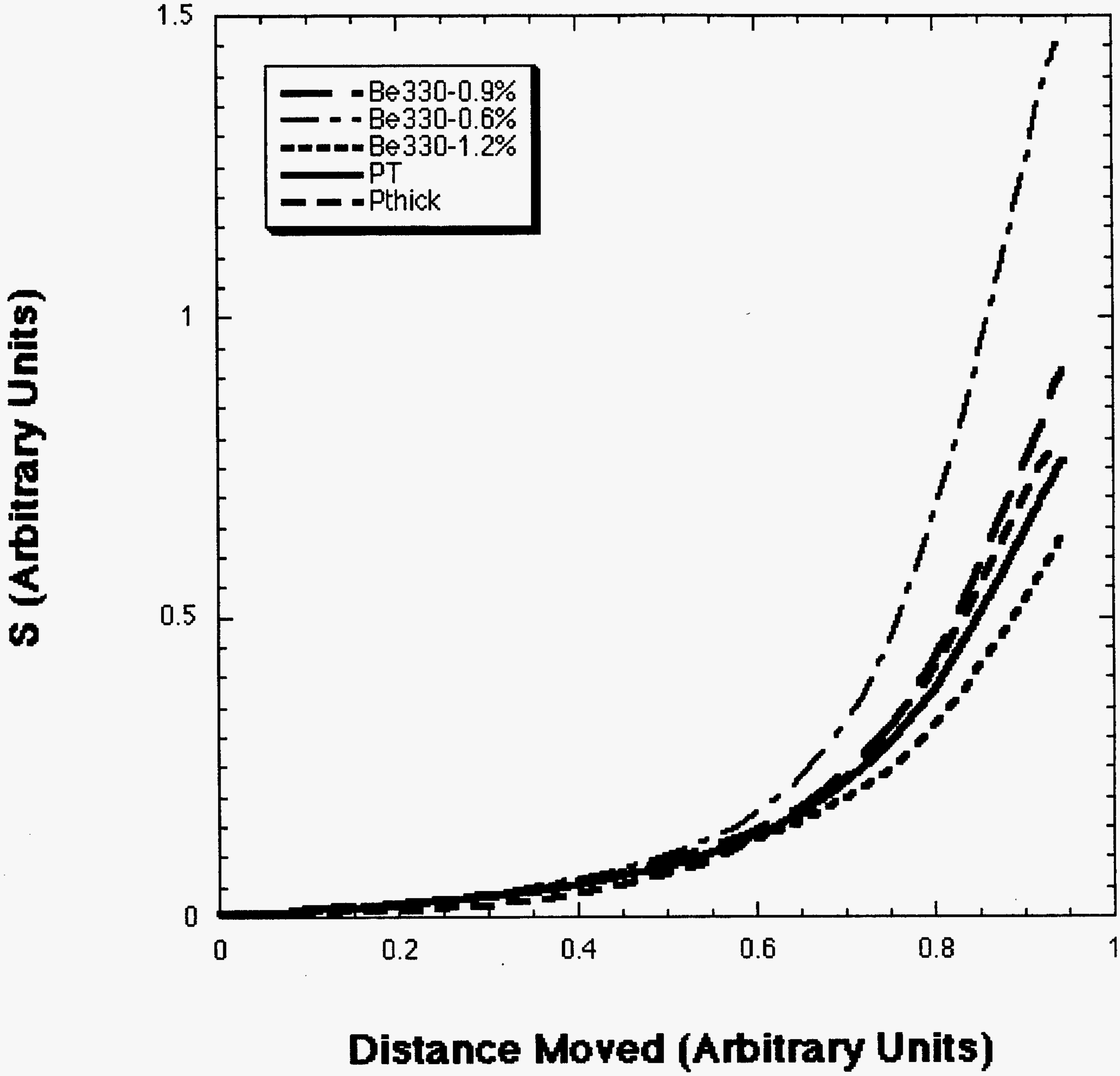
3-D Be300 Capsule
3-D PT Capsule
2-D PT Capsule
2-D Be330 Capsule
20
15
10
5
0
Yield (MJ)
0
1
2
3
4
5
6
7
8
Ice Roughness (microns rms)

Figure 3



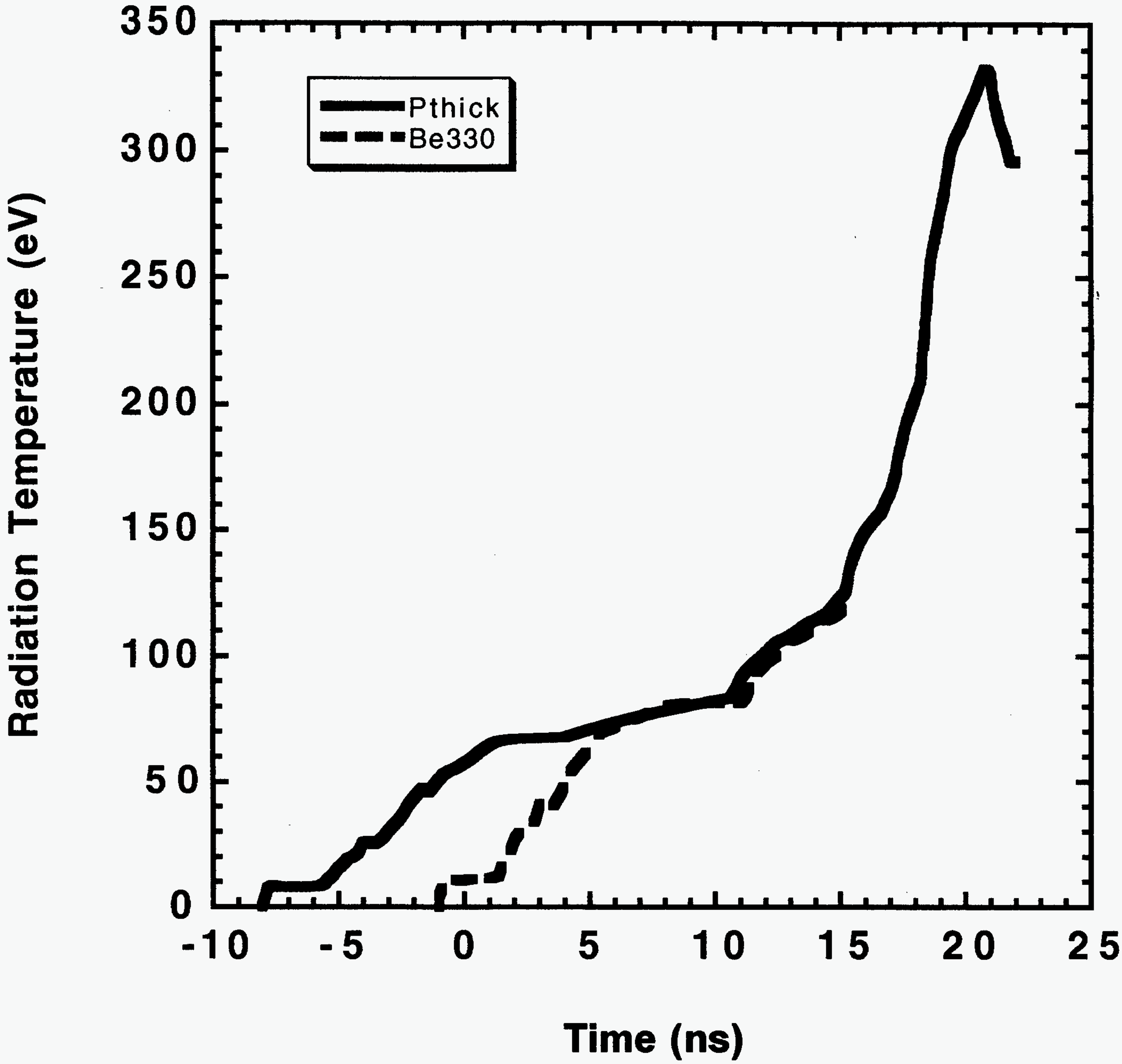
1.2
1
0.8
0.6
0.4
0.2
0
S (arbitrary units)
Be330-0.9%
Be330-0.6%
Be330-1.2%
PT
Pthick
0.4
0.5
0.6
0.7
0.8
0.9
1
Distance Moved (Arbitrary Units)

Figure 4



Be330-0.9%
Be330-0.6%
Be330-1.2%
PT
Pthick
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
S (Arbitrary Units)
Distance Moved (Arbitrary Units)

Figure 5



Radiation Temperature (eV)
Time (ns)
Pthick
Be330
350
300
250
200
150
100
50
0
-10
-5
0
5
10
15
20
25

Figure 6

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