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CHARACTERIZATION SPECIFICATIONS FOR BASELINE INDIRECT DRIVE NIF TARGETS

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ABSTRACT

Successful ignition in NIF will require targets that meet stringent standards as to symmetry, composition, and dimensions. We describe here the current understanding of specifications for baseline indirect drive targets of each of the three types of ablators: beryllium, polyimide, and plasma polymer. These specifications include the range of values for all targets of each group, and the variation in value allowed in a specific target of that group. They cover all of the components which make up a target, and which are critical to an implosion: the hohlraum and its components — windows, capsule support foil and gas fill — and the shell and its DT ice layer. These specifications are preliminary and incomplete; they will necessarily evolve with design details and with increasing understanding of target dynamics. They are compiled here as a reference for the ICF community and a basis on which to plan future work: to fill in the gaps and to develop thenecessary characterization techniques. Future work will also include the requirements for direct drive targets.

I. INTRODUCTION

NIF targets (shells and their hohlraums) will be substantially different than any targets being made today. They will be used at cryogenic temperatures (T<19 K), will be 2–4 times larger than current Omega targets and will undergo a similarly larger compression.[1-6] Each of the target components (Fig. 1 shows specifications typical of a target using a polyimide ablator) must be constructed with great precision in order to assure successful ignition.

The target specifications shown in Fig. 1, and detailed in the Appendix, are one of a large family of possible designs; their specified parameters, and their tolerance for deviations from the specified parameters will vary with expected drive temperature and energy, and with design optimization. The numbers quoted here are in the mid-range, suitable for a target which absorbs ~150 kJ of x-rays. These targets, while calculated to ignite and burn with gain ~10, stress the physics, and do not have much margin. If we are constrained to attempt ignition with such

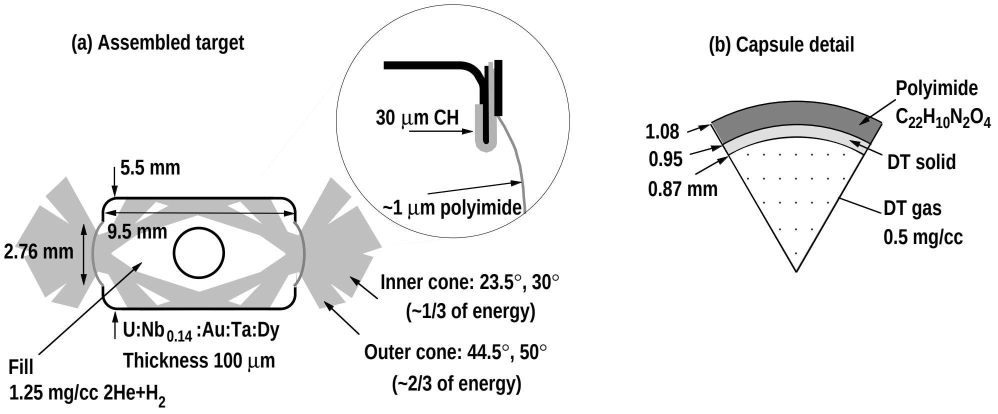

Fig. 1. Components of a typical NIF target. (a) the assembled target, and (b) the capsule structure.[1-4]

a target, it will be vital that all the specifications be met or exceeded. Getting ignition with half of NIF, if possible at all, would require some specs to be tighter than tabulated here. On the other hand, if we end up able to field high absorbed-energy capsules[4] the situation is likely to be much more forgiving with respect to fabrication specs, although not with respect to some of the laser and target physics issues. Current work by target designers[6] is expanding the parameter space under consideration. The specifications can also be modified by trading off deviations in one area with those in another. The numbers presented here are meant to represent approximately equal tradeoff of the various issues; failure to meet some of them is acceptable provided that appropriate other quantities are better than specified. Of course all numbers and their trade-offs are changing as our modeling capability improves and experiments are conducted on Omega and Z, and as the understanding of target fabrication limits improves.

We have attempted to be comprehensive, but only in so far as target performance is affected. We have not incorporated other system requirements (e.g. shrapnel considerations or other chamber survival issues). The numbers were originally generated separately by Haan and Wilson.[1,2] They were combined and then reviewed in a workshop at GA last fall. Some of the numbers are simply our judgement and are wide open to discussion. Others have a great deal of work behind them. The specifications and the design they reference are, of course, subject to change as work, understanding, and negotiations progress.

This compilation of specifications is published as a reference and resource for the ICF community. Its primary purpose is to identify the gaps and deficiencies for the target design community to fill in. In that regard, there are several major issues, mostly dealing with spatial fluctuations of target properties such as surface, composition, and density. We will discuss those in detail in the body of this manuscript.

Its secondary purpose is to establish and document the requirements for characterization of a NIF target. This is an area that is recognized as difficult, and there is substantial work on characterization development,[7-12] but it is being done piecemeal. Existing characterization capability should be evaluated against the complete set of requirements described here, areas requiring upgrade or new approaches identified, and efforts coordinated and annually reviewed to ensure that nothing is missed. These discussions will also benefit present and near-future experiments.

The next section describes the organization of the specifications, detailed in the Appendix, and summarizes their status. Subsequent sections then go into detail on three of the major unfinished areas: surface fluctuations in the ablator and in the ice, and compositional fluctuations in the ablator wall. The final section summarizes the areas needing work to generate a complete specification set.

II. TARGET SPECIFICATION LIST ORGANIZATION

The target characterization specifications have been put into three groups: The hohlraum, the shells, and setup in the target chamber. The target setup was judged to be a straightforward extension of cryogenic experimental setup, first on Nova and now on Omega, and presented no outstanding issues. The other two groups were further divided into sub-groups for different components and types of measurements. Table I shows each of those subgroups with a summary of the items that need work within each area. Each of the subgroups listed in Table I corresponds to a table in the Appendix with specifications for that area described and commented on in detail. The comments reflect the consensus of our discussion at a workshop last Fall, with some minor updating to take account of subsequent work.

There are three major areas needing work in the above specifications: 1) the allowed fluctuation spectrum of capsule surfaces, 2) of the inner ice surface, and 3) compositional variations within the capsule wall. They will each be discussed in more detail in the following sections.

III. CAPSULE SURFACE FLUCTUATION LIMITS

It is difficult or impossible for the designers to specify a unique surface roughness requirement since there are a large number of modes that can be traded off with each other. To date the approach has been to take a particular spectrum (Fig. 2) and consider multipliers on it. The “NIF reference” curve was developed by Cook[13] as the best shell one might reasonably expect to fabricate by extrapolation of the best shells shot on Nova. It is based on, and should be compared to, the average power spectrum of one dimensional surface profiles. The curve labeled “Haan formula” is a fit to the high-mode part of this spectrum, which the target designers have used as an assumed spectrum for simulations. The “low mode specs” were developed from calculating the yield of capsules with surfaces of increasing fluctuation power, and are shown in Table II. The “low mode specs” and the “Haan formula” are both meant to define the maximum allowed power spectrum of the 2-D surfaces. The 1-D and 2-D power coefficients are not exactly equivalent measures, but on the scale of this graph, the transformation correction is small. The Haan formula is given by:

Table I. Summary of specification issues. Details of specifications and their status are shown in expanded tables in the Appendix

	Category	Major outstanding issues
1	**Hohlraum**	
A	Walls	Work out details around LEH and window
B	Tenting (capsule support)	Design suitable anti-convection structure
C	Hohlraum gas Fill	
2	**Capsules**	
A	shape/thick	Develop specifications for isolated defects and for smoothness of inner surface
B	composition, density	Develop specifications for density fluctuations and impurities. The Be shell needs specs for spatial distribution of minor constituents and grain structure. The CH shell needs specs for spatial distribution of dopants. It might be necessary in some cases to estate specs in terms relevant to fabricators. Define the yield strength requirement for PI shell
C	ice composition	Set specifications for protium concentration and impurities
D	ice surface and thickness	Check consistency among specifications
3	**Target setup in target chamber**	

$$R_{lm} = 10/l^{1.5} + 0.08/[(l/60)^{0.7} + (l/1200)^{4}] \quad \text{(nm)} \qquad (1)$$

where R_{lm} is the spherical harmonic amplitude in nm, with normalization such that the rms in interval (l_1,l_2) is

$$\sigma = \sqrt{\frac{1}{4\pi}\sum_{l=l_1}^{l_2}(2l+1)\left|R_{lm}\right|^2} \qquad (2)$$

The index m is inactive, since surfaces are presumed isotropic (that is not necessarily true; see discussion below). The power in mode l, as plotted in Fig. 2, is $(2l+1)|R_{lm}|^2$.

Limits are set for particular targets by using a multiplier, M = typically 1 to 3, depending on the target robustness and drive spectrum. Some typical current values are M = 3 for baseline 300 eV beryllium capsules, M = 2 for baseline polyimide, and M = 4 for high-absorbed energy 250 eV beryllium capsules (assuming that the hohlraum physics for these designs ends up being possible). With M = 1, the rms σ = 10.3 nm for the Haan curve. Generally, this area requires more attention from the target designers; it would be useful to have an actual specification if possible, rather than multipliers on an assumed spectrum. There are also issues to be addressed in the overlap region between low and high modes.

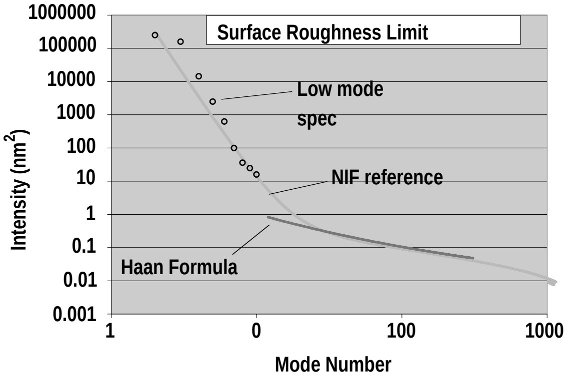

Fig. 2. Surface roughness requirements expressed as power spectrum of various fluctuation models. The “NIF reference” curve is an empirical requirement based on the best capsules used on Nova, and refers to the average fluctuations of 1-D profiles. The “Haan formula” curve is an analytic approximation to the high-mode part of this curve, and has been used by the target designers for their simulations. The “low mode specs” are allowed values of the two dimensional power spectra (assuming the fluctuation power is uniformly distributed) based on model calculations. The low mode specs are listed in Table 2. The high-mode limits are used with a multiplier, M = 1 to 3, depending on target robustness. Roughly, M = 3 for polyimide and Be, 1 for CH. The difference between 1-D and 2-D power spectra for both these cases is negligible.

It appears that when the low mode and high mode 2-D calculations are stitched together between modes 10 and 20, we will have a complete surface specification. But actually there are significant details that need to be worked out. There will be localized defects, especially on Be shells — an equatorial joint, and/or a fill hole — and many shells have a small but random number of additional

Table II. The allowed long wavelength deviations from sphericity for low modes of the outer surface and the ablator and fuel thickness. Excessive fluctuation in one mode may be offset by reduced fluctuations in other modes; the sum of the squares of the capsule mode amplitudes, each divided by its allowed values must be less than 30*M,[6] where M is a multiplier whose value depends on the robustness of the target

Mode	Outer radius (nm)	Ablator thickness (nm)	Fuel thickness (nm)
1	—	50	400
2	500	75	400
3	400	75	400
4	120	75	400
5	50	25	200
6	25	17	120
7	10	10	80
8	6	8	70
9	5	7	50
10	4	6	40

defects that present a large, localized concentration of fluctuation power in the area of mode 10–100. There is no understanding yet of the size of allowable fluctuations.

IV. DT ICE FLUCTUATION LIMITS

There are also multiple ice roughness specifications (Fig. 3). The spectrum used by the designers for most past calculations is:

$$R_{lm} = 1/(3l^{0.6} + 2.2\times10^{-7}l^{4}) \quad (\mu m) \qquad (3)$$

Recent work by Koch et al.,[14] has suggested that a better spectrum might be:

$$R_{lm} = 2.8/l^{1.5} \quad (\mu m) \qquad (4)$$

In Fig. 3 we have plotted these along with the low mode limit on the ice thickness fluctuations (since the ablator is much smoother than the ice, there is not a significant difference between ice thickness and inner ice surface roughness. Even for the ablator, this distinction becomes less and less important as the mode number increases — a trend evident in Table II). The notable difference in the overlap regime, around mode 10, is an indication of the different meaning of these numbers, in particular how much margin is allowed in the different cases.[6]

V. COMPOSITIONAL FLUCTUATION LIMITS

The compositional limits present two different sorts of problems. The first is the need to have specifications stated in a useful way. This problem came out most strongly in discussions of Be grain structure. The Be crystals are anisotropic, with sound speed variation of ~10% along different axes. As a result, there may be a fluctuation in the acoustic thickness seen by the first shock wave (even if individual grains are randomly oriented), which is separate from any physical thickness variation.[9] One can specify an upper limit on the fluctuation of the wall's parameters needed for successful ignition, in a manner entirely analogous to the allowed fluctuation power spectra shown in Figs. 2 and 3; it is easy to evaluate the additional degradation when considered in that manner. However, the target fabricators cannot look at and manipulate acoustic depth fluctuations; they deal with grain sizes and orientations. There was a strong feeling in our workshop that the specifications must be stated in ways that can be related to fabrication parameters; that will require discussions between fabricators and designers to develop multiple, but equivalent, descriptions of some specifications, and to make sure that they remain equivalent as the specifications evolve.

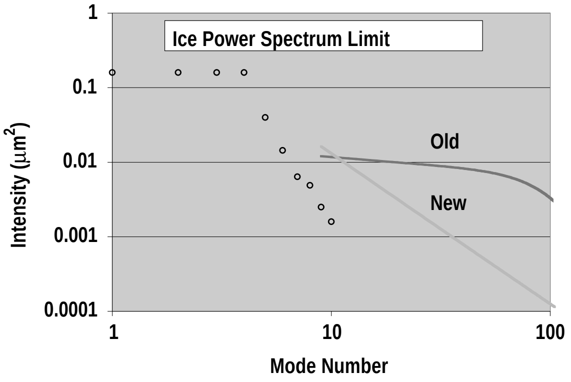

Fig. 3. Surface fluctuation limits for the inside fuel surface. There are three possible specs; the circles come from Table 2, the lines labeled "old" and "new" from Eqs. (3) and (4) in the text, respectively. This is used with a multiplier, M = 1 for CH, 1.5 for polyimide, and about 4 for Be. With the new spectrum the allowed multipliers will be somewhat bigger.

The second problem is in the non-uniform distribution of impurities in polycrystalline material such as Be. Neither oxygen (certainly an impurity, possibly a dopant) nor aluminum (a possible diffusion bonding agent) are actually soluble in Be; they concentrate in the grain boundaries. But there is no guidance regarding limits on the amplitude or scale length of the non-uniform x-ray opacity. This is an area of active work by the target designers.

VI. SUMMARY

The Appendix contains our best understanding of the characterization specifications for the three baseline indirect drive NIF targets. It is a snapshot of a work in progress. In general more detail is needed and the designers should strive to write their specifications in ways useful to fabricators.

Specifications for allowed surface distortions need substantial work. The designers have to combine their various limits to develop unified, complete and agreed upon sets of allowed power spectra that can be readily adapted to the widely varying shot conditions and target robustness. These specifications should give guidance on the allowed spatial variation in the fluctuation power that occurs on real shells.

It is evident in target development that one could have more specs than those listed. We concentrated on ones directly necessary for a successful shot; one could also consider properties necessary for successful fabrication such as transparency of capsule for IR enhanced DT ice layering, permeability of shell for DT filling, or measurements necessary for quantitative evaluation of experiments. Perhaps they or others should be added to the list presented here.

The effort culminating in this paper was started with an eye to verifying characterization capability. We have not focussed on that in this paper, but several areas jump out as needing extensive development—we just don't know how to do some of the measurements required by these targets—it is worst, but not limited to opaque targets.

It is clear that there is much to do to fully develop indirect drive NIF target specifications and the characterization techniques required to validate targets. We intend to publish an annual update to track the evolution and progress in these areas.

APPENDIX A

Table A-I. Specifications for: 1A. Hohlraum – walls

Specifications	Outstanding issues
Hohraum - dimension: Length 5 to 15 mm, diameter ~2/3 of length, laser entrance holes diameter approximately 1/2 of diameter. Dimensions measured to <10 µm, cylinder deviation of inner wall <10 µm. Any cracks, tubes, steps, or other details on the interior hohlraum wall should be measured with ~10 µm precision, depending on specific dimensions	Required precision needs further discussion & detailed drawing of specific hohlraums
Hohlraum – thickness: High-Z material in wall ~20 µm, measured to <0.5 µm if the high-Z wall is thinner than 10 µm. The thickness not important if >10 µm	
Hohlraum – composition: The hi-Z inner wall composition (U:$Nb_{0.14}$:Au:Ta:Dy is one example) should be measured to <5% for each ingredient	Specifications still in flux; experiments are underway to detail "cocktail" benefit
LEH tamper – thickness: If the LEH area is coated with plastic; the thickness of the plastic (~30 µm, within 10% of requested), measured to <1 µm	Verifying coating thickness on the inside wall of a hohlraum might be difficult; must we also verify uniformity? This might be made as a separate part
LEH tamper – dimension: The inner wall coating radius (probably about 500 µm past the LEH, within 50 µm of nominal), measured to ~50 µm	
LEH tamper – composition: CH	The composition needs to be determined, with special notice of any high-Z contaminants
LEH window – thickness: ~0.8 µm thick, measured to 10%	
LEH window – yield strength: sufficiently high to contain hohlraum fill gas	polyimide should be strong enough at above thickness, but that should be verified
LEH window – composition: polyimide	The actual material composition needs to be determined, with special notice of any high-Z contaminants

Table A-II. Specifications for: 1B. Hohlraum – Tenting

Specifications	Outstanding issues
Tent – Thickness: <100 nm, measured to 10 nm	Understand effect on thickness of stretching film over shell. Addition of more films for convection suppression is a possibility
Tent – uniformity: Surface & thickness uniformity the same as ablator layer	Specified over area of contact with shell
Tent – composition: The material needs to be determined, with special notice of any high-Z contaminants	Characterization requirements same as for ablator composition

Table A-III. Specifications for: 1C. Hohlraum – Gas Fill

Specifications	Outstanding Issues
Hohlraum Gas – Composition: He-H_2 mixture 2:1, measured to ~10% for all atomic fractions	
Hohlraum Gas – Density: 1.25 mg/cc, measured to ~10%	

Table A-IV. Specifications for: 2A. Capsule – Shape/Thick

Specifications	Outstanding issues
Capsule – outer radius: 0.6 to 2 mm, within 3 µm of specified, measured to 1 µm	Must be known when cold
Capsule – ablator thickness: 1/12 to 1/5 of radius, within 0.5 µm of specified, measured to 0.25 µm	
Capsule – surface distortions: Low modes of outer surface within specs shown in Table 2, with appropriate multiplier, measured to <25%	Are there distortions on cooling?[11] Need specification for isolated defects or an adequate trace pattern for averaging properties. The spec includes the area over the joint and/or fill hole in a Be shell
Capsule – wall fluctuations: modes ≤ 10 (up to 15 would be better) within specs shown in Fig. 2, with appropriate multiplier, measured to <25%	Further discussion is necessary. Is it better to specify inner surface and concentricity instead? Need spec for isolated known defects, like a fill hole or joint in Be shell, and an understanding of an adequate trace pattern for unknown defects
Capsule – surface roughness: characterize modes ≤120 (up to 200 would be nice). Ensure measurements representative of surface to 10-20%	Further discussion is necessary. What about isolated defects? What is an adequate trace pattern?
Capsule – ablator inner surface roughness: specs TBD if relevant (might also be important as seed for formation of ice crystals to control DT ice surface roughness)	Perhaps use a multiplier relative to outside surface?
Be Capsule – fill hole: < ~ 2 µm in diameter. Its dimensions and detailed shape should be measured to <20% on all numbers	This is for a hole filled with DT. A glue or Cu filled is worse. A Be plugged one would be characterized as an isolated surface and wall defect

Table A-V. Specifications for: 2B. Capsule – Composition, Density

Specifications	Outstanding issues
Capsule – composition: Each element measured to <5% of its nominal fraction for all materials expected to be present. Be is expected to be doped with Cu (0.9%) or O (2.5at%), and CH doped with Ge with a radially varying concentration. Polyimide will be undoped	Perhaps polyimide composition varies? Expected materials include impurities above an insignificant contribution, defined next
Capsule – Low level impurities: <100%/Z^2 (*i.e.*, 0.1% for Si, 0.01% for Sn)	Further discussion needed to define spec
Capsule – High level impurities: if acceptable their concentration must be measured to <50%/Z^2	Further discussion needed to define spec
Capsule – x-ray density: variations should be <0.01% in optical depth through the shell, at lateral scales between 50 and 500 µm (modes 12–120 — up to 200 would be nice), and x-ray energies between 0.1 and 3 keV	This includes porosity
Capsule – mass density: average measured to 2% absolute and 0.5% relative to other targets	Need more detail; some ablator shells have layers with noticeable local density fluctuations; experiments will be needed to determine fluctuation amplitude
Capsule – dopant variation: for Be spatial distribution measured to 0.1% (Cu) or 0.2%(Al) over 10 µm. For Ge in CH spec TBD. Polyimide is not currently expected to be doped; Br dopant may be called for, spec similar to Ge in CH	Further discussion needed to define spec for CH
Be Capsule – acoustic depth: Spec TBD	Needs experiments and discussion[9] – connection between room temp properties and shock wave properties unclear
Be & PI Capsule - yield stress: > 200 Mpascal (~30 kpsi)	To avoid cryogenic storage. Similar for polyimide?? Needs further discussion

Table A-VI. Specifications for: 2C. Capsule—Ice and Gas Composition

Specifications	Outstanding issues
DT ice – Tritium: concentration 47–53%, measured to <2%	
DT ice – Protium: concentration <0.05% measured to ~0.03% (preliminary estimated numbers)	Needs off-line research to see amount of proton exchange, and more detailed work from designers
DT gas - He^3: density <0.1 mg/cc, within 0.025 mg/cc of nominal, known to 0.01 mg/cc	Measure at fill time, calculate effect of delay before shot
DT ice – other impurities: concentration <0.002%, measured to 0.002%	Needs further discussion
DT ice – mass: measured to 2%	Not needed as a separate spec – we separately specify density and thickness

Table A-VII. Specifications for: 2D. Capsule —Ice Surface and Thickness

Specifications	Outstanding issues
DT ice – thickness: Average thickness (50–120 µm, within 1 µm of request), known to 0.5 µm	Perhaps measured at filling using mass?
DT ice – thickness fluctuations: Low mode variation less than specified in Table 2, using appropriate multiplier, known to 25%	Measured at shot time with shell inside hohlraum. Overlap of low and high modes must be sorted out
DT ice surface roughness: High modes less than specified in Fig. 3, with appropriate multiplier, known to 25%	Measured at shot time inside hohlraum. For subsequent analysis of shot, power spectrum of the surface should be known versus mode number in 3-D, to within 25 to 50% of the power per mode, at all modes 1–120. (up to 200 would be better)

Table A-VIII. Specifications for: 3. Target setup in target chamber – all are measurements which have to be done in the target chamber at shot time. They seem straight-forward extensions of experience at Nova and Omega, so are well in hand

Specifications	Outstanding issues
The centroid of the laser entrance holes within 5 µm of nominal	
The capsule positioned relative to the hohlraum within 10 µm	
The axis of the hohlraum needs to be within 1×10^{-3} radians of the target chamber axis, within 1×10^{-3} radians (5 µm displacement with a 5 mm lever arm)	
The DT gas density (0.3 to 0.5 mg/cc, <0.025 mg/cc of requested) measured to <0.01 mg/cc – corresponds to knowledge of temp inside capsule < ~50 mK	The requested DT density, and therefore capsule temp. may be affected by calculated amount of He^3 at shot time

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