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The Prospects for High Yield ICF with a Z-pinch Driven Dynamic Hohlraum

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Recent success with the Sandia Z machine has renewed interest in utilizing fast z-pinches for ICF. One promising concept places the ICF capsule internal to the imploding z-pinch. At machine parameters relevant to achieving high yield, the imploding z-pinch mass has sufficient opacity to trap radiation giving rise to a "dynamic hohlraum." Our concept utilizes a 12 MJ, 54 MA z-pinch driver producing a capsule drive temperature exceeding 300 eV to realize a 550 MJ thermonuclear yield. We present the current high-yield design and its development that supports high-yield ICF with a z-pinch driven dynamic hohlraum.

1. Introduction

During the past few years there has been extraordinary progress in developing fast z-pinches for intense, high-energy density x-ray sources [1]. These sources are produced by converting the imploding z-pinch material's kinetic energy into radiation as it stagnates on the axis of the machine. The Sandia Z machine in this configuration routinely produces 2 MJ of soft x-rays with peak powers of ~ 200 TW utilizing tungsten wire array loads [2]. For driving an ICF capsule internal to the z-pinch, the conversion of imploding kinetic energy to radiation occurs off the axis providing an open channel filled with radiation. This conversion can be realized through collision with a thin annulus of solid density material or a low-density solid foam cylinder called a converter. If the imploding z-pinch material in combination with the converter has sufficiently high opacity, radiation can be trapped internal to the imploding z-pinch. This gives rise to what is called a "dynamic hohlraum". Historically this has also been known as a flying radiation case [3] or an imploding liner hohlraum [4]. Implosion of this optically thick radiation case formed by the converter and z-pinch mass increases the internal radiation energy density resulting in high radiation temperatures. Recent experimental work at Sandia on the Z machine has produced radiation temperatures exceeding 200 eV in optically thin volumes of approximately 1 mm diameter [5] for LANL applications. Analytic scaling work and detailed modeling have shown that for machine currents approaching 60 MA, radiation temperatures near 300 eV can be obtained. These high temperatures coupled with adequate pulse shaping are sufficient for driving ICF capsules [6].

Utilizing a dynamic hohlraum concept for driving ICF capsules offers a complimentary approach to high yield compared with two-pinch systems such as the Z-pinch Driven Hohlraum [7]. By placing the capsule internal to the imploding z-pinch plasma, high efficiencies of ~ 20% in converting driver energy to absorbed capsule energy can be realized which is approximately a factor of 2 higher than the two-pinch systems. Furthermore, for comparable single pinch drive currents the peak dynamic hohlraum drive temperatures are ~

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50 eV higher than the two pinch systems providing more capsule design flexibility. However, the penalty for the high coupling efficiency and high temperature is the close coupling of the capsule with the z-pinch; this means a designer must be concerned with direct shock coupling to the capsule and the details of the Rayleigh-Taylor unstable z-pinch sheath which may influence the radiation field. A two pinch system essentially de-couples the capsule from the z-pinch which improves symmetry but at a reduced drive temperature. Hence for the dynamic hohlraum concept, the risk is concentrated in the target while for the two-pinch systems, the risk is mostly in the pulsed power which demands precise timing of two nearly identical stagnating z-pinch plasmas. With both common and complimentary risk factors, the dynamic hohlraum and z-pinch driven hohlraum are the two concepts being pursued for achieving high-yield on a future z-pinch machine.

2. Concept Design

The high-yield dynamic hohlraum point design that has recently been developed is shown graphically in *Figure 1*. This design embeds a 5.5 mm diameter cryogenic capsule in a low-density (5 mg/cc) polystyrene foam. Dimensions of the A-K gap, wire array radius, wire array length and foam radius are similar to those currently in use on the Sandia Z machine. *Table I* contains the physical dimensions and capsule specifics for the high-yield design shown in *Figure 1.* The peak current for this high-yield design is 54 MA with an implosion time of ~ 125 ns which is based on a pulsed power design option for the next generation Sandia z-pinch machine named ZX. Having a ZX machine at 54 MA would allow full-scale design testing with high yield on a future machine achieved only through addition of cryogenics and blast containment.

The radiation field seen by the capsule is produced in three phases: shock and PdV heating of the foam; collision between expanding capsule ablator material and imploding wire array and foam mass; and shock and material stagnation on the axis. As current starts flowing in the

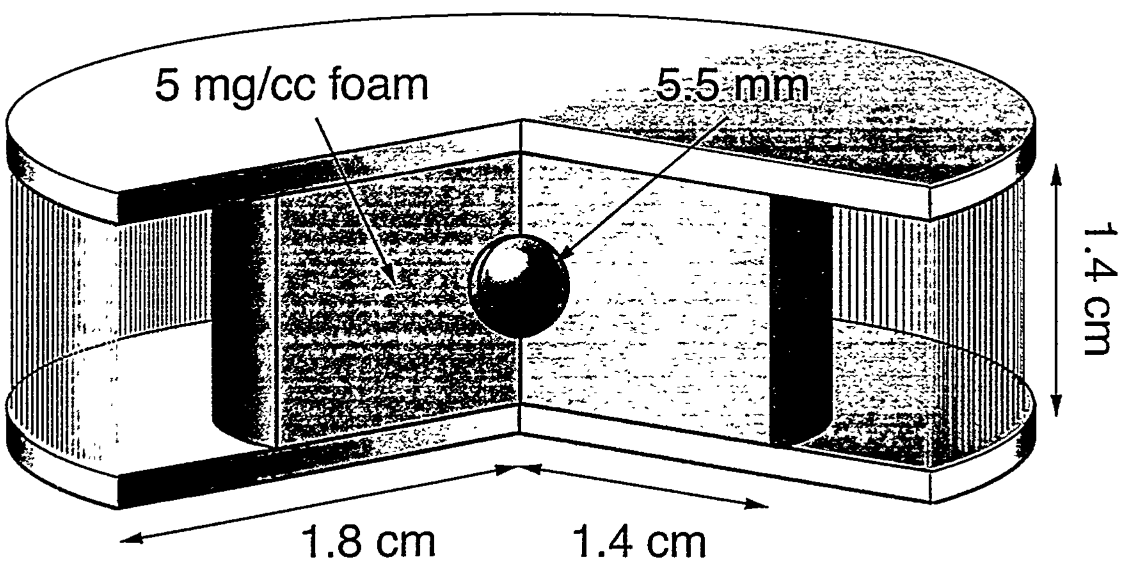

Figure 1: Dynamic hohlraum high yield design geometry.

wire array plasma, magnetic field and radiation interact with the low density polystyrene foam. The result of this interaction is a weak shock in the foam that quickly attenuates. However, once the wire array plasma impacts the foam, a strong shock is created which starts heating and compressing the foam. From simulation it is observed that the shock velocity is only slightly higher than the imploding wire array plasma velocity resulting in a "snowplowing" of the foam. At the shock front, the foam heating is equally divided between shock heating and PdV heating while between the shock front and the wire array plasma/foam material interface, PdV heating is the dominant mechanism.

This heating of the foam produces radiation that forms the initial foot-pulse for driving the capsule. For this phase of radiation production it is important to note that the 52 mg of imploding wire array mass (tungsten) has sufficient opacity to form a radiation case trapping the radiation produced in the foam. However, calculations have shown that Rayleigh-Taylor instability growth can result in regions of low-optical depth (~ 1) allowing radiation loss. Future fully-integrated calculations will be required to ultimately determine the R-T impact on the capsule-observed radiation field. During this foam heating phase, radiation transport is a critical physics issue as the foam ahead of the radiation front is still optically thick until the radiation wave has burned through. It should be noted that for most of the foot-pulse duration the radiation field is slightly "equator hot" resulting in an initially asymmetric implosion.

Table I. High yield design dimensions and parameters.

Wire array material:	W	Capsule ablator:	Be
Wire array radius:	1.8 cm	Ablator radius:	0.2750 cm
Wire array length:	1.4 cm	Ablator thickness:	0.0220 cm
Wire array mass:	52 mg	Capsule preheat layer:	Be + 3% Cu
A-K gap:	3.5 mm	Preheat layer thickness[a]:	0.0040 cm
Foam radius:	1.4 cm	Fuel:	DT
Foam density:	5 mg/cc	Fuel thickness:	0.0240 cm
Foam material:	CH	Fill gas:	DT
Foam mass:	43 mg	Fill density:	0.0005 g/cc

The main radiation drive pulse begins when the expanding ablator material (beryllium) meets the inrunning shock and imploding foam and tungsten. This collision results in a significant increase in the radiation temperature and a slowing of the imploding foam and tungsten. Effectively, the expanding capsule ablator is able to "standoff" the imploding mass allowing the tungsten to form a quasi-spherical case surrounding the capsule. This is known as "ablative standoff" and is a critical physics issue for this concept. In reality this collision interface will be unstable and further complicated by both the ablator and foam/tungsten surfaces being perturbed due to R-T instability. Understanding "ablative standoff" is key to credibility of this design.

The third and final phase of radiation production occurs when the shock and material start to stagnate on the axis beyond the capsule position. The result is a significant increase in the radiation temperature that is higher at the capsule pole. Consequently the current capsule is designed to implode such that the late-time pole hot drive will not heat the fuel and spoil ignition. However, since the stagnation occurs very near ignition time, the design needs to be tested for robustness to variations which alter the drive temperature history since this can impact the "race" to ignition and burn. The capsule performance parameters for this high yield dynamic hohlraum design are given in *Table II.*

Table II. Hohlraum and capsule parameters for present high yield dynamic hohlraum design.

Peak drive temperature	eV	350
IFAR		48
Implosion velocity	cm/μs	33
Convergence ratio		27
Peak density	g/cc	444
Total ρr	g/cm^2	2.14
DT KE @ ignition		50%
Driver energy	MJ	12
Absorbed energy	MJ	2.3
Percent absorbed		19%
1D clean yield	MJ	527
Burnup fraction		34%
Outer shell radius	mm	2.75
Inner shell radius	mm	2.49

3. Physics Issues and Credibility

Discussing the prospects for achieving high yield with a dynamic hohlraum fundamentally addresses the issue of credibility for a given design. Establishing credibility must be done both computationally and theoretically for the design and experimentally by demonstrating an understanding of the critical physics and scaling. Since high yield is destined for a future machine and we must rely on scaling, the critical physics issues (*Table III*) are determined from the design simulations and the need to establish computational credibility. A complementary experimental program will be also be needed to validate our modeling tools and investigate issues beyond our current modeling capability (e.g. 3D features). Ultimately

Table III. Partial listing of dynamic hohlraum high yield design critical physics issues.

Z-pinch/converter interaction and radiation production
Array/converter collision hydrodynamics Radiation production via shock & PdV heating Radiation trapping
Radiation transport
Transport through converter Transport in capsule materials
Standoff
Ablative standoff Shock wave standoff Imploding material standoff
Radiation symmetry
Macroscopic (cylinder to sphere) Macroscopic (azimuthal) Microscopic (R-T instability)
ICF Capsule performance
Ignition margin Instability & mix Yield sensitivity Implosion symmetry Preheat tolerance

the credibility for the high yield design will be based on confidence in the design calculations and our ability to successfully validate the modeling and simulation.

With both advantages and disadvantages, credible design calculations for the dynamic hohlraum concept are inherently fully integrated. Over the past year we have made significant progress in our ability to credibly model these complex dynamic hohlraum systems. At this point all of our design simulations have been performed with the 2D radiation magnetohydrodynamics code Lasnex [8]. Inclusion of the Rayleigh-Taylor unstable z-pinch dynamics has required a significant effort in the development of ALE algorithms to handle complex computational mesh evolution. *Figure 2* shows a snapshot taken from a Lasnex simulation of the high-yield design. Adequate resolution of the R-T instability along with detailed atomic physics leads to very expensive simulations which currently limit our modeling progress. This is clearly a disadvantage to performing fully integrated simulations; faster processors and a parallel capability will greatly help this effort.

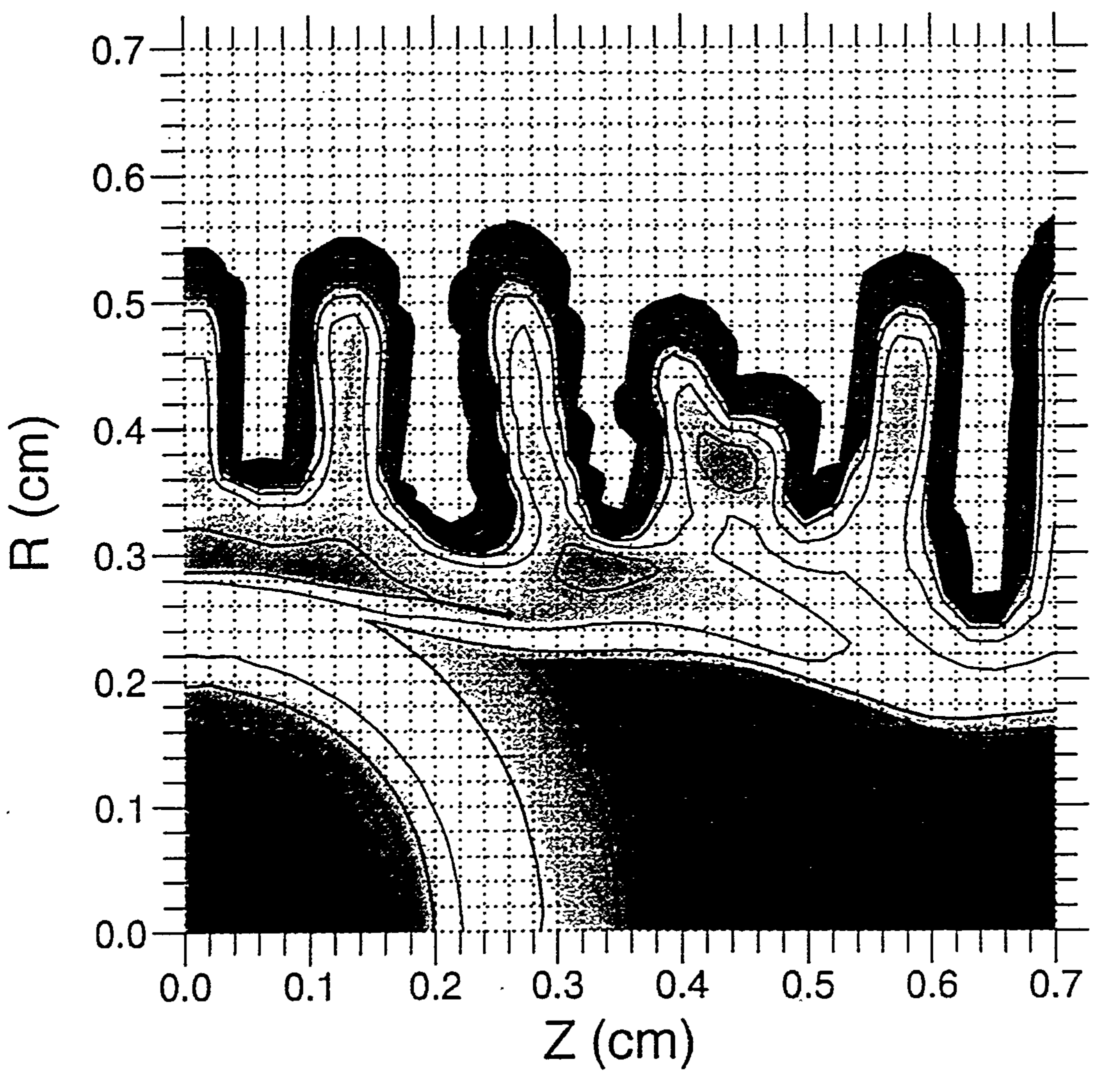

Figure 2: Shaded log(density) contour plot from 2D Lasnex design simulation showing unstable z-pinch plasma wrapping around imploding capsule.

Lengthy fully integrated simulations have led to a two-step iterative design process. From the 2D simulations a capsule drive temperature history is extracted which is used in very finely zoned 1D capsule implosion calculations. These 1D capsule simulations are very fast and quickly allow determination of "clean" capsule performance. Due to the close coupling between the capsule and the imploding z-pinch, the capsule dynamics affect the radiation field and vice-versa. Hence any significant changes to the capsule design are made in the 2D simulations and the process continues iterating. This process is required since this design critically depends on the "ablative standoff" of the capsule ablator material against the imploding foam and z-pinch mass for producing radiation. *Table II* shows that the high-yield capsule used in this dynamic hohlraum design has performance parameters very similar to the NIF ignition designs [9] and hence has a high degree of 1D credibility.

Recently we have started to examine the inherent implosion stability of the high yield capsule utilized in this design. While the fully-integrated design simulations allow investigation of low-order mode instability growth, limitation on capsule zoning due to simulation run time prohibits investigation of the full mode spectrum instability development. Hence separate capsule stability calculations are required. These are finely zoned 2D simulations of a small angle (~ 15 degrees) capsule sector that have been seeded with both ice layer surface and ablator surface perturbations. Perturbations are based on measured β-layered DT ice surface [10] and Nova plastic shell surface roughness for determining the mode spectrum (modes 12-160) and rms roughness. The numerical procedure for configuring these multimode simulations is outlined in Dittrich *et al.* [11]. *Figure 3* shows the impact of ice and ablator surface roughness on capsule yield. At an intrinsic ice surface roughness of 1 micron, the yield is degraded by only 10% demonstrating that no ice layer smoothing will be required for this capsule. Further optimization of the capsule design will explore the inherent capsule stability increasing the tolerance to surface roughness.

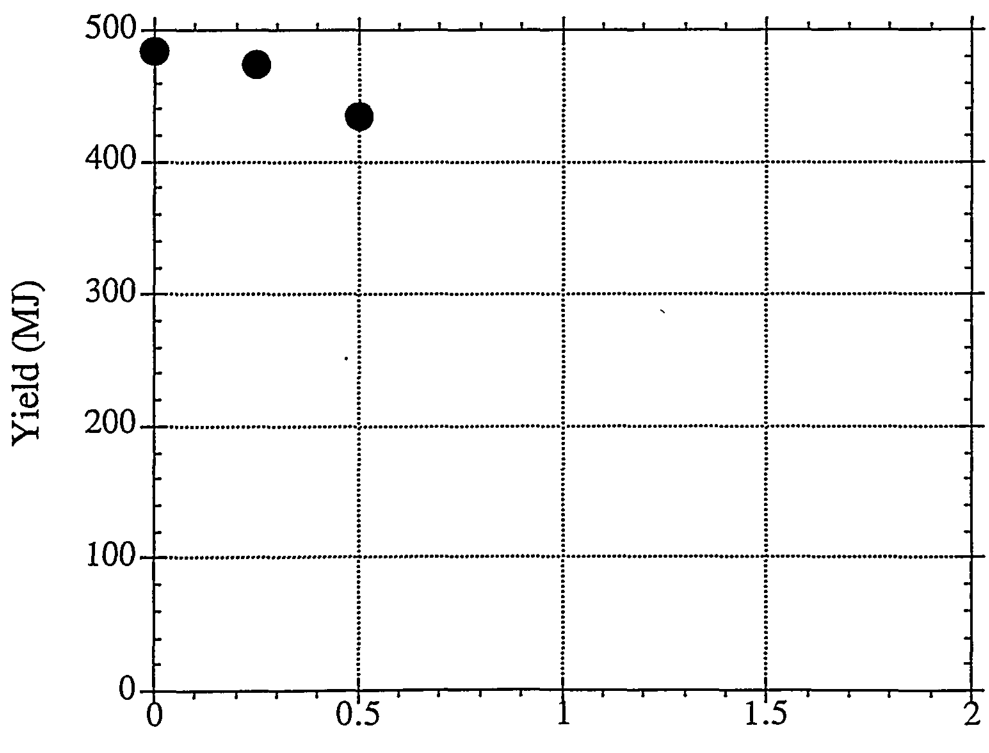

Figure 3: Ice and ablator surface roughness degradation of capsule yield.

In addition to the development of computer simulation capability for the dynamic hohlraum, an analytic theory has been developed (S. A. Slutz, manuscript in preparation) for determining radiation temperature scaling. This model currently uses an annular foam converter and includes radiation transport, detailed energy accounting and radiation losses to electrode walls and the capsule. *Figure 4* shows scaling curves of radiation temperature versus z-pinch drive current for various case-to-capsule ratios along with data points from 1D

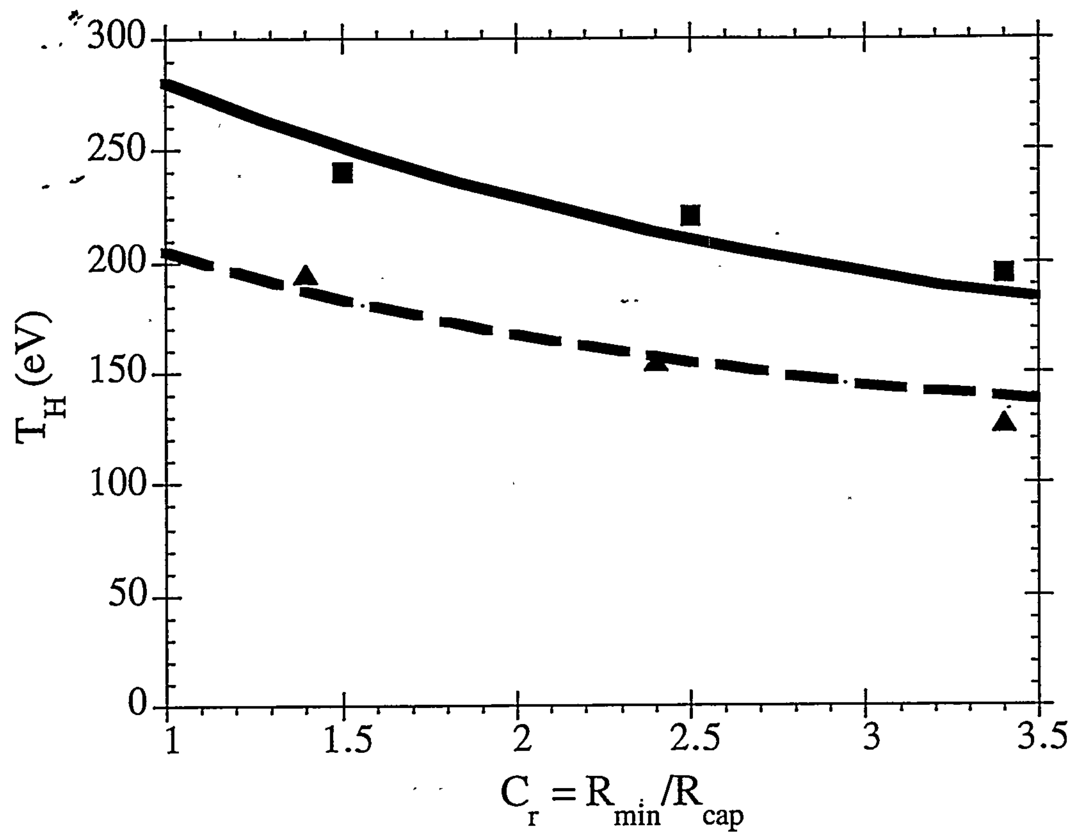

Figure 4: Dynamic hohlraum analytic scaling model temperature as a function of tungsten/converter minimum radius and initial capsule radius ratio. Dashed curve corresponds to Z machine (20 MA, R_{cap} = 1mm) with solid curve a future machine (60 MA, R_{cap}=2mm). Single points are from optimized Lasnex simulations.

Lasnex simulations. The model shows that even without benefit of ablative standoff, a 60 MA driver can produce temperatures necessary for driving ICF capsules. Currently work is underway to include ablative standoff in this analytic model; this will aid in fast coverage of parameter space for optimization of the design and minimization of the required z-pinch driver.

4. Summary

Based on recent success with fast z-pinches for x-ray sources and the high-temperatures obtained in dynamic hohlraum configurations, we have designed a high yield ICF target configuration for a future z-pinch facility. Significant progress has been made in developing a necessary fully integrated modeling capability for these highly coupled systems. The current design is moving toward credibility computationally with key capsule performance parameters similar to NIF designs. Further work is being done to determine the effects of the wire array R-T instability on the capsule. Additionally, the experimental effort is being restructured and focussed on issues required to validate our modeling capability and understand the fundamental physics issues for this high yield concept.

5. Acknowledgement

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References

[1] M. K. Matzen, Z pinches as intense x-ray sources for high-energy density physics applications, Phys. Plasmas 4 (1997) 1519-1527.

[2] R. B. Spielman, C. Deeney, G. A. Chandler, M. R. Douglas, D. L. Fehl, M. K. Matzen, D. H. McDaniel, T. J. Nash, J. L. Porter, T. W. L. Sanford, J. F. Seamen, W. A. Stygar, K. W. Struve, S. P. Breeze, J. S. McGurn, J. A. Torres, D. M. Zagar, T. L. Gilliand, D. O. Jobe, J. L. McKenney, R. C. Mock, M. Vargas, and T. Wagoner, Tungsten wire-array Z-pinch experiments at 200 TW and 2 MJ, Phys. Plasmas 5 (1998) 2105-2111.

[3] J. Brownell, R. L. Bowers, K. D. McLenithan, and D. L. Peterson, Radiation environments produced by plasma z-pinch stagnation on central targets, Phys. of Plasmas 5 (1998) 2071-2080.

[4] M. K. Matzen, T. W. Hussey, G. R. Montry, and J. E. Morel, A 1D scaling study of radiation sources using imploding liners, submitted for deposit to the National Technical Information Service, Springfield, VA 22161.

[5] T. J. Nash, M. S. Derzon, G. A. Chandler, R. Leeper, D. Fehl, J. Lash, C. Ruiz, G. Cooper, J. F. Seaman, J. McGurn, S. Lazier, J. Torres, D. Jobe, T. Gilliland, M. Hurst, R. Mock, P. Ryan, D. Nielsen, J. Armijo, J. McKenney, R. Hawn, and D. Hebron, High-temperature dynamic hohlraums on the pulsed power driver Z, Phys. of Plasmas 6 (1999) 2023-2029.

[6] J. Lindl, Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain, Phys. Plasmas 2 (1995) 3933-4024.

[7] J. H. Hammer, M. Tabak, S. C. Wilks, J. D. Lindl, D. S. Bailey, P. W. Rambo, A. Toor, and G. B. Zimmerman, High yield inertial confinement fusion target design for a z-pinch-driven hohlraum, Phys. of Plasmas 6 (1999) 2129-2136.

[8] G. B. Zimmerman and W. L. Kruer, Comments Plasma Phys. Control. Fusion 2 (1975) 51.

[9] T. R. Dittrich, S. W. Haan, M. M. Marinak, S. M. Pollaine, D. E. Hinkel, D. H. Munro, C. P. Verdon, G. L. Strobel, R. McEachern, R. C. Cook, C. C. Roberts, D. C. Wilson, P. A. Bradley, L. R. Foreman, and W. S. Varnum, Review of indirect-drive ignition design options for the National Ignition Facility, Phys. of Plasmas 6 (1999) 2164-2170.

[10] J. K. Hoffer, L. R. Foreman, J. J. Sanchez, E. R. Mapoles, and J. D. Sheliak, Surface roughness measurements of beta-layered solid deuterium-tritium in toroidal geometries, Fusion Technol. 30 (1996) 529-513.

[11] T. R. Dittrich, S. W. Hahn, M. M. Marinak, S. M. Pollaine, and R. McEachern, Reduced scale National Ignition Facility capsule design, Phys. Plasmas 5 (1998) 3708-3713.