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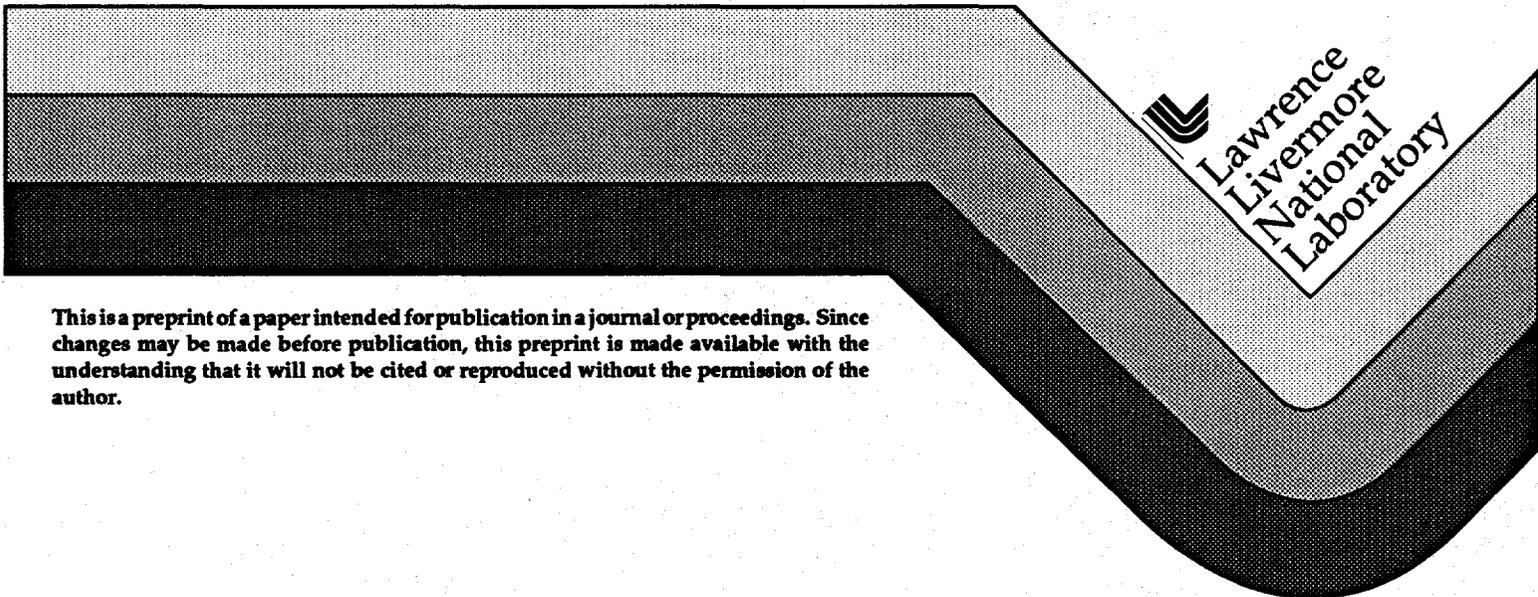
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The Physics of Radiation Driven ICF Hohlräume
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Abstract

On the Nova Laser at LLNL, we have recently demonstrated many of the key elements required for assuring that the next proposed laser, the National Ignition Facility (NIF) will drive an Inertial Confinement Fusion (ICF) target to ignition. The target uses the recently declassified indirect drive (sometimes referred to as "radiation drive") approach which converts laser light to x-rays inside a gold cylinder, which then acts as an x-ray "oven" (called a hohlraum) to drive the fusion capsule in its center. On Nova we've demonstrated good understanding of the temperatures reached in hohlraums and of the ways to control the uniformity with which the x-rays drive the spherical fusion capsules. In this lecture we briefly review the fundamentals of ICF, and describe the capsule implosion symmetry advantages of the hohlraum approach. We then concentrate on a quantitative understanding of the scaling of radiation drive with hohlraum size and wall material, and with laser pulse length and power. We demonstrate that coupling efficiency of x-ray drive to the capsule increases as we proceed from Nova to the NIF and eventually to a reactor, thus increasing the gain of the system.

I. Introduction to ICF

In the inertial confinement approach to fusion, (ICF), spherical capsules containing Deuterium and Tritium (DT)-the heavy isotopes of hydrogen- are imploded, creating conditions of high temperature and density similar to those in the cores of stars required for initiating the fusion reaction. When DT fuses an alpha particle (the nucleus of a helium atom) and a neutron are created releasing large amounts of energy. If the surrounding fuel is sufficiently dense, the alpha particles are stopped and can heat it, allowing a self sustaining fusion burn to propagate radially outward and a high gain fusion micro-explosion ensues.

To create those conditions the outer surface of the capsule is heated (either directly by a laser or indirectly by laser produced x-rays) to cause rapid ablation and outward expansion of the capsule material. A rocket-like reaction to that

outward flowing heated material leads to an inward implosion of the remaining part of the capsule shell (called the "pusher"). The pressure generated on the outside of the capsule can reach nearly a gigabar (a billion times atmospheric pressure), generating an acceleration of the shell of about 10 trillion gees, and causing that shell to reach, over the course of a few nanoseconds, an implosion velocities of 300 km/sec. When the shell and its contained fuel stagnates upon itself at the culmination of the implosion, most of the fuel is in a compressed shell which is at 1000 times solid density. That shell surrounds a hot spot of fuel with sufficient temperature (roughly 10 keV or 100 million degrees) to ignite a fusion reaction.

The capsule must be uniformly heated over its entire surface to cause uniform compression of the fuel to the center. With direct drive, this uniform heating of the capsule is caused by simultaneously illuminating the capsule from all sides with many laser beams. With the recently declassified concept of indirect drive, the capsule is positioned in the center of a cylindrically symmetric container called a hohlraum. Laser beams enter the hohlraum through holes in the end caps, heat the walls of the cylinder, which then radiate soft x-rays, filling the hohlraum with a bath of radiant energy. This energy causes the fuel capsule to implode. Typically, 70-80% of the laser energy can be converted to x-rays. The hohlraum concept leads to a natural, geometric uniformity of x-ray flux on the capsule surface, since two points close to one another on the capsule surface "look out" at the heated hohlraum walls and see a nearly identical sections of the walls and hence a nearly identical heat environment.

II. The National Ignition Facility

We have designed targets for a new laser, the National Ignition Facility (NIF), a 1.8 MJ, 500 TW glass laser. The hohlraum is made of a high atomic number material such as gold which maximizes the production of x-rays. The hohlraum is roughly 1 cm long and 1/2 cm in diameter, and is predicted to contain an x-ray intensity of about 10^{15} W/cm² or an equivalent black body radiation temperature of about 300 eV (=3 million degrees- a very hot oven indeed!). The capsule is composed of a low atomic number shell (e.g. beryllium or plastic) which maximizes the ablation pressure created by the absorbed x-rays. The DT is mainly in the form of a frozen layer on the inside of that shell. The capsule diameter is roughly 2mm.

The target is predicted to give a yield of 10-20 MJ or a gain of 10-20. Similar gains are expected from direct drive targets, which the NIF will also explore.

Since it only requires about 10 MJ/gm to compress DT to 1000 times its solid density, and fusion yields about 100 GJ/gm, we might expect gains of 10,000. However, only about 10% of the x-ray energy is coupled to the capsule (the rest soaks into the hohlraum walls and escape out of the laser entrance holes in the endcaps). The hydrodynamic "rocket efficiency" of absorbing heat on the capsule surface, ablating the material, and converting that energy to kinetic energy of the imploding shell turns out to be about 20%. On the NIF scale target, only about 10% of the fuel burns before it disassembles. These factors lead to the gain 10-20 result. For a larger scale, reactor size driver, the physics of hohlraums and its diffusive loss of x-rays to the walls, allow for closer to 20% coupling to the capsule. Moreover the larger scale target has more inertia, hence will stay confined longer before it disassembles, and will burn 30% of its fuel, leading to gains in excess of 100, allowing the possibility of ICF commercial reactors.

III. Experiments on Nova

Recently¹ we have used the Nova laser at LLNL to study the target physics issues that can most impact the NIF target performance. A significant fraction of the experiments were done as a collaborative effort between ICF researchers at LLNL and their counterparts from the Los Alamos National Lab. As a result of these experiments we are building up confidence in the success of the NIF target.

III.a Plasma Physics Issues

The first issue is laser plasma coupling. Laser driven parametric instabilities might result in laser light scattering and production of high energy electrons. The light scattering might degrade symmetry and/or represent a loss of potential drive energy, and the high energy electrons can cause capsule preheat which reduces the achievable compression.

To study these issues we used 9 of Nova's 10 beams to create a large 2-3 mm scale plasma similar in conditions of temperature and density to a plasma a typical beam of NIF might traverse. The 10th beam was configured as close as possible to NIF conditions and used as a probe to measure whether or not it would couple properly to the target. We measured acceptably low levels of scattering, (about

5%) and the hot electrons created were of sufficiently low temperature so as to not cause any problems for the NIF target.

III.b Drive and Symmetry

The second issue, assuming the laser has succeeded in entering the hohlraum and absorb on the walls, is x-ray drive and symmetry. We must understand the efficiency of converting laser light to x-rays, and the relative amounts of energy absorbed by the capsule vs. those absorbed by the walls. The flux onto the capsules must be sufficiently uniform to allow the capsules to converge a factor of 25–35. For a capsule to achieve convergences this large and remain nearly spherical, the time integrated x-ray fluxes must be uniform to 1–2%.

On Nova we measured the temperatures reached by laser heated hohlraums by observing the spectrum of x-rays emitted by the walls and by observing the radiation driven shock emerging through a plate of aluminum positioned on the hohlraum wall. Both methods gave consistent results. Temperatures up to 300 eV were achieved. Our simulation codes matched the data quite well. Since temperature is the result of a balance of x-ray sources (the conversion of laser light to x-rays) and x-ray sinks (the loss of x-rays absorbed by the walls of the hohlraum) this agreement could be the result of compensating errors. Therefore we separately measured the "sinks" by measuring the time it took for x-rays to burn through thin patches of the hohlraum wall. This too turned out to be in excellent agreement with our theoretical predictions. Thus our confidence in the predicted hohlraum temperatures on the NIF is quite high.

Since hohlraums naturally, geometrically provide smooth drive for points relatively close to one another on the capsule surface, an important issue is to ensure uniformity between those points furthest from one another- typically a point on the pole of the spherical capsule compared to a point on the equator. Achieving this symmetry has been demonstrated by imploding capsules and imaging the imploded fuel volume. X-ray emission from the fuel is imaged using an x-ray pinhole framing camera. By adjusting the pointing of the laser beams (in this case by varying the hohlraum length- experiments have also been done with constant length hohlraums in which symmetry is changed by varying the beam focal position relative the laser entrance hole.) we can control the imploded capsule shape to the 1-2% precision required by NIF and achieve round implosions. Moreover our calculations accurately predict the optimal beam placement as well. Data like this, combined with the fact that the NIF will have 192 beams (vs: Nova's

10) give us high confidence in our ability to provide good symmetric drive for the NIF capsule.

III.c Capsule Implosions

The third issue involves implosion physics. The Rayleigh Taylor (RT) instability is prevalent in ICF implosions. An inverted glass of water is in principal in equilibrium (the atmosphere's 14 lb./sq. inch can keep the water in the glass) but it is an RT unstable equilibrium- the dense water would "prefer" to lower the energy of the system by being lower in the gravitational potential than the lighter air it will soon replace on its way to the soon-to-be-wet floor. An ICF capsule is similar. The low density ablated material accelerates the dense shell. The shell feels a huge "gravity" much like the gee force an astronaut feels at launch time. Thus again we have dense matter in a "gravity" field wishing to exchange places with low density matter. The target crinkles on its way towards implosion. The instability is mitigated somewhat by the ablative acceleration process- the ablation tends to effectively burn-off or smooth the perturbations. Upon deceleration at the culmination of the implosion, the low density hot spot DT gas, holds up the dense DT shell, again in an effective gravity, and again an unstable RT situation arises and the cold shell mixes into the hot fuel. Understanding these quantitatively is required to ascertain just how smooth an initial target must be since initial small perturbations will grow due to the RT instability.

We have performed many experiments on Nova with planar targets that confirm our quantitative understanding of the acceleration phase of the RT instability and the important mitigating effects of ablation. Moreover, significant progress has been made toward experimentally verifying the deceleration phase of the instability and to modeling mix in ICF capsules. These latter experiments rely on spectroscopic measurements of emission from dopants in the fuel (e.g. Ar) and pusher (e.g. Cl) of ICF capsules. As the degree of mix or distortion at the pusher fuel interface varies, the temperature and density of materials at that interface also varies. We observe the increase in emission from the pusher relative to the fuel dopants as the mix increases due to the capsule surface finish increase. Quantitative agreement between model and experiment for (Cl/Ar) line ratios vs. initial surface perturbation once again raises our confidence in NIF predictions.

III.d Integral Tests of Symmetry and Hydrodynamic Instability

Finally on Nova we integrated all the aforementioned target physics knowledge and successfully imploded capsules in hohlraums that have stringent convergences (initial radius divided by final fuel radius) of order 25, which is well into the NIF ignition target regime. These targets performed as predicted, furthering our confidence in NIF target performance.

III.e Summary of Nova Experiments

The experiments on Nova¹ have addressed many of the key issues that can impact the performance of the NIF target. As a result of the success of these experiments and in the aftermath of the good agreement between our theoretical predictions and the Nova data we approach the coming years of NIF construction with increasing confidence in our ability to achieve, for the first time in the laboratory, fusion ignition and thermonuclear burn, thus creating a star on Earth.

IV. Introduction to Marshak Wave Scaling

As mentioned above, understanding the radiation drive in laser heated hohlraums is a crucial first step in building confidence in the predicted target performance for a National Ignition Facility (NIF) ignition target. In the remainder of this paper we will review the basic theory of hohlraum drive scaling, and compare results for the wall loss due to radiation diffusion derived by assuming a constant temperature boundary condition compared to a constant absorbed flux boundary condition. We will also present temperature data and simulations from hohlraums driven by 1 nsec flat top laser drives which will imply that the constant absorbed flux boundary condition is the more appropriate one. In addition we will present simulations and measurements of the radiation burn-through times through thin patches of Au on the sides of a hohlraum wall, which also lead to the same conclusion.

In ICF hohlraums (mm scale gold cylinders), laser light enters the hohlraum interior through laser entrance holes located in either end cap of the cylinder. The light is absorbed at the cylinder walls, converting laser light into soft x-rays. These x-rays are rapidly absorbed and reemitted by the walls setting up a radiation driven thermal wave² diffusing into the walls (a so called "Marshak Wave"). Some of the x-rays escape out the laser entrance holes while others are absorbed by the target capsule and drive its implosion. In Section V the basic scaling of hohlraum wall loss due to the Marshak Wave

will be derived. As an aside, basic and useful concepts such as wall reflectivity (albedo) will be presented. In Section VI methods of measuring hohlraum drive³ will be described. Results from 1 nsec flat top laser drives will also be presented there. Sophisticated LASNEX⁴ simulations will be presented there as well, which show excellent detailed agreement with the drive measurements. Radiation burn-through experiments dedicated to separately measuring wall loss will be described in Section VII as well as LASNEX simulations that agree very well with the burn-through data. In Section V we will summarize our findings that on the basis of the data and simulations of Sections VI and VII, the constant absorbed flux boundary condition is the appropriate one to use.

V. Marshak Wave Scaling

Va. Basics

The theory will be presented here in steps, building up complexity so that the reader can keep up with the understanding of the issues and results. The model system under consideration is a heat wave driven by a radiant flux impinging on a material boundary at $x=0$ and at $t=0$, and penetrating into that material. Since the x-rays are constantly being reabsorbed and reemitted as they progress deeper into the material, a classical diffusive situation arises. We seek to find an expression for the temperature profile $T(x,t)$ within that material at any deeper position x and subsequent time t . To do so we must solve a basic diffusion equation, which is always in the form:

$$\frac{\partial}{\partial t} \left(\frac{\text{energy}}{\text{density}} \right) = \frac{\partial}{\partial x} \left(\frac{\text{energy}}{\text{flux}} \right) = \frac{\partial}{\partial x} \left[D \frac{\partial}{\partial x} \left(\frac{\text{energy}}{\text{density}} \right) \right] \quad (1)$$

where here the energy density on the lhs of the equation is the matter energy density, $\rho\epsilon$, where ρ is the matter density and ϵ is the specific matter energy. The energy flux, however, is carried by thermal radiation, hence the energy density on the rhs of the equation is radiant energy density aT^4 , and the diffusion coefficient D is given, as always, by a free streaming velocity, (in this case, c , the speed of light) times $1/3$ of a mean free path, which for optically thick systems is the Rosseland mean free path λ_R . Thus Eq. (1) becomes:

$$\frac{\partial}{\partial t} (\rho\epsilon) = \frac{\partial}{\partial x} \left[\frac{c\lambda_R}{3} \frac{\partial}{\partial x} (aT^4) \right] \propto \frac{\partial}{\partial x} \left[\frac{\sigma T^4}{x/\lambda_R} \right] \quad (2)$$

where the Stephan Boltzman constant $\sigma = ac/4$. The second half of Eq. (2) serves as a reminder to the reader that in radiation diffusion, as in any diffusion, diffusive flux is free streaming flux reduced by the number of mean free paths in the system. Further progress can be made by fitting powers of T into power laws for the key variables, ϵ and λ_R . To simplify the problem for the moment, we will assume the density of the matter stays constant in time and space: $\rho = \rho_0$, and that the temperature at the material boundary T_0 is constant in time: $T(x=0,t) = T_0 t^0$. Thus we set $\epsilon = \epsilon_0 T^l$. We define the Rosseland mean opacity as $\kappa_R \equiv 1/\rho_0 \lambda_R$, and set $\kappa_R = \kappa_0 T^{-n}$. As presented in Refs. (2), it is then a straightforward exercise to find a similarity solution to Eq. (2), thus turning it from a P.D.E. into an O.D.E. and solving near the steep nonlinear heat front, we find:

$$T(x,t) = T_0 \left(1 - \frac{x}{x_M(t)} \right)^{\frac{1}{l+n-1}} \quad (3)$$

where $x_M^2 \propto T^{4+n-1} t / \kappa_0$. For gold walls we find $n=1$ and $l=3/2$ to be reasonable fits (motivated shortly), thus Eq. (3) leads to:

$$T = T_0 \left(1 - \frac{x}{x_M(t)} \right)^{\frac{1}{3/2+1-1}}; x_M \propto T_0^{1.75} \sqrt{\frac{t}{\kappa_0}} \quad (4)$$

We see that the temperature profile is flat until very near the heat front where it nose-dives to zero, and that the front position, $x_M(t)$, moves into the wall with the expected $t^{1/2}$ diffusive behavior. This heat front position is referred to as the Marshak depth, named after the late Robert E. Marshak whose paper in Phys. Fluids 1, 24 (1958) was a landmark contribution to this field.

Most reasonable choices for n and l lead to similar flat-topped, steep fronted T profiles. The particular choices for l and n are derived from fits to LASNEX data. We find $l=3/2$ a reasonable result since $\epsilon \propto ZT$ (where Z is the ion charge state) and $Z \propto T^{1/2}$ by simple arguments of temperatures being of order the ionization potential which scales as Z^2 . For the average atom XSN opacity model in LASNEX, we find we can fit XSN's κ_R as varying as $1/T$, thus, $n=1$.

We now investigate the wall loss scaling. The wall loss E_W is given by the product of the specific energy ϵ with the heated mass, which is ρx_M times the wall area A_W . Thus,

$$E_W \propto \epsilon \cdot (\rho x_M) \cdot A_W \propto T^{1.5} \cdot T^{1.75} \sqrt{t/\kappa_0} \propto T^{3.25} \sqrt{t/\kappa_0} \quad (5)$$

from which we can derive the scaling of absorbed energy flux,

$$\dot{E}_w \propto T^{3.25} / \sqrt{t\kappa_0} \quad (6)$$

Note too that we could have derived this flux from a different but equivalent point of view. Recall our discussion following Eq. (2):

$$Flux \propto \frac{T^4}{x/\lambda_R} \propto \frac{T^4}{x_M \rho K} \propto \frac{T^4}{T^{1.75} \sqrt{\frac{t}{\kappa_0}} \frac{\kappa_0}{T}} \propto \frac{T^{3.25}}{\sqrt{t\kappa_0}} \quad (7)$$

which gives the same result as Eq. (6). [Note that we have been a bit "sloppy" in ignoring the difference between $T(x,t)$ and the boundary value $T(x=0,t)=T_0$. This is because of the nearly flat T profile, which makes $T(x,t)$ nearly identical to $T_0=T(x=0,t)$ for almost all of $x < x_M$, namely for all of x within the heat front.]

These results are rather well known in the field and I refer to them as the old paradigm, in which the boundary value of T is constant in time. Note that with that constraint, the absorbed flux required to maintain the T decreases in time. Conversely, if a constant flux (driven, say, by a flat top laser drive) were impinging on a wall, and there were no other sinks for this flux, the wall would absorb this constant flux. Since the losses decrease in time at constant T , this constant absorbed flux would result in a temperature in the wall that would rise. This is far more realistic a situation for flat top laser drive, and the implications of this simple fact will be addressed shortly.

Vb. Albedoes

As a useful digression, let us now define a useful quantity, the wall reflectivity or albedo α .

$$\alpha \equiv \frac{\dot{E}_{out}}{\dot{E}_{in}} = \frac{\dot{E}_{out}}{\dot{E}_{out} + \dot{E}_w} = \frac{\alpha T^4}{\alpha T^4 + \dot{E}_w} = \frac{1}{1 + \frac{const.}{\alpha T^{0.75} \sqrt{t\kappa_0}}} \quad (8)$$

Here we have assumed that a flux T^4 is incident on a wall (a convenient system of units, to be discussed later, has $\sigma = 1$) so that by definition, αT^4 is the flux that is reflected. From Eq. (8) we see that the albedo approaches 1 for long times, large T , or large opacity. In any of those three cases, the number of mean free paths in the diffusive heat wave increases, presenting an increasingly difficult barrier for the thermal wave to diffuse inward, thus decreasing the net absorbed flux and correspondingly increasing the reflectivity to approach unity. Thus for the NIF targets where the drive is on for a

relatively long time, the wall loss will decrease allowing better coupling to the capsule. There are other important implications of Eq. (8). If we measure the albedo at a given T and t , we are essentially measuring the opacity coefficient, κ_0 . Any future wall loss in the NIF at a longer pulse but at the same T will follow from Eq. (8), thus making the measurements performed on Nova (at the same T as the NIF) extremely relevant and useful. These experiments and concomitant LASNEX simulations will be discussed in Sections VI and VII.

It may be instructive to consider albedo from a different but equivalent perspective. We see from Eq. (4) that the temperature drops from its boundary value to zero at the heat front. A detector looking into the wall will see 1 optical depth into that temperature profile and see a T less than T_0 . Effectively the wall will be "radiating" at a T lower than T_0 and that ratio to the 4th power is the albedo.

$$T = T_0 \left(1 - \frac{x}{x_M}\right)^{\frac{1}{3.5}} = T_0 \left(1 - \frac{x/\lambda_R}{x_M/\lambda_R}\right)^{\frac{1}{3.5}} = T_0 \left(1 - \frac{\tau}{\tau_M}\right)^{\frac{1}{3.5}} \quad (9)$$

where τ represents the optical depth, and τ_M represents the number of optical mean free paths within the Marshak depth. Thus

$$\alpha = \frac{T(\tau=1)^4}{T_0^4} = \left(1 - \frac{1}{\tau_M}\right)^{1.14} \approx 1 - \frac{1.14}{const. T^{0.75} \sqrt{t \kappa_0}} \quad (10)$$

which goes to the same limits as the formulation of Eq. (8) when α is near unity. In Eq. (10), $\tau_M = x_M/\lambda_R = x_M \rho \kappa_R$ is derived in the same way it is in the denominator of Eq. (7). More formally, the albedo can be derived via this approach by solving the transfer equation:

$$\alpha = \frac{\int_0^{\tau_M} T^4 e^{-\tau} d\tau}{T_0^4} \approx 1 - \frac{(1 - e^{-\tau_M})}{\tau_M} \quad (11)$$

which for both large and small values of τ_M goes to the proper limits of $(1 - (1/\tau_M))$ and $(\tau_M/2)$ respectively. To derive the last expression in Eq. (11) we approximated the 1/3.5 exponent of Eq. (9) as 1/4. Had we used the STA opacity code, (described below) which has an opacity scaling of $1/T^{1.5}$, (vs. XSN's $1/T$) Eq. (9) would indeed have exactly an exponent of 1/4.

The concept of albedo is useful in that we can parameterize the wall loss in terms of it, and with that, systematize hohlraum energy balance. Since α is reflectivity, $(1-\alpha)T^4$ is the flux not reflected, namely the wall loss (per unit area). Thinking globally then, a laser power P_L absorbed within a hohlraum is converted to soft x-rays with an efficiency η_{CE} . This source flux goes into the walls at a rate $(1-\alpha)T^4 A_W$ and out the laser entrance holes at a rate $A_H T^4$, where A_W, A_H are the wall and hole areas respectively. Of course if there is a capsule in the hohlraum that would be an additional sink of energy. In summary, in an empty hohlraum, this simple source=sink model yields:

$$\eta_{CE} P_L = [(1 - \alpha)A_W + A_H] T^4 \quad (12)$$

Later in this paper we will use this formulation to systematize a wide variety of observations of T vs. P_L , thereby coming to some conclusions as to the values of η_{CE} and α .

Vc. Beyond Basics

It should be noted that we have introduced a significant simplification here. The x-rays emitted from the laser illuminated spot have, in general, a hotter spectrum than the reemission from the majority of the hohlraum wall which is unilluminated by direct laser light. A more sophisticated two temperature hohlraum model is conceivable⁵, but we believe that the simple one temperature model presented here is sufficient for putting a large body of hohlraum drive results into a simple systematics. This conclusion is demonstrated later in this paper by the agreement of the simple model systematics with LASNEX simulations (which provide a far more detailed description of the hohlraums than any two temperature model). Part of the reason for the success of the simple model is that the harder spectrum from the laser produced x-rays are quickly absorbed by the walls and reemitted as softer x-rays.

Another simplification introduced here is the neglect of convergent geometry. We have assumed planar expansions. In a hohlraum it is possible that later in time the radiation driven blowoff will stagnate and create a new source of x-ray emission and possibly send a pressure wave back toward the high density region near the Marshak wave front. For the "scale 1" hohlraum sizes and the nsec time scales of interest in the bulk of the data base discussed later in this paper, we do not believe stagnation plays a major role in the energy balance and is therefore ignored.

With these fundamentals as a base, we can now build up a more realistic picture of the wall loss in a real system. The first extra element to add to our picture is time

dependence of $T_0(t) = T(x=0,t)$, which up to this point has been held constant in time. As we have seen from Eq. (6) or (7), the absorbed flux required to maintain such a constant T decreases with time as $t^{-1/2}$. As mentioned above, in a hohlraum driven by a laser pulse with a "flat-top" temporal power profile, a flux of x-rays that is either constant or slightly increasing with time will be produced. As this incident flux is absorbed by the walls, it is more than sufficient to maintain a constant T , so in fact T will rise. A short cut at deriving the time dependence of that rise, is to set the flux of Eq. (6) or (7) equal to a constant in time. That requires T to scale as $t^{1/6.5}$. As we shall see, this weak but noticeable rise with time is in good agreement with experimental observations. What also follows from this behavior is that the Marshak depth, x_M , no longer scales as $t^{1/2}$ (see Eq. (4)), because of the time dependence of T . Inserting that $t^{1/6.5}$ dependence of T into Eq. (4) we find x_M scaling as $t^{0.77}$, much closer to the nearly linear dependence of burn-through times with sample thickness that is observed in albedo experiments to be discussed later. Another quantity of interest that does not change too dramatically is the time dependence of $1-\alpha$. When α is near 1 (which is typical) Eqs. (8) or (10) or (11) predict a scaling of $1-\alpha$ as $1/T^{.75}t^{1/2}$, so the previously predicted $t^{-1/2}$ behavior for that quantity (when T was constant in time) is now, with T scaling as $t^{1/6.5}$, slightly modified to be $t^{-0.61}$.

The next level of complication necessary for a more accurate description of our experiments, is to account for the change in density of the wall material. As the Marshak wave soaks into the solid wall, the heated portion blows back outward into near vacuum, thus producing a density profile that must self consistently be accounted for in the solution to Eq. (2). Up to this point in our presentation we have artificially set the density ρ to be constant in time and space. A way to still obtain similarity solutions is to set ρ equal to $\rho_0 x_M / C_s t$ (where C_s is the sound speed of the heated material at temperature T and scales as $\epsilon^{0.5}$). This formula for ρ represents the idea that an amount of solid material (originally at solid density ρ_0) heated to a depth x_M , is now spread out over a distance $C_s t$ after a time t , and is thus at the lower density ρ . Along with this necessary complication we must generalize the power law dependencies of ϵ and κ_R to include ρ in addition to T , namely $\epsilon = \epsilon_0 T^1 \rho^{-Q}$ and $\kappa_R = \kappa_{R0} T^{-n} \rho^R$. For Au we find $Q = 0.2$ and $R = 1/3$. The sign of the dependence of ϵ on ρ can be understood from the LTE notion that higher density drives recombination of the free electrons back down into the ions, lowering the ionic charge Z and lowering the specific heat due to the free electrons. Redoing the similarity solutions with these more complicated scalings, (again, details can be found in Refs (2)) yields:

$$\begin{aligned}
\text{For } T \text{ constant in time: } \quad EW &\propto T^{3.0} t^{0.63} \kappa_0^{-0.37} \\
\rho_0 \times M &\propto T^{1.7} t^{0.53} \kappa_0^{-0.47} \\
(1-\alpha) &\propto 1/T \quad t^{0.37} \kappa_0^{0.37}
\end{aligned} \quad (13)$$

For Absorbed Flux that is constant in time: ($T \propto t^{0.12}$)

$$\begin{aligned}
EW &\propto T^{3.0} t \quad \kappa_0^{-0.37} \\
\rho_0 \times M &\propto T^{1.7} t^{0.74} \kappa_0^{-0.47} \\
(1-\alpha) &\propto 1/T \quad t^{0.48} \kappa_0^{0.37}
\end{aligned} \quad (14)$$

We have tested these scalings by performing LASNEX simulations of test cases of Marshak waves in gold. Before presenting those results, let us first introduce convenient 'hohlraum units' in which T is measured in hectovolts (hundreds of eV), area in mm^2 , time in ns, mass in gm and energy (a bit clumsily) in hectojoules. With these units, as alluded to in the discussion following Eq. (8), $\sigma = 1$, and normalized irradiance is $10^{13} \text{ W} / \text{cm}^2$ ($=hJ/\text{mm}^2 \text{ ns} = 10^2 \text{ J} / 10^{-2} \text{ cm}^2 10^{-9} \text{ s}$) and similarly, normalized power is 10^{11} W ($=hJ/\text{ns} = 10^2 \text{ J} / 10^{-9} \text{ s}$). In these units, we find the LASNEX test problems, using XSN opacities whose κ_R in (cm^2/gm), can be fit as $3500 \rho(\text{gm}/\text{cm}^3)^{0.33} / T(\text{heV})$ yield:

$$\begin{aligned}
\text{For } T \text{ const. in time: } EW &= 0.6 \quad T^{3.2} t^{0.65} \kappa_0^{-0.37} \quad (\text{hJ}/\text{mm}^2) \\
\rho_0 \times M &= 1.8 \times 10^{-3} T^{1.7} t^{0.57} \kappa_0^{-0.47} \quad (\text{gm}/\text{cm}^2) \\
(1-\alpha) &= 0.52 / T \quad t^{0.37} \kappa_0^{0.37}
\end{aligned} \quad (15)$$

where κ_0 represents a multiplier on the opacity. The XSN fit was based on XSN results taken for $100\text{eV} < T < 300 \text{ eV}$ and $.01 \text{ gm}/\text{cc} < \rho < 10. \text{ gm} / \text{cc}$. The LASNEX simulations were run for a similar range in T , for 1 nsec pulses impinging onto initially solid gold, and for opacity multipliers between 1 and 3.

Using Eq. (15) we find, for example, at 1 ns ($t=1$), a 260 eV source ($T=2.6$), at nominal opacity, ($\kappa_0 = 1$) would yield a $(1-\alpha)$ of 0.2 or an albedo of 0.8. Comparing Eqs. (15) with (13) we see a fairly close agreement of power dependencies between our simplified approach to the problem and the detailed, multigroup radiation transport answer from LASNEX. For test problems with constant absorbed flux, we find:

$$\begin{aligned}
\text{For } T \propto t^{0.1}: \quad EW &= 0.44 T^{3.2} t \kappa_0^{-0.37} \quad (\text{hJ}/\text{mm}^2) \\
\rho_0 \times M &= 1.6 \times 10^{-3} T^{1.7} t^{0.8} \kappa_0^{-0.47} \quad (\text{gm}/\text{cm}^2) \\
(1-\alpha) &= 0.57 / T \quad t^{0.42} \kappa_0^{0.37}
\end{aligned} \quad (16)$$

where we see the LASNEX opinion of how time dependence of T leads to changes between Eqs. (16) and (15) similar to those changes we predicted between Eqs. (14) and (13). Note too the coefficients for wall loss are lessened in Eqs. (16) vs. (15) because with (16), if we have arrived at T at time t, it implies the system spent its previous history at a temperature less than T, thus there should be less loss.

More sophisticated opacity treatments are available to us, for example the STA (Super Transition Arrays) code which has a far more detailed treatment of bound bound opacity than the average atom XSN code, but can only be run in LASNEX in LTE via a look up opacity table. We are grateful to Bill Goldstein of LLNL for supplying us with the gold STA table. We find we can fit STA's κ_R in (cm^2/gm) to $6000 \rho(\text{gm}/\text{cm}^3)^{0.3} / T^{1.5}$. This gives opacities quite close to XSN at T=3 eV, but at 100 eV (T=1) we see a difference of 2 between code predictions. The formalism we have presented can be redone for this STA opacity model. Basically the stronger power law for T in κ_R leads to a slightly higher power law dependence of E_W and $\rho_0 \times M$ on T, namely an additional 0.2. Indeed, the LASNEX simulations with STA confirm that. For example for STA we find:

$$\text{For } T \text{ const. in time: } E_W(\text{STA}) = 0.5 T^{3.4} t^{0.65} \kappa_0^{-0.37} \text{ (hJ/mm}^2\text{)} \quad (17)$$

The fits of STA and LASNEX were done under the same range of variations as described for the XSN results. In Eq. (17), note the change from $T^{3.2}$ to $T^{3.4}$ as predicted. Note too the coefficient for wall loss is smaller for STA than for XSN by 20%, and can be derived quite easily by considering the respective opacity coefficients, and calculating $(6000/3500)^{-0.37}$ as predicted by the κ_0 scaling. Of course the actual value of E_W for either case at T=3 is quite close, as we would expect given the two opacity models' agreement at T=3. For completeness, we quote:

$$\text{For } T \propto t^{0.1} : E_W(\text{STA}) = 0.35 T^{3.4} t \kappa_0^{-0.37} \text{ (hJ/mm}^2\text{)} \quad (18)$$

Vd. Examples

Before embarking on a discussion of the experimental data base it may be instructive to go through a numerical exercise in using some of these equations to find the T of a given hohlraum. Consider a cylindrical hohlraum of length 2.55 mm and diameter 1.6 mm, with laser entrance holes on either endcap of 0.8 mm diameter, and a diagnostic hole of 0.5 mm diameter. This means A_W is 16 mm^2 and A_H is 1.2 mm^2 . A flat top laser power of 30 TW, on for 1 ns (therefore 30 KJ) irradiates the hohlraum. LASNEX

calculations, to be described below, find a conversion efficiency into soft x-rays of about 75% by the end of the pulse. It also finds an albedo then of about 0.8. Thus the lhs of Eq. (12) would yield $(0.75 \times 300 =) 225$ in normalized power units of 10^{11} W (= hJ/ns recall the discussion of units following Eq. (14)). The rhs would be $(0.2 \times 16 + 1.2) \times T(\text{heV})^4$, or $225 = 4.4 T^4$, or $T=2.67$, (namely 267 eV) quite close to what turns out to be LASNEX predictions (and the data!). A different approach would be an energy balance rather than power balance consideration:

$$\eta E_L = E_W + E_H \quad (19)$$

where E_W is given by Eq. (16) and E_H can be found by:

$$E_H = A_H \int_0^t \left(T_0 \left[\frac{t}{t_0} \right]^{0.1} \right)^4 dt = A_H \frac{1}{1.4} T_0^4 \left(\frac{t^{1.4}}{t_0^{0.4}} \right) \quad (20)$$

Thus, for our problem we have (at $t=t_0=1$) :

$$0.75 (300) (\text{hJ}) = (0.44 \times T^{3.2} (\text{hJ}/\text{mm}^2) \times 16 (\text{mm}^2)) + (0.71 \times T^4 (\text{hJ}/\text{mm}^2) \times 1.2 (\text{mm}^2))$$

$$\text{or: } 225 = 7.0 T^{3.2} + 0.9 T^4$$

whose solution, $T=2.73$, is quite close to the previous result and to the data.

Ve. Scaling to NIF and beyond

To calculate coupling efficiency of energy into the capsule of an ICF hohlraum we can generalize Eq. (12). . Being low Z the capsule generally soaks up black body radiation at a rate $A_C T^4$ just like the laser entrance hole does. Thus we should add that term to the r.h.s. of Eq. (12). When actually calculating the capsule area A_C however, we should not simply use the original capsule area since it implodes. As a general rule of thumb using half the original area gives an accurate representation of the capsule energy absorption. Redoing the calculation of section Vd. above with a typical Nova capsule, we get an effective A_C of about 0.25 mm^2 , lowering T slightly to 2.64 eV. Defining a coupling efficiency as $A_C T^4$ divided by the original 300 ($\times 10^{11}$ W) we get a 4% coupling efficiency for Nova. Using the scaling of Eq. (16) for the albedo, we find the 0.8 Nova albedo is expected to rise for a 300 eV 3 ns main pulse NIF hohlraum to about 0.89. The area of the NIF hohlraum (about a scale 3.5 compared to Nova) is about 200 mm^2 . The 1 mm radius NIF capsule would thus have an effective area of 6 mm^2 while the laser entrance hole is expected to have an area of 12 mm^2 . With these numbers the r.h.s. of the generalized Eq.

(12) reads $[(0.11)200 + 6 + 12]T^4$, while the l.h.s. is NIF's 470 TW with an (conservatively) assumed conversion efficiency of light to x-rays of 75%, or 3525 in our r.h.u. units. We then obtain $T=3.06$ eV, and a coupling efficiency of 11%. For a reactor scale with another scale of 2 in hohlraum size (4 in area and power, 2 in time scale) the albedo rises to 93% and the coupling to 15%. If conversion efficiency of light to x-rays continues to increase with pulse length than our conservative estimate of constant 75% conversion efficiency will be underestimating the coupling which could then be quite close to 20%. These coupling efficiency numbers for NIF and for reactors are similar to the one's discussed in section II which motivated estimates of gain for NIF and beyond.

VI Experiments and LASNEX Simulations on Drive :

The hohlraum temperature is measured in two independent ways. An aluminum wedge witness plate is placed on the hohlraum wall. The radiation ablates away at the Al that faces the hohlraum interior, launching a shock wave that propagates through the aluminum, eventually to break-out to the wedge shaped backside that faces the outside world. An optical pyrometer, streaked in time, records the optical emission that ensues upon shock breakout. The wedge shape allows us to measure the shock speed continuously throughout time. The shock speed is indicative of the drive, which is derived via comparison with LASNEX simulations. The EOS of aluminum is sufficiently well known to make this a very powerful and accurate technique. These experiments have been carried out by Chris Darrow and Don Phillion of LLNL.

A second method to measure drive involves the Dante sub-keV broadband spectrometer. Approximately 10 broadband filtered channels cover the entire sub keV spectrum in which the bulk of the emission occurs. The Dante looks at a laser-unilluminated portion of the wall, and thus sees a radiation heated wall reemitting as αT^4 . Thus, Dante must be corrected for albedo if it is to be directly compared with a measurement of drive such as would drive a capsule or the Al wedge witness plate. The Dante is time resolved with about 100 psec resolution. These experiments have been carried out by Harry Kornblum of LLNL.

We use the 2-D hydrodynamic simulation code LASNEX to model the drive in hohlraums. These simulations were carried out by Larry Suter and Ron Thiessen of LLNL, and the details of the simulation technique as well as extensive comparisons with a large data base, have been published elsewhere.³ Nominal gold opacities, as calculated

by the XSN average atom package in LASNEX are used. The problems are run either non LTE or LTE with very little difference in results.

The problems, once run to completion are post processed in a variety of ways to mimic the measurements. The TDG post processor can, for instance, look into a wall just as the Dante channels do, and the time evolution of the spectrum (which is roughly Planckian) and its frequency integral, the drive, characterized by a T_R derived from the fourth root of the energy flux, can be directly compared with the measurement. Moreover, the drive derived from the calculation can be applied, in a subsidiary calculation, to a wedge of aluminum, and the predicted trajectory of the radiation ablation driven shock can be compared with the measurement as well.

In general when we compare the two measurements along with the respective LASNEX predictions for a 1 nsec flat top, 30 TW, scale 1 Au hohlraum, we see excellent agreement of LASNEX with both independent measurements. (Equally excellent agreement is seen for a lower power irradiance of 10 TW.) In Fig. 1a we show the witness plate data vs. incident power, and its good agreement with the LASNEX simulations. Also plotted are the predictions of Eq. (12) with a 75% conversion efficiency and an albedo that follows Eq. (16).

It is important to note that we observe via Dante and in LASNEX a slight rise with time of T_R despite the laser power being flat in time. This behavior was predicted in Section V when the constant absorbed flux boundary condition is used. Quantitatively, we expected a $T \propto t^{0.1}$ behavior, and we observe in the data and in the simulation something closer to a $T \propto t^{0.15}$ behavior instead. This is probably due to the fact the flux is not constant, despite the laser power being flat topped, due to the conversion efficiency of laser light to x-rays having a slight dependence on time. Thus the x-ray source flux increases slightly in time, leading to a slightly larger power dependence of T on t . The implication of this on the burnthru time, to be discussed in the next section, can be anticipated by inspecting the second line of Eq. (16). The expected $X_M \propto t^{0.8}$ will increase to about an $X_M \propto t^{0.9}$ since the power law of T with t is slightly higher than assumed. As we shall see presently, this is precisely what is observed!

VII Experiments and LASNEX Simulations on Wall Loss :

To study wall loss more fundamentally we have performed a series of measurements, looking at the burn-through times of thin patches of gold (1 to 3 μm)

stretched across a hole in the hohlraum wall (which is typically 25 μm thick). The shorter the measured burn-through time (at a given thickness and drive) the lower is the inferred Rosseland averaged gold opacity. The observations have been made with the 10 channels of Dante at a given drive and thickness, and also with a spatially resolved, single channel detector, which allows, for the same shot (and drive) a measure of the burn-through times through several different thickness patches, all aligned along the side of the hohlraum. These experiments were designed by Ron Thiessen and Larry Suter of LLNL, and carried out by John Porter and Ted Orszecowski of LLNL, and will be published shortly.⁶

Burn-through time is defined as the time when the signal rises to half its peak value. In Fig. 1b we plot the results of burn-through time vs., thickness for two energy channels. LASNEX simulations used the measured drive and via TDG post processing simulated the burn-through signal for the appropriate channels, and defined burn-through time the same way the experiment did. The LASNEX curve is also plotted in Figure (1b). Note the excellent agreement between LASNEX and the data. The errors due to drive uncertainty etc. lead to a tight 30% uncertainty in opacity. Note too the nearly linear relationship between burn-through time and thickness, a consequence of a TR rising in time (recall our discussion at the end of the previous section). These experiments were originally motivated under the old paradigm of Eq.(4) in which we expected the burn-through times to scale as thickness squared, and to be sensitive linearly with opacity. As the new paradigm (Eq. (16)), and the data, and LASNEX, indicate, the experimental burnthrough isn't quite that optimistically sensitive to thickness and opacity- it scales linearly with thickness, and as the square root of opacity. Nonetheless, that is good enough to tie down the opacity to 30%.

As an additional check on the XSN opacity we reran the calculations using the LTE STA opacity package, available to be run in LASNEX via a look-up tabular opacity. The STA code is far more sophisticated than the average atom XSN code, and cannot be run non-LTE in line with LASNEX. The STA results gave nearly identical results as the XSN, another confirmation of XSN's veracity. When we compare the detailed opacity of the two codes and see that indeed at 260 eV they give the same Rosseland mean opacity. As mentioned in Section V, the two codes give different predictions at 100 eV, and burnthrough experiments such as these, redone at 100 eV would be most illuminating. For the record we note that the good agreement between LASNEX and data persist for all the other Dante channels as well. Also for the record we note that independent experiments, in which the shock breakout of a radiation ablation driven shock is monitored through thick samples of gold are also consistent with nominal opacities.

VIII Summary

We have seen that the constant absorbed flux boundary condition leads to several qualitative differences in predicted scaling when compared with the old paradigm of constant temperature. In particular the rise of T with time is predicted, and is observed in both simulation and measurement of hohlraums driven by flat top pulses. Moreover, with this slight rise of T with time, due to the non linear dependence of the Marshak depth with T , the paradigmatic, diffusive $x_M = t^{1/2}$ behavior now changes to one nearly linear with time, an effect indeed observed by experiment and simulation.

We have also given the reader the tools to make reasonably accurate estimates of hohlraum temperatures, given initial conditions. We also applied such tools to motivate the increase of efficiency of coupling initial laser energy to absorption by the fuel capsule as we increase in scale from Nova to NIF to reactors. This helps motivate the predictions of the complex LASNEX simulations that NIF will achieve moderate gains of 10-20, and reactors will achieve higher gains allowing them to be competitive energy sources for the next century.

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Figure caption

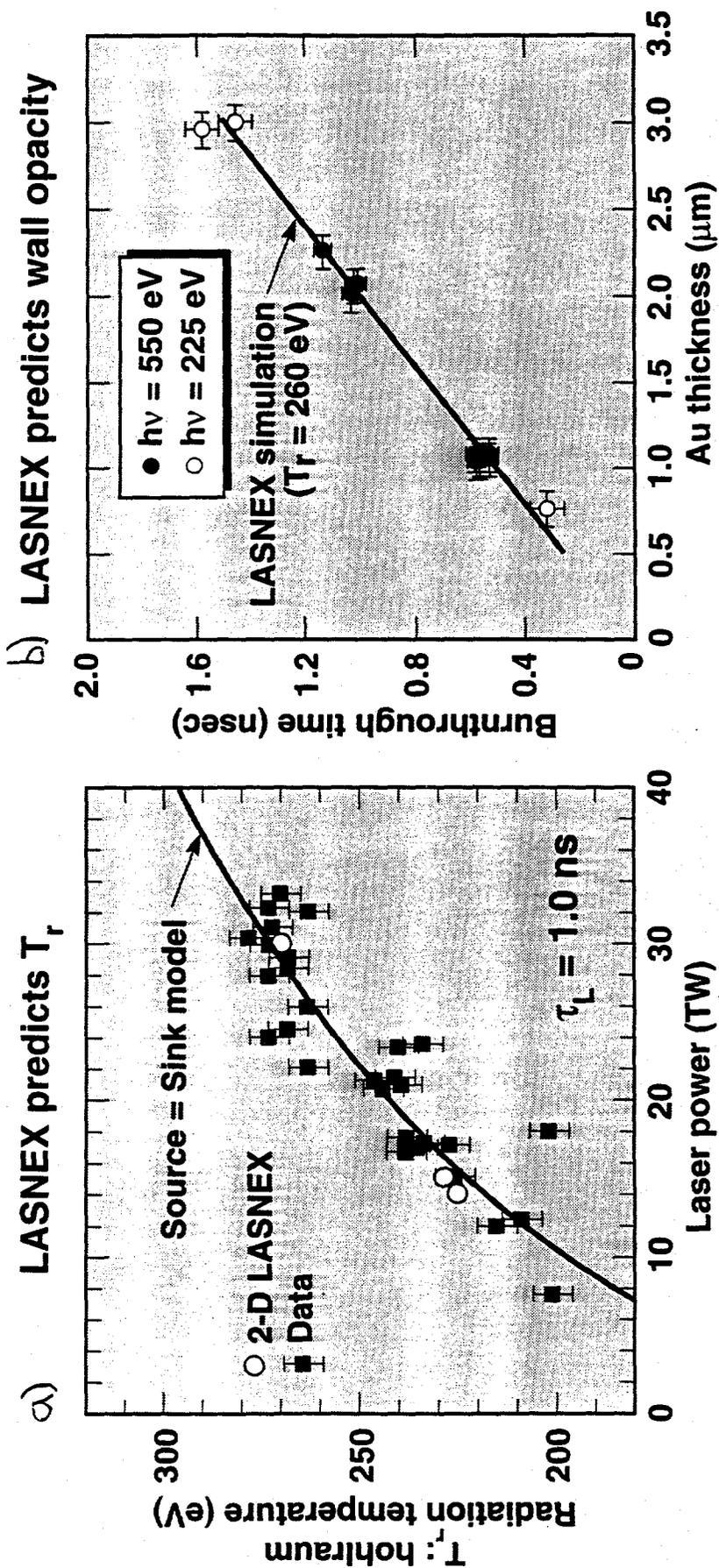
Figure 1. a) T vs. laser power as measured by witness plates and as simulated by LASNEX. b) Burn through time of thin Au vs. Au thickness for two Dante-like broad band channels at 250 and 500 eV and comparison with LASNEX predictions.

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Figure 1:

Demonstrated understanding of hohlraum drive on Nova



These results instill high confidence in NIF drive predictions