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CRITICAL ELEMENTS OF HIGH GAIN LASER FUSION.(U)

JAN 81 S E BODNER

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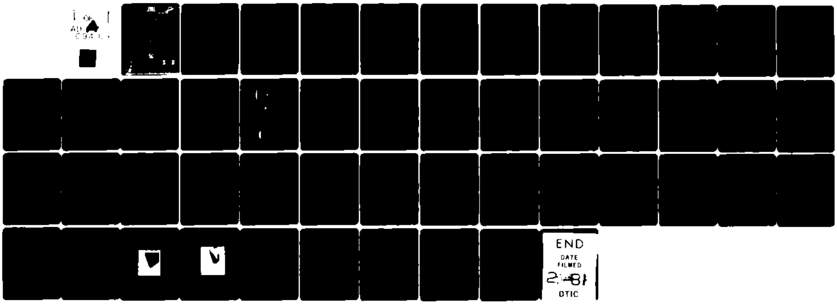

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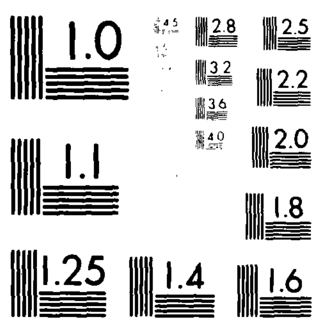

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Progress toward high gain laser fusion can be measured by a set of five critical elements. They are (1) the laser-to-fuel coupling efficiency, (2) the cold fuel isentrope, (3) the implosion asymmetry, (4) the ablation pressure, and (5) the ignition concept.

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CONTENTS

CRITICAL ELEMENTS OF HIGH GAIN LASER FUSION

I. INTRODUCTION

How should we measure progress in laser fusion? What yardsticks are there to evaluate the differing lasers and pellet designs? Various overall milestones have been suggested, such as high compression, scientific breakeven, and fuel ignition. Progress can also be measured at the basic physics level, through our increased understanding of the various laser-plasma interactions such as resonance absorption, self-generated magnetic fields, stimulated Brillouin scatter, etc.

All of the above are necessary components of a laser fusion program. But we could have all of the basic understanding that it is possible to obtain, we could achieve more than ignition and breakeven, and still we might never be able to achieve high enough pellet gains to be useful in a reactor system. It is the purpose of this paper to suggest that there is another possible set of criteria, defined here as the critical elements, which (except for some relatively minor physics) is both necessary and sufficient for measuring progress toward a high gain pellet. This set of critical elements encompasses the uncertain laser-plasma interaction physics, and also much of the implosion physics.

This paper is aimed at providing a framework for laser fusion. But it is not a general survey or review paper on the current status of laser fusion. Such a survey might include literally hundreds of references. The references to NRL research are usually given only as examples.

The title and contents of this paper refer explicitly only to laser-driven fusion, and more particularly to the approach to laser fusion using direct illumination of the pellets. It is not possible to give a balanced framework here on alternate approaches which first convert laser or ion energy to x-rays which

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then implode the pellet. The laser fusion concept using near-infrared lasers forms an interesting, complete, and self-consistent framework and, in the opinion of this author, is as viable as the other approaches using ultraviolet lasers.

Various parts of this paper have been presented in invited papers at the DOE Target Design Meeting, June 4, 1980, and the APS Plasma Physics Division Meeting, Nov. 13, 1980.

II. ELEMENTS OF HIGH GAIN LASER FUSION

Because of the rather modest efficiency of laser systems, fusion pellets must be designed to have a very large gain. Typically, reactor-sized pellets must have gains of 100 to 200, where the gain is defined as the thermonuclear energy output divided by the laser energy input. The high gain of the pellet in turn places a set of requirements on the critical elements of laser-target coupling.

The following sections contain a review of the basic concepts of pellet design, in terms of these *critical elements.* Much of the material in Part II of this paper is also contained in Ref. 5 (Nuckolls, et al.), Ref. 6 (Fraley, et al.), Ref. 7 (Kidder), and Ref. 8 (Brueckner and Jorma).

Reactor System Requirements

A schematic diagram of the electrical power flow in a fusion reactor is shown in Fig. 1. The driver produces laser energy which impinges on the pellet. Thermonuclear output of the pellet (α-particles, neutrons, and x-rays) is converted to electricity, part of which is then recycled back to the driver. (The tritium breeding cycle has been ignored here). We define

$$\eta_d = \text{driver efficiency} = \frac{\text{(laser energy on target)}}{\text{(energy into laser)}}$$

$$Q = \text{pellet gain} = \frac{\text{(thermonuclear energy output)}}{\text{(laser energy on target)}}$$

$$\eta_{te} = \text{thermal-to-electric conversion efficiency}$$

$$f = \text{recycled fraction of energy.}$$

Multiplying the energy factors around the closed loop yields

$$\eta_d Q \eta_{te} f = 1. \tag{1}$$

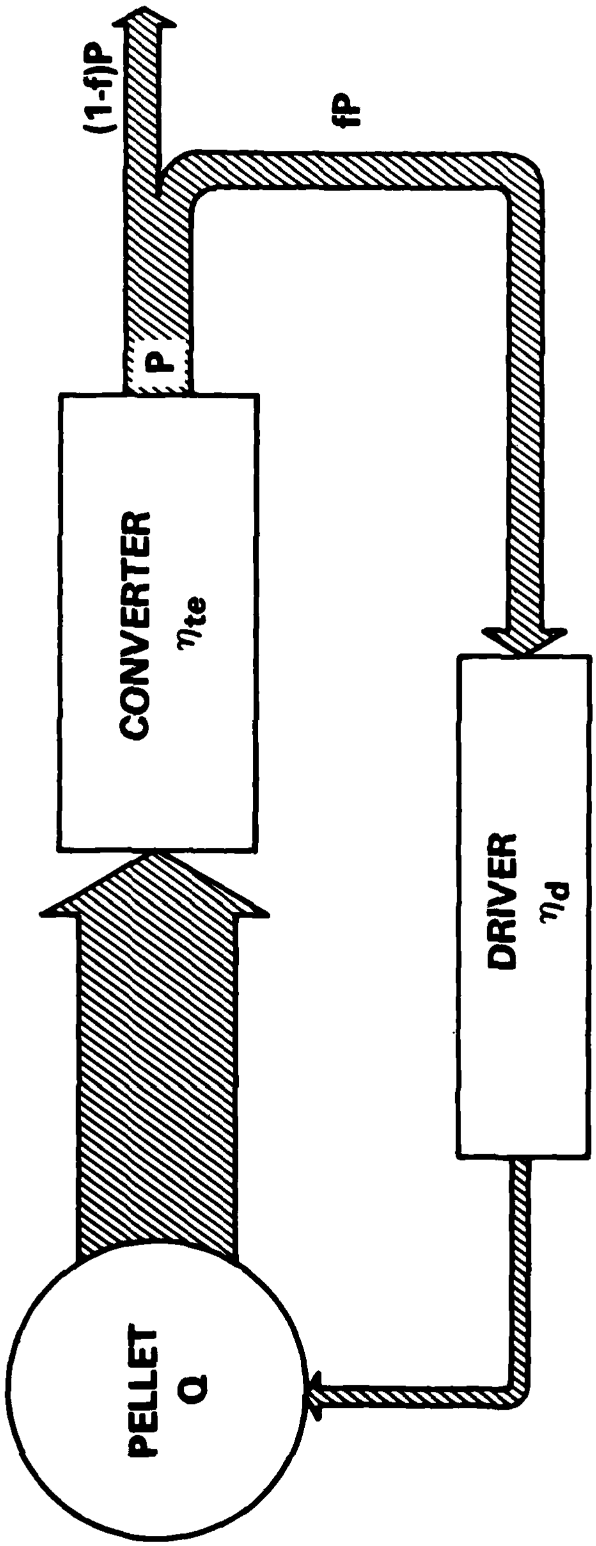

Fig. 1 — Electrical power flow in a reactor

The maximum value of η_{te} is limited by basic thermodynamics to about 30% to 40%. However, the recycled fraction f is limited only by capital costs. If capital costs are the dominant component in the cost of electricity, then

$$\frac{\text{mills}}{\text{KWH}} = \frac{A + Bf}{1 - f}. \tag{2}$$

Here A is the converter cost per-unit-of-power (consisting of chamber, pipes, steam cycle, etc.), and B is the laser cost per-unit-of-power (it is assumed that changes in f in Eq. (1) are balanced by changes in Q).

In Eq. (2) the cost of electricity becomes very large as f approaches unity. To minimize the costs of electrical energy, the recycled fraction f should therefore be kept small. The laser fusion community has typically assumed that $f \leqslant 25\%$. Then with $\eta_{te} = 40\%$. Equation (1) becomes

$$\eta_d Q \geqslant 10. \tag{3}$$

This is the oft-quoted relation which implies that lasers of 5% to 10% efficiency require pellet gains of 100 to 200.

As the reader can see, the derivation of Eq. (3) is rather soft. If instead it is assumed that society and the economy will accept energy at about 3 times this minimal cost, then Eq. (3) becomes $\eta_d Q \geqslant 4$.

The following sections will use the more conservative inequality given in Eq. (3). But the "softness" of this inequality should be noted.

Driver Efficiencies

There are several candidates for high average power lasers. Each has a potential efficiency greater than 5% in a 10 nanosecond laser pulse, and each might be scaled to a reactor-sized system. None has been developed adequately, and work continues on all of them. The leading contenders, and their associated minimum pellet gain, are listed. (The efficiency percentages are known only approximately.)

Table I
Driver Characteristics

Laser	Wavelength	Efficiency	Minimum Pellet Gain
CO_2	10.6 μm	10-14%[1]	70-100
HF	2.6-3.1 μm	4-8%[2]	125-250
KrF	0.25 μm	4-8%[3]	125-250

A number of other laser systems are being evaluated, including solids, gases, and the free electron laser, with wavelengths between .25 μm and 2 μm. However it is not yet possible to evaluate their overall potential or even to assign an efficiency to some of them. Except possibly for CO_2, the laser contenders have efficiencies of 5% to 10%, and therefore the pellets must have gains of at least 100 to 200.

Lasers have the inherent advantage of rather precise control over the spatial and temporal quality of the energy delivered to the pellet. But with newer pellet designs that do not require careful pulse shaping, particle beams have become a more viable option. Light-ion or heavy-ion beam drivers have potential efficiencies[4] of 15% to 25%, so that a reactor system might only require a pellet gain of 40 to 60. As will be shown later, this can substantially relax some of the physics constraints on a pellet. But pellets for light-ion and heavy-ion drivers have their own unique physics constraints, which will not be considered here because of classification restrictions. The following sections examine the implications of requiring the pellet gain to exceed 100 to 200.

Pellet Gain and Propagating Burn[5,6,7,8]

As indicated earlier, the *pellet gain Q is defined as the thermonuclear energy output divided by the laser energy input* onto the pellet.

$$Q = \frac{E_{\text{output}}}{E_L}. \tag{4}$$

The energy output is the product of m, *the fuel mass*, $\mathcal{E}_b$, *the burn output per-unit-mass* (assuming 100% burnup), and ϕ, *the fractional burnup.*

$$E_{\text{output}} = m\,\mathscr{E}_b\,\phi. \tag{5}$$

If all of the fuel mass is heated to the same temperature, then the laser energy input can be found from Eq. (6).

$$\eta\,E_L = m\,\mathscr{E}_h \tag{6}$$

where $\mathscr{E}_h$ is *the energy per unit mass required to initially heat and compress the D-T fuel*, and η *is the coupling efficiency*, or the fraction of the incident laser energy that ends up in the D-T fuel.* Substituting Eqs. (5) and (6) into (4),

$$Q = \eta\phi\frac{\mathscr{E}_b}{\mathscr{E}_h}. \tag{7}$$

To obtain a large fractional burnup, and to ensure that the thermonuclear burn output exceeds the bremsstrahlung radiation losses, detailed computer calculations have shown that the D-T ions should be heated to more than 5 keV. This temperature determines $\mathscr{E}_h$.

$$\mathscr{E}_b = 3.4 \times 10^{11}\ \text{joules/gram} \tag{8}$$
$$\mathscr{E}_h = 5.8 \times 10^{8}\ \text{joules/gram (at 5 keV)}. \tag{9}$$

It is difficult to design a pellet whose fractional burnup ϕ is more than 40%-50%, or whose coupling efficiency η is more than 10%-15%. Substituting these values into Eq. (7), the pellet gain $Q \lesssim 22\text{-}43$. This gain is too low for a reactor system.

Much larger pellet gains can be achieved by the trick of *not* heating all of the D-T fuel.[5,6] Note that the energy requirement to compress D-T is small compared to the energy requirement to heat this fuel. For example, if the DT is kept near zero temperature, and compressed *isentropically* then the energy required to compress the fuel is $\mathscr{E}_c$, and

$$\mathscr{E}_c \gtrsim \mathscr{E}_f = 1.1 \times 10^{7}\ \text{joules/gram (at } 1000 \times n_{\text{solid}}) \tag{10}$$

$\mathscr{E}_f$ is the energy requirement to compress a fermi-degenerate electron gas when the temperature is small compared to the fermi temperature. $\mathscr{E}_f$ varies with the electron density as $n^{2/3}$.

*The coupling efficiency is proportional to the product of the absorption efficiency and the implosion efficiency.

Comparing Eqs. (9) and (10), it is clear that much higher pellet gain is accessible if only a small central portion of the fuel is heated, and the rest is kept cold. The energy output from the small central hot spot (consisting of α-particles, thermal transport, shocks, etc.) subsequently heats the adjacent cold compressed material so that it too can burn. The central hot spot is called the *ignitor*, and the process of heating the rest of the fuel is called *propagating burn.* Figure 2 illustrates the concept. High gain pellets exploit these concepts of central ignition, near-isentropic compression of the main fuel, and propagating burn.

The gain of a pellet can now be written

$$Q = \eta\phi \frac{\mathscr{E}_b}{\mathscr{E}_c + \frac{m_h}{m} \mathscr{E}_h}. \tag{11}$$

Here m_h/m is the fraction of the fuel that is heated.* For a high gain, $\mathscr{E}_c$ is not much larger than the *fermi-degenerate value* $\mathscr{E}_f$ *given in* Eq. (10).

This formula for the pellet gain uses a simplified pellet concept: (1) It assumes that each element of the fuel mass is in one of two distinct groups: the hot central ignitor or the cold main fuel. Unless modified, Eq. (11) does not allow for a smoothly varying temperature interface between the hot and cold regions. (2) In a real implosion, the dynamics and shocks are more complicated than can be calculated with the formula we will use for the fractional burnup.

The net result of these simplifying assumptions is that *Eq. (11) overestimates the pellet gain.* Real pellets will have *less* gain. Nonetheless, Eq. (11) can be a very useful tool. It allows us to calculate the gain of the best possible pellet design for a given set of attainable values of the parameters. As we learn how sensitive the pellet gain is to these parameters, we will be able to develop some yardsticks by which to measure progress toward high gain laser fusion.

*Here, and in the rest of this report, $\mathscr{E}_h$ is defined as the *extra* energy needed to heat the ignitor. Thus the energy in the ignitor fuel is now defined as $m_h(\mathscr{E}_h+\mathscr{E}_c)$.

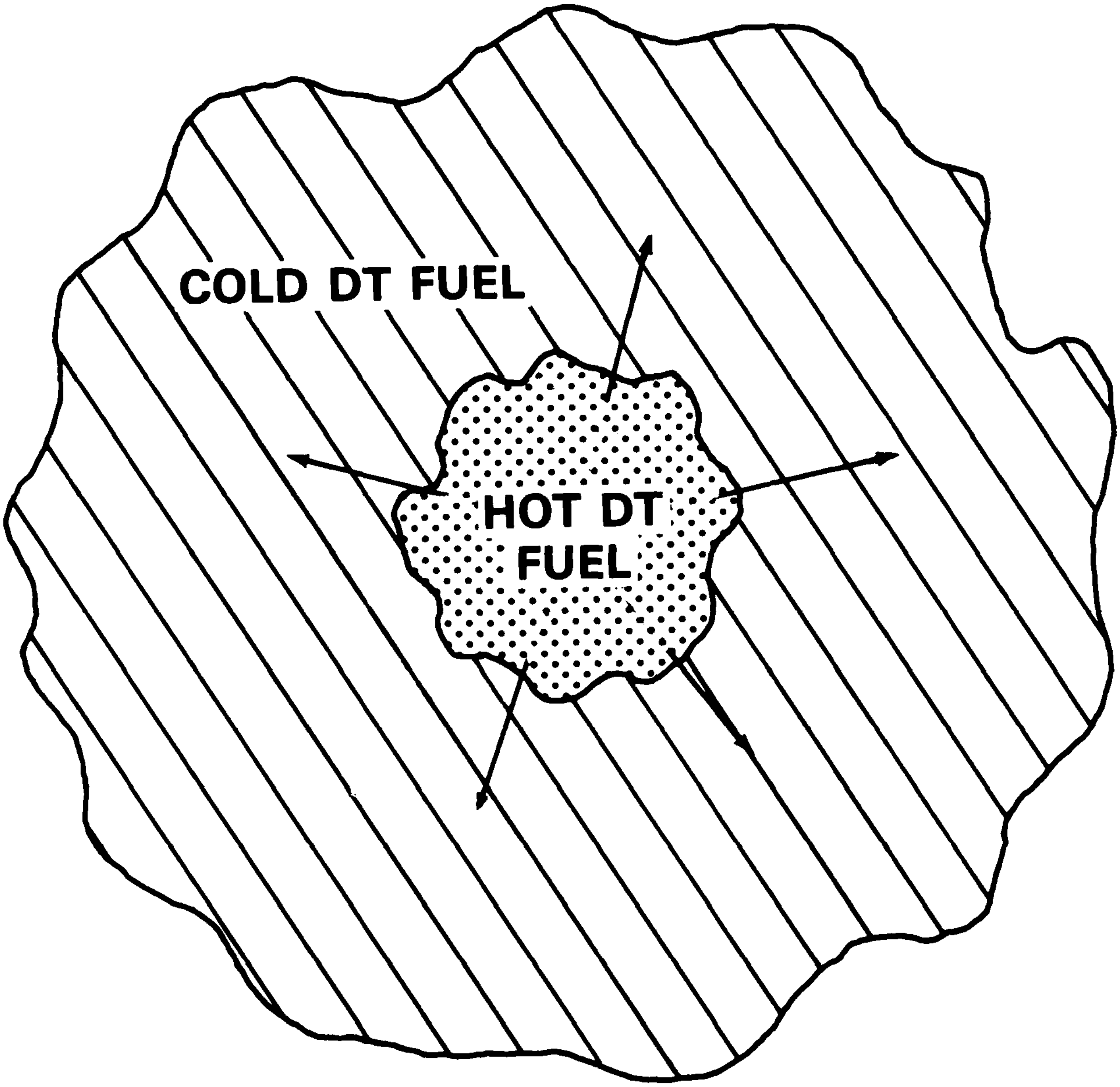

Fig. 2 — Ignition concept: at the moment of peak compression, cold compressed fuel surrounds hot compressed ignitor fuel. Energy from the ignitor then propagates into the cold fuel.

Fractional Burnup[5,6,7,8]

In order to use the above equation for pellet gain, there must be an additional equation that solves for the fractional burnup ϕ. If the fuel is 50%-50% D-T, and if "n" is defined as the total ion number density (deuterium plus tritium), then

$$\frac{dn}{dt} = -\frac{1}{2} n^2 <\sigma v>.$$

The fractional burnup ϕ equals $1 - n/n_0$ (where $n_0 = n(t = 0)$ is the compressed density prior to ignition). The solution of the above equation can then be written

$$\phi = \frac{\frac{1}{2} <\sigma v> n_0 \tau}{1 + \frac{1}{2} <\sigma v> n_0 \tau}.$$

The confinement time τ is proportional to the time it takes a sound wave to propagate a signal from the edge to the center of the pellet.

$$\tau \cong \frac{R}{4 C_s}.$$

The factor of 4 comes primarily from the fact that the outer 20% of a sphere's radius contains about 50% of its mass.[9] R is the radius of the compressed pellet. Converting from ion number density n to ion mass density ρ, the equation becomes simply

$$\phi \cong \frac{\rho R}{\beta + \rho R} \tag{12}$$

The function β is proportional to $\sqrt{T_i}/<\sigma v>$, and is strongly temperature dependent only for low ion temperatures. At 5 keV, $\beta \cong 200$ gms/cm^2, at 10 keV, $\beta = 19$ gms/cm^2, and at 20 keV, $\beta \cong 7$ gms/cm^2. If the fuel starts its ignition at 5 keV, but self-heats to 20 keV or more, then the relevant β is about 7 to 10 gms/cm^2. (This ρR relation is analogous to the $n\tau$ relation in magnetic fusion.)

Ignition

One more equation is needed, to give the *size* of the ignitor region. The hot central ignitor must exceed a certain size in order to then ignite the rest of the cold fuel mass. Numerous calculations in the laser fusion programs at Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Scientific Laboratory (LANSL) have always shown that the central ignitor must be large enough to confine some of its α-particle burn products. The ignitor then self-heats, or bootstraps. This sustains the ignitor temperature while the adjacent cold fuel is heated by various combinations of α-particles, ion and electron conduction, and shocks.

If the ignitor radius is R_h, then

$$R_h \geqslant R_\alpha \tag{13}$$

where

$$\rho\, R_\alpha \cong .3 \text{ gms/cm}^2 \text{ (at } T_e = 10 \text{ keV).}$$

The laser energy required to achieve ignition is an important physical (and fiscal) quantity, because the pellet gain will rise rapidly for laser energies greater than this ignition energy. The ignition energy can be obtained from the following simple derivation. Starting with Eq. (6), we set the fuel radius equal to R_h

$$\eta\ E_{\text{ignition}} = \frac{4}{3}\,\pi\ R_h^3\,\rho\ \mathscr{E}_h \tag{14a}$$

$$R_h \geqslant R_\alpha. \tag{14b}$$

Or,

$$E_{\text{ignition}} = \left(\frac{4}{3}\,\pi\ \mathscr{E}_h\right)(\rho\, R_h)^3\,\frac{1}{\rho^2\eta}. \tag{15}$$

Since the terms in the parentheses are nearly constant,

$$E_{\text{ignition}} \propto \frac{1}{\rho^2\eta}.$$

Historically, the first interesting high gain pellets were designed to produce a very large ρ, (about 10,000 times solid density). Their ignition energy was about a kilojoule. Since then, physics limitations have reduced the predicted ρ to about 500-1000 times solid density. In addition, pellet designers use a more conservative (larger) value for ρR_h, and the coupling efficiency η under some conditions has been poor. As a result of all this, probable ignition energy for some systems has risen to more than

100,000 joules. We will not know the best value for the ignition energy until we have more detailed knowledge on the maximum attainable values of η and ρ.

Symmetry Limitations

In the previous section, the ignitor radius R_h was solely determined by the requirement that $R_h \geqslant R_\alpha$. With R_0 the initial (pre-compression) fuel radius, and with R_h the size of the "target" one has to hit with the imploding shell, the ratio R_h/R_0 can become a very small quantity for large pellets. With a small enough R_h/R_0, the required symmetry of the implosion can become too severe to be practical. There is a lower bound to R_h/R_0, given by the asymmetry in the implosion velocity, which is in turn given by the asymmetry in the applied pressure on the pellet shell. If the shell velocity is

$$\mathbf{v} = -\mathrm{v}_r \, \mathbf{e}_r + \delta \mathbf{v}\,(\theta, \phi)$$

then roughly

$$\frac{R_h}{R_0} \geqslant \frac{|\delta \mathbf{v}|}{\mathrm{v}_r} \equiv \epsilon. \tag{16}$$

Given this lower bound on R_h/R_0, one can solve for the lower bound on m_h/m.

$$\frac{m_h}{m} \geqslant \frac{1}{3} \frac{\rho}{\rho_0} \left[\frac{R_h}{R_0}\right]^2 \frac{R_0}{\Delta R_0} \tag{17}$$

(The initial density and thickness of the fuel shell are ρ_o and ΔR_0).

There are thus two lower bounds on the radius of the ignitor region: the standard R_h inequality given by Eq. (14b), and the symmetry inequality given by Eq. (16). R_h will be given by the larger of these two relation.

Ablation Pressure Requirements

During a pellet implosion, the input energy changes form several times. Laser energy is first converted into plasma thermal energy. The blowoff of this thermal plasma then produces an *ablation pressure* which gives kinetic energy to the imploding shell. Then, if the pellet *ignitor concept* is optimal, this kinetic energy is converted back into the proper amounts of heating and compressional energy.

Let us assume (1) that the pellet is designed for high gain, and (2) that the inward kinetic energy of the shell is almost completely converted to compressional energy, because (3) the energy required to heat the ignitor is small compared to the compressional energy. Then there is a simple relation between the velocity of the implosion and the compressional energy. If the laser-target coupling is optimal, then the cold fuel will be on a low isentrope, with $\mathscr{E}_c/\mathscr{E}_f \cong 2-4$. Using Eq. (10) at 1000 times solid density, we obtain

$$v_r \cong 2-3 \times 10^7 \text{ cm/sec.} \tag{18}$$

If the pellet shell's aspect ratio is not too small, $(R/\Delta R >> 1)$, then the momentum equation becomes

$$\frac{d}{dt}\left(m\,\frac{dR}{dt}\right) \cong -\,P_a\,4\pi\,R^2. \tag{19}$$

Equation (19) can be solved for various pressure profiles, $P_a(R)$, and various mass ablation rates, $m(R)$. For our purposes it is sufficient to consider the simplest case, where the ablation pressure and shell mass are approximately constant. Equation (19) can then be solved for the spherical analog to the freshman physics equation, $v^2 = 2$ as:

$$v_r^2 \cong \frac{2}{3}\,\frac{P_a}{\rho_0\ \ \Delta R_0}\,R_0 \tag{20}$$

Inverting Eq. (20) gives the sought-after equation for the ablation pressure.

$$P_a \cong \frac{3}{2}\,\rho_0\,v_r^2\,\frac{\Delta R_0}{R_0}. \tag{21}$$

The required ablation pressure P_a can be obtained from the initial pellet density, the final implosion velocity, and the initial aspect ratio.

As one example, take $R_0/\Delta R_0 = 10$, $<\rho_0> = 0.5$ gms/cm^2, and $v_r = 3 \times 10^7$ cm/sec. Then $P_a \cong 65$ megabars. As a second example, take $R_0/\Delta R_0 = 30$, $<\rho_0> = 0.3$ gms/cm^2, and $v_r = 1.4 \times 10^7$ cm/sec, then $P_a \cong 3$ megabars. More complicated hydrodynamic codes predict a similar range of required ablation pressures: 5-40 Mbar, for various average densities, implosion velocities, and aspect ratios.[10]

High Gain Ignitor Concepts

Several pellet concepts used in small laser systems, such as the "exploding pusher" design, do not extrapolate to a reactor-sized system. In this section, as in the whole report, we are only considering pellet designs which, at one time or another, have been proposed to have the potential for high gain.

One of the first pellet designs, based on the "shaped pulse," was proposed at LLNL[5] in 1969. See Fig. 3. This concept proposed using a rapidly rising laser pulse to isentropically compress the fuel to very high density (10,000 times solid), followed by a shock-heating of the center to achieve ignition. This technique tended to also produce some heating in the outer portion of the fuel. Since extra laser energy was required to heat this outer portion, the predicted pellet gain was always less than 100. In addition, this "shaped pulse" concept used relatively high laser intensities. Numerous laser-target coupling experiments with small systems strongly suggest that this pellet concept would suffer from poor coupling (due to stimulated Brillouin backscatter, fast-ion blowoff, and inhibited transport) and from preheat of the cold fuel (due to suprathermal electrons) perhaps even with ultraviolet lasers. The low optimal pellet gain combined with the high risks of even further reductions due to poor coupling and preheat has led most laser fusion scientists to downgrade this pellet concept.

The "thin shell" pellet concept was then proposed in 1974 in the U.S.S.R.[11] as a way to avoid these problems. This pellet was claimed to have a higher pellet gain ($Q \cong$ 3C0-1000), and used a low laser intensity to avoid the deleterious plasma effects. This pellet has been criticized for two reasons. First, the initial pellet aspect ratio is very large, ($R_0/\Delta R_0 \cong$ 60-100). These high aspect ratio targets may be much more sensitive to shell breakup during the implosion, due to hydrodynamic instability. Second, even if one ignores the instability, the predicted high pellet gains have not been verifiable at the U.S.D.O.E. laser fusion laboratories.

For example, in 1978 J. Nuckolls of LLNL wrote,[12] "However, for single shell hollow targets it is not possible to simultaneously achieve maximum efficiency compression and ignition. If the pulse shape is varied to put the inner edge of the shell on a drastically different isentrope than the outside,

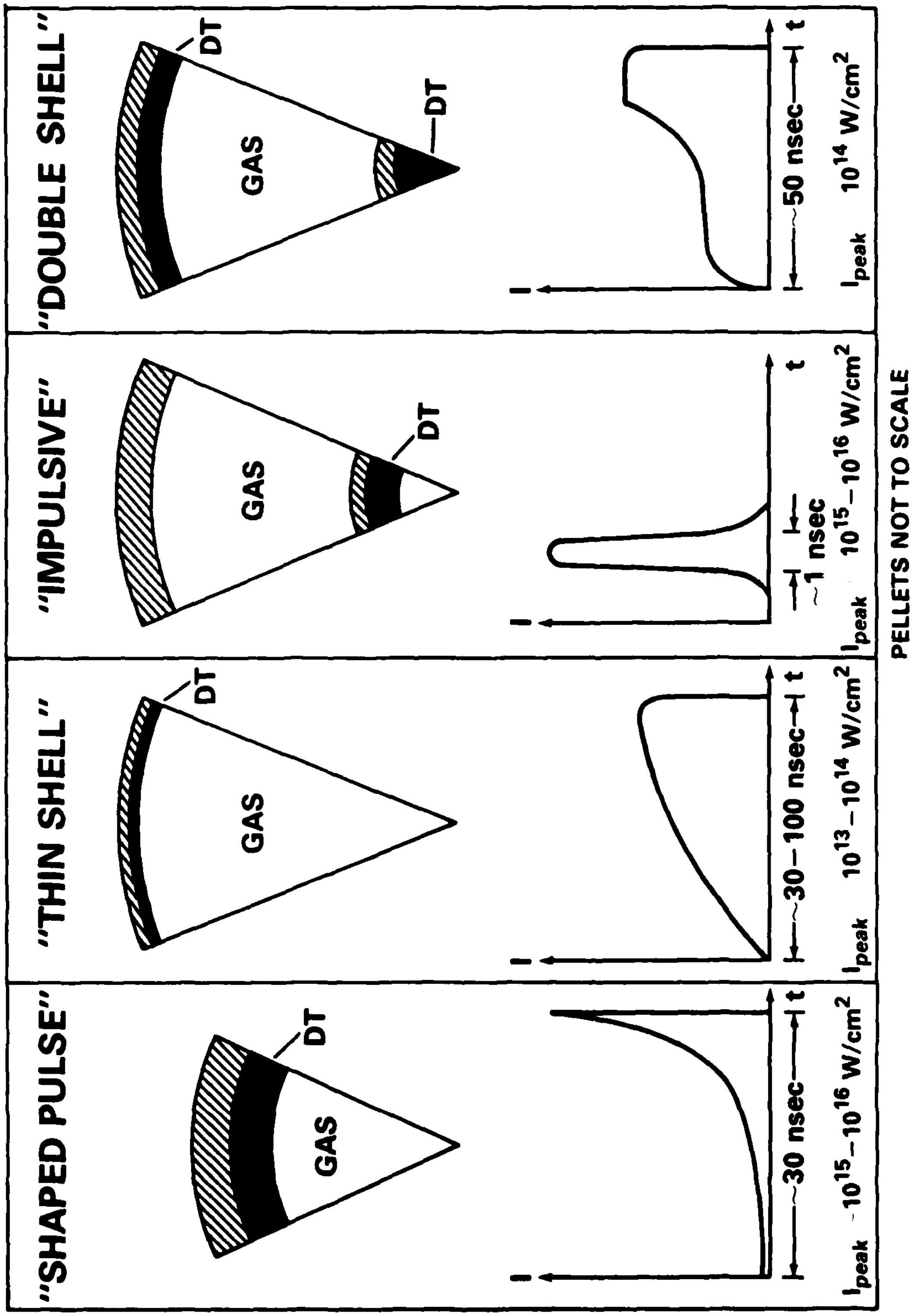

Fig. 3 — Four pellet concepts that have been proposed for high gain

then the inside will implode and ignite prematurely. If the inner edge is shocked to a higher adiabat late in the implosion, then much higher driver powers are required. Consequently, much higher gains can be achieved at low power if an ignitor capsule is positioned at the implosion center." For these two reasons—possible destruction of the implosion by hydrodynamic instability and a non-verifiable ingnition concept—the "thin-shell" pellet concept is not being actively pursued at the U.S. laser fusion laboratories that have implosion design capabilities, although some of the relevant laser-target coupling physics has been investigated at N.R.L.

The third type of pellet in Fig. 3, labeled as the "impulsive" concept, was proposed at LANSL.[13] It approaches the plasma instability problem in a different way to take advantage of the physics of CO_2 laser-plasma coupling. All of the laser energy is in a 1-2 nanosecond pulse, producing very high laser intensities on target. Copious quantities of high temperature electrons are generated ($T_e \geq 50$ keV). The outer shell is designed to be a few mean-free-paths thick to these electrons. As the outer part of this shell heats up and blows off, it impulsively drives the rest of the shell inward. Calculations have shown that the central shell then experiences a rising pressure profile, very much like that designed for the "shaped pulse" target. This "impulsive" pellet concept has been criticized because the ignition of the inner pellet fuel is unduly sensitive to details of spherical shock behavior; in other words, it is unduly sensitive to any asymmetries in the implosion. In addition, the impulsive load drives a shock through the outer shell, so that no extra DT fuel can be placed against this outer shell. This pellet concept is now under review.

The fourth pellet concept, the so-called "double shell" design, is currently favored among LLNL designers as a high gain design. It was developed by J. Lindl.[14] The main fuel region in the outer shell is physically distinct from the ignitor fuel in the inner pellet. This allows the designer to keep the main fuel on a cold isentrope, thereby maximizing the pellet gain. The laser pulse is relatively unshaped, with a moderate peak laser intensity. This minimizes the deleterious plasma effects.

This pellet concept has also been criticized. To properly drive the outer shell, its radius has been chosen to be about 10 times the inner sphere radius. The inner DT fuel compresses to about 1000 times solid DT. Therefore it also moves radially inward a factor of ten. The symmetry factor, R_h/R_0, is thus about 1%. This is a severe symmetry requirement, and it is not clear that in this design one can trade off a good coupling efficiency for a relaxed symmetry requirement (say ~3%). This pellet concept has also been criticized for its fabrication difficulties. It is not clear that the inner pellet can be easily supported in the center (±0.5%) of the large pellet without creating excessive perturbations due to the support membrane.

It is likely that there will be further evolutions in high gain pellet concepts. We will assume, in the rest of this report, that any such pellet designs will share some of the characteristics of the "thin shell" and "double shell" concepts. That is, we will assume that there is a shell of material that is ablated and driven inward by a multi-nanosecond laser pulse, at moderate laser intensities, with little pulse shaping. This will produce the most efficient implosions, with the shell on the best isentrope. We can then address the question: what combinations of laser intensity, wavelength, and pulse shape will produce the highest coupling efficiency, the lowest isentrope, and the best implosion symmetry?

Critical Elements of High Gain

The previous sections contained a review of some of the basic concepts in laser fusion. Most of these concepts have already appeared in the scientific literature.

We first developed a set of equations that give an upper bound to the pellet gain. Calculation of this gain required knowledge of just 7 physical parameters.

(a) Coupling efficiency, η

(b) Cold fuel isentrope, $\mathcal{E}_c$

(c) Implosion symmetry, R_h/R_0

(d) Compression, ρ

(e) Initial shell aspect ratio, $R_0/\Delta R_0$

(f) Ignitor temperature, T_i

(g) Self-ignition radius, R_h/R_α.

But these equations for the pellet gain assume that one can in fact reach the non-equilibrium state of a hot compressed ignitor surrounded by cold compressed fuel. To reach this state requires 2 more concepts: a sufficient ablation pressure P_a and an ignition concept for efficiently converting the kinetic energy of the imploding shell into the correct mixture of hot and cold fuel regions, with the cold region surrounding the hot region.

All of the above concepts and parameters can now be subsumed into 5 *Critical Elements*. These are

(1) Coupling Efficiency

(2) Cold Fuel Isentrope

(3) Implosion Symmetry

(4) Ablation Pressure

(5) Ignitor Concept

Parameters a, b, and c are the same as critical elements #1, #2, and #3. Parameters d and e are contained in critical elements #2, #3, and #4. Parameters f and g are always achievable for a big enough laser, and are contained in critical element #5.

These 5 critical elements are in a sense fundamental. The values that can be achieved in the first 4 depend directly on the uncertain physics of laser-plasma coupling.

In the following parts of this report we shall see that there are minimum values for these critical elements, and we shall see how these critical elements depend upon the laser-plasma coupling physics.

III. SENSITIVITY OF PELLET GAIN TO THE CRITICAL ELEMENTS

We now have a set of relatively simple algebraic equations for the pellet gain, which can be solved with a programmable hand-calculator.

Basic Equation Set

1. Gain:

$$Q = \eta \frac{\phi \, \mathcal{E}_b}{\mathcal{E}_c + \dfrac{m_h}{m} \mathcal{E}_h} \tag{11}$$

2. Fractional Burnup:

$$\phi = \frac{\rho R}{\beta + \rho R} \tag{12}$$

$$7 \leqslant \beta \leqslant 113 \text{ gm}^2/\text{cm}^2$$

3. Sub-Ignition Mass ($E_L < E_{\text{ignition}}$):

$$m_h = m = \frac{4}{3} \pi \rho R^3 = \eta \frac{E_l}{\mathcal{E}_h + \mathcal{E}_c}$$

4. Over-Ignition Masses ($E_L > E_{\text{ignition}}$):

$$m_h = \frac{4}{3} \pi \rho R_h^3$$

$$m = \frac{4}{3} \pi \rho R^3 = 4 \pi \rho_0 R_0^2 \, \Delta R_0$$

$$\eta E_L = m_h \mathcal{E}_h + m \mathcal{E}_c$$

5. Ignition Energy:

$$\eta E_{\text{ignition}} = \frac{4}{3} \pi \rho R_h^3 \mathcal{E}_h \tag{14a}$$

6. Ignition Radius:

$$R_h = \text{larger of } (\sigma/\rho, \; \epsilon R_0)$$

where

$$\sigma \geqslant \rho R_\alpha \tag{14b}$$

$$\epsilon = |\delta \mathbf{v}| / \mathrm{v}. \tag{16}$$

Parametric Variations

During the evolution of pellet design in the U.S., various values have been suggested for the 7 parameters. Let us first calculate the gain of a prototypical pellet with one optimal choice for this set. Then we can see how sensitive the pellet gain is to a change in these parameters. None of these parameters are inconsistent with today's knowledge.*

Table II — Prototypical Pellet

$\eta = 15\%$	$R_0/\Delta R_0 = 10$
$\mathscr{E}_c/\mathscr{E}_f = 2$	$T_i = 5$ keV
$\epsilon = 1\%$	$\rho R_h \geqslant .4$ gms/cm^2
$\rho = 1000\,\rho_{solid}$	$\beta = 10$ gms/cm^2

This prototype pellet ignites at 28 kilojoules. At 4 megajoules the gain is about 1000. Not a bad design. The following sections contain variations of the parameters with respect to this prototype, so that we will be able to see how sensitive pellet gain is to deteriorations in laser-target coupling.

For decreasing laser energies, the pellet mass also decreases. Eventually the pellet shell becomes so thin that it heats all the way through, and explodes instead of ablating. To avoid this limit, the calculations have a lower bound on the laser of 10 kilojoules.

At the other limit, too large a laser with too large a yield is not of interest, since eventually it becomes difficult to contain the explosion inside a reactor chamber, and difficult to fabricate the very large final optics. A 4 megajoule laser with a pellet gain of 250 produces a thermonuclear yield of 1,000 megajoules, or an equivalent of about 500 pounds of TNT.

For the purposes of this study, we will not consider laser drivers above 4 megajoules, or below 10 kilojoules.

Remember also that these formulas tend to over-estimate the pellet gain. They provide an upper bound for various attainable parameters. No real set of pellets will necessarily achieve these gains. In

*Note that these values of T_i and β are most appropriate for pellets above ignition size, when the fuel self-heats. Choosing an invariant T_i and β has no effect on the energy required to ignite, or on the gain of large pellets, but it may overestimate the gain of sub-ignition pellets by a factor of 5 to 10.

particular, the calculations here show a very sudden steep increase in pellet gain when the laser energy exceeds the ignition energy. These portions of the gain curves have been dashed, to emphasize that real pellets will have a more gradual increase in gain beyond ignition.

Variation of η

In Fig. 4 the coupling efficiency has been varied, with all other parameters kept at their prototypical value. If the coupling efficiency drops from 15% to 5%, there are two effects. First, the laser energy to achieve ignition increases by a factor of 3, from 28 kilojoules to 83 kilojoules. Second, the gain for a 4 megajoule driver drops from about 1200 to 275. A low coupling efficiency means that the pellet cannot achieve high gain even with a large driver! If the coupling efficiency drops to 2%, then the ignition energy rises to 200 kilojoules; with a 4 megajoule driver the associated gain is only 80.

There is clearly a lower limit to the laser-to-fuel coupling efficiency if high gains are to be achieved. For a 5%-10% efficient laser, and a pellet gain of 100-200, the coupling efficiency should exceed 3% to 4%, assuming that all the other parameters are as listed in Table II.

Variation of $\mathscr{E}_c/\mathscr{E}_f$

Figure 5 shows the effect of compressing the cold fuel to the same final density on a higher isentrope (due to preheat). For example, if the cold compressed fuel has 8 times (rather than twice) the fermi-degenerate energy density, then the pellet gain drops to 200.

According to these results, changing the preheat levels of the fuel has no effect on sub-ignition pellets where the fuel energy is supposed to be heated. But too much preheat can also affect sub-ignition pellets in a more insidious fashion. If the fuel is heated too much, too early in the pulse, then the internal pressure of the fuel can become comparable to the external pressure used to drive the pellet shell inward. The fuel will then explode prematurely, instead of imploding to high density. This secondary effect on small pellets is not included in our analysis. But for large megajoule-sized pellets, the pellet gain should be more sensitive to the type of effects shown in Fig. 5.

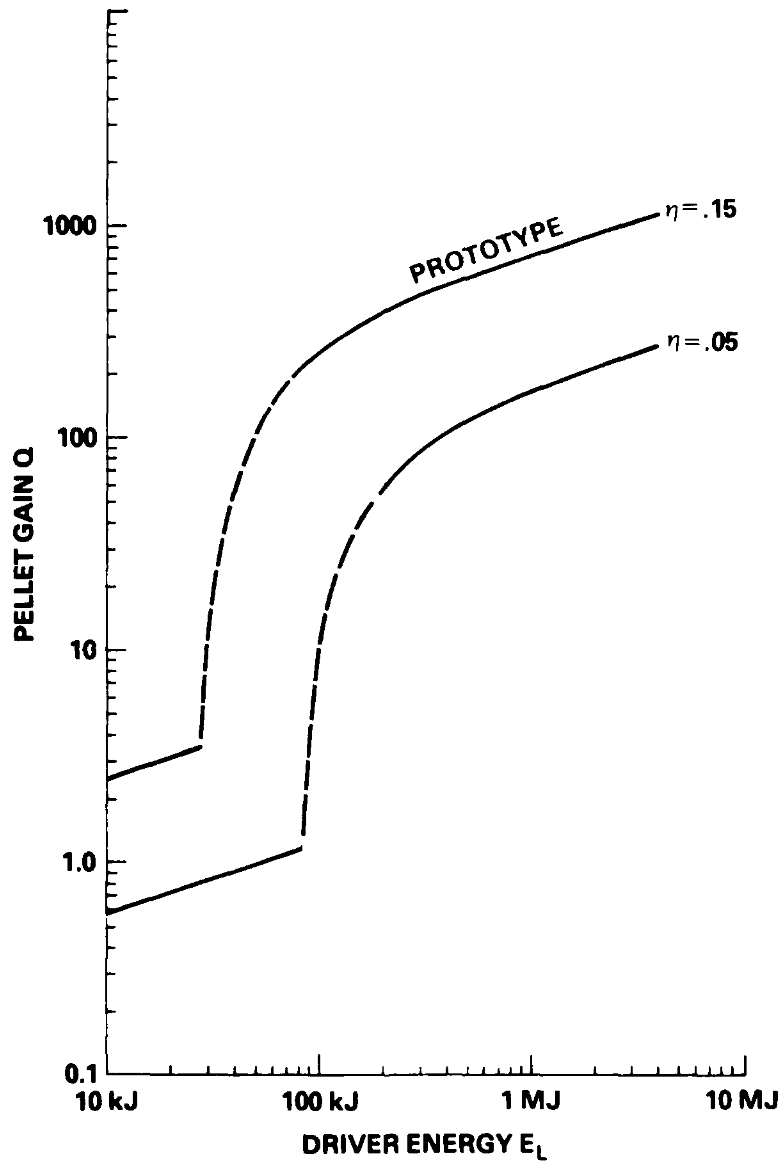

Fig. 4 — Variation of η, the laser-to-find coupling efficiency

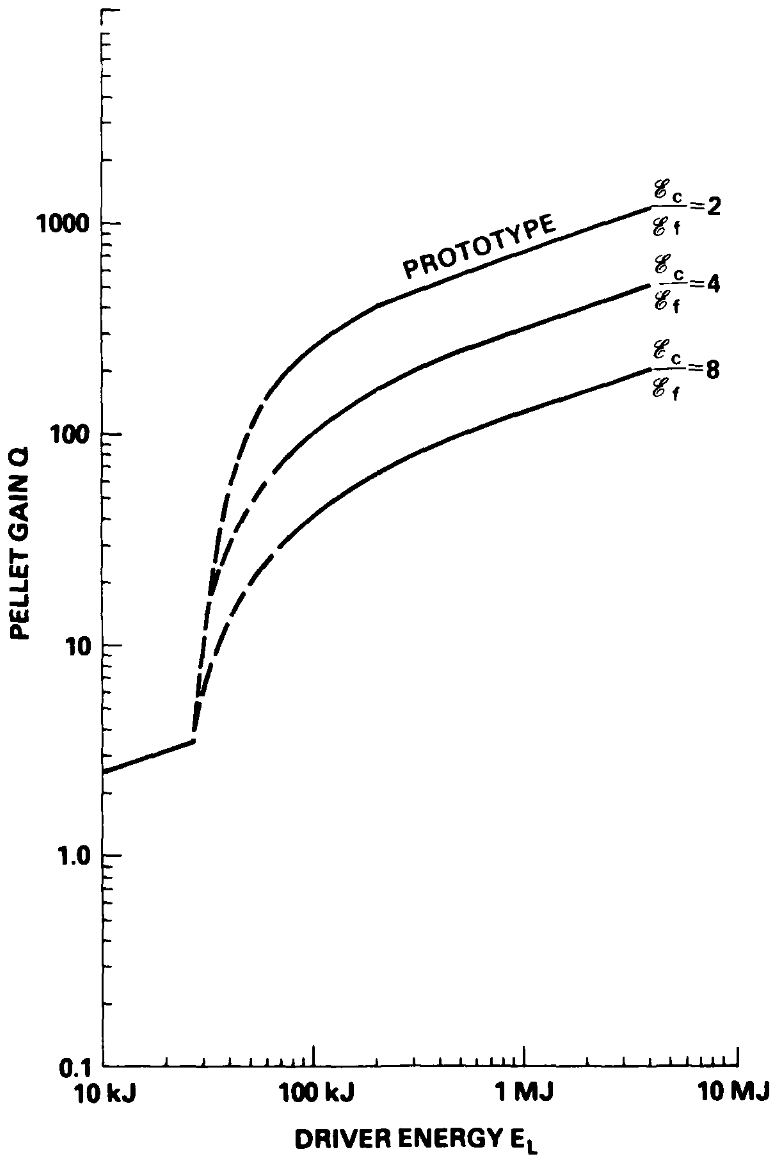

Fig. 5 — Variation of $\mathscr{E}_c/\mathscr{E}_f$, the cold fuel energy of compression, as impared to the fermi-degenerate value

Asymmetry Variations

In the prototypical pellet, the radius of the hot ignitor can be as small as 1% of the initial pellet radius. This means that every section of the pellet shell must implode at about the same time, such that all sections of the pellet are aimed at a region whose radius is about 1% of the initial pellet radius.

Figure 6 shows the effect of greater two-dimensional asymmetries. If the asymmetry limit is raised from 1% to 2.5% or 4%, then the 4MJ driver will produce maximum gains of 440 or 115, respectively, because a larger fraction of the laser energy must then be used in the ignitor region. Pellets with gains above 100 must have velocity asymmetries below about 4%, assuming all other parameters have the prototypical values listed in Table II.

Density Variations

Since the ignitor mass varies as

$$m_h \sim \rho\ R_h^3 \sim \frac{(\rho\ R_h)^3}{\rho^2}$$

high compression will reduce the required energy for ignition. Figure 7 shows the impact of reducing the compression perhaps because of a higher hot-fuel isentrope. As the fuel density decreases from 1000 ρ_{solid} to 500 ρ_{solid} to 200 ρ_{solid}, the energy for ignition rises from 28kJ to 110kJ to 700kJ. Note that at the 4 MJ level, the gain of the pellet is actually slightly larger with less compression, since it takes less energy, $\mathcal{E}_c$, for less compression.

Mixed Cases

Figure 8 shows a case where many of the basic parameters have been simultaneously degraded. The ignition energy rises from 28kJ to 330kJ, and the 4MJ driver gain drops to 120. This may marginally suffice for a laser fusion reactor.

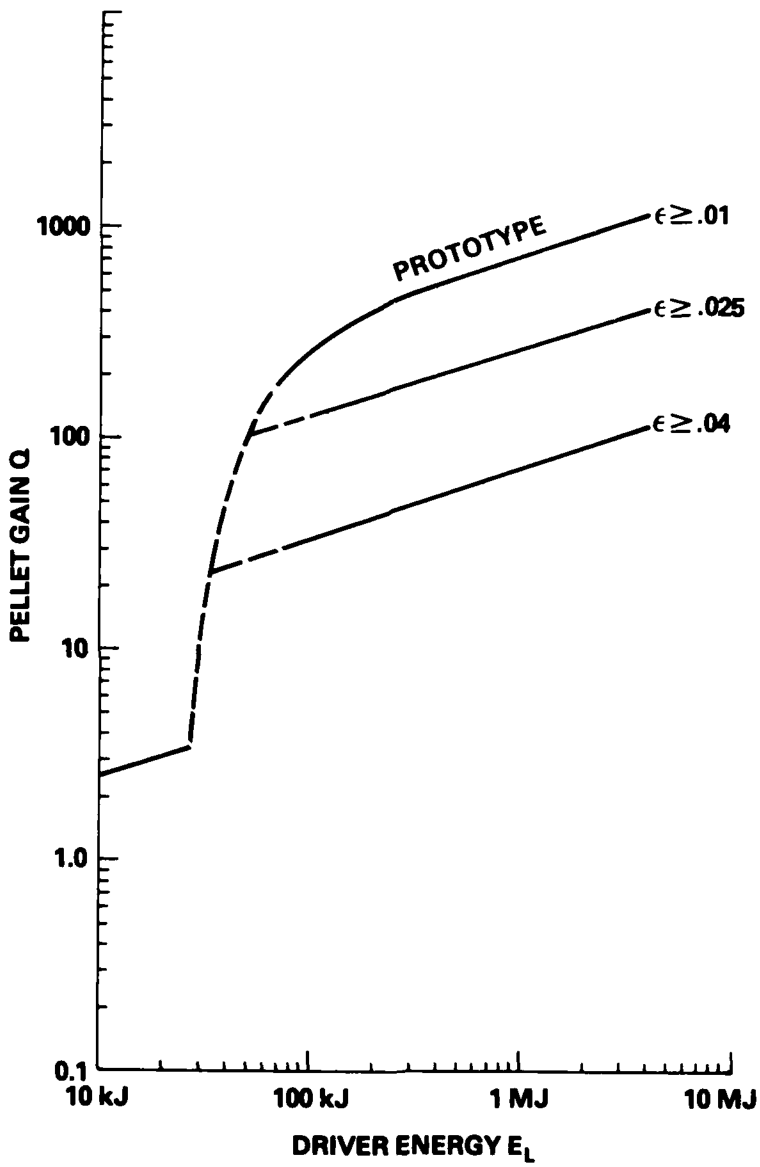

Fig. 6 — Variation of the implosion asymmetry $\epsilon = R_h/R_0$

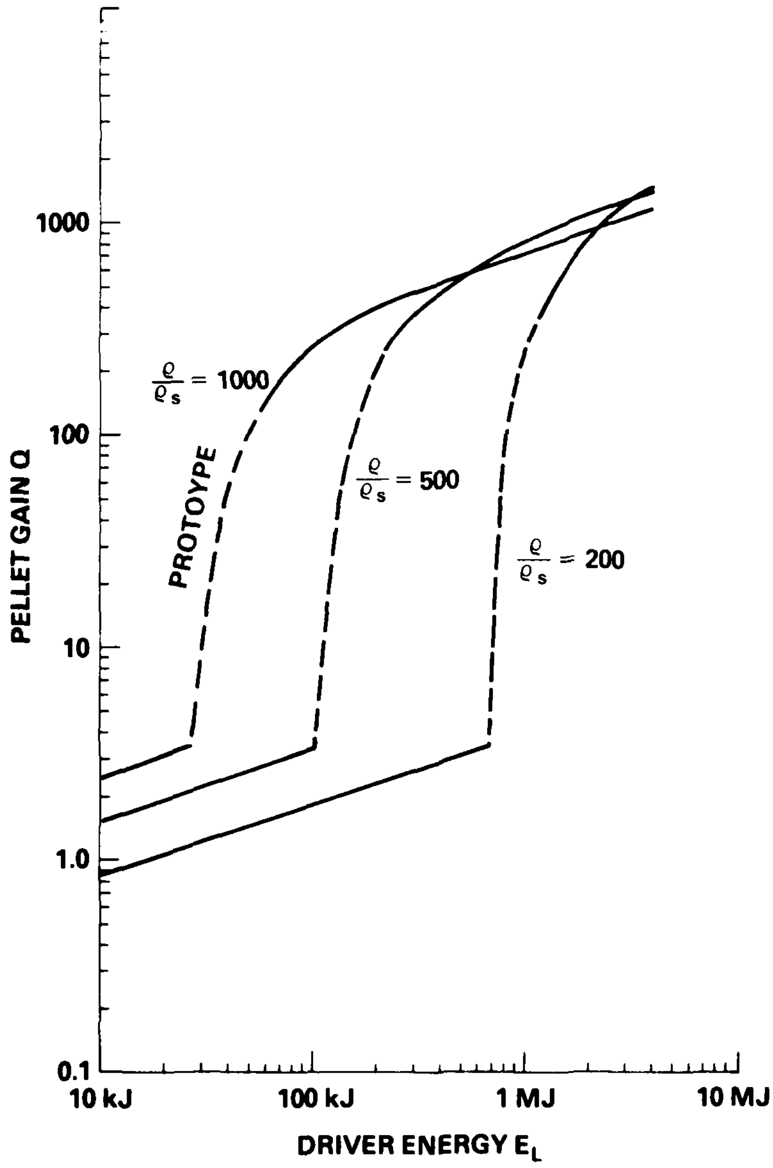

Fig. 7 — Variation of ρ/ρ_s, the compression over solid density

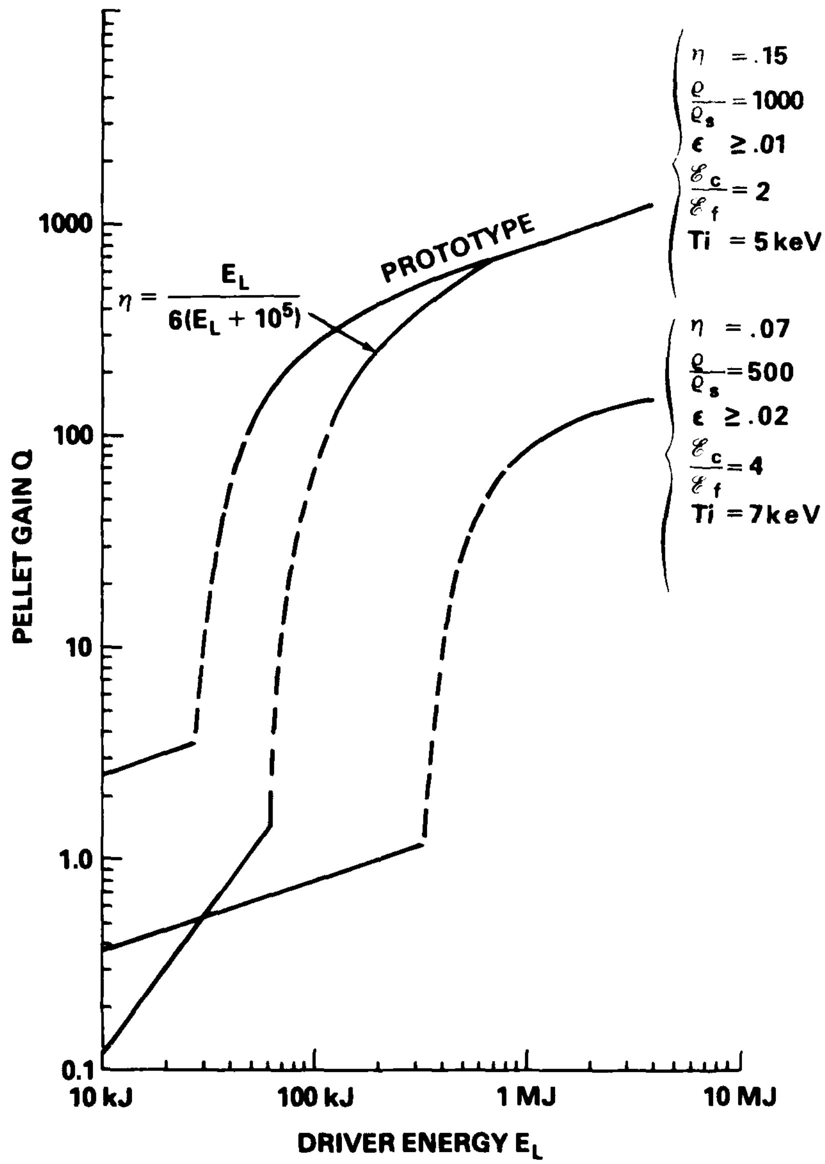

Fig. 8 — (1) Simultaneous variation of several parameters. (2) Variation of coupling efficiency with laser energy such that η = 1.5% at 10 kJ and 16% at 4 MJ

In a second case, the coupling efficiency has been made a function of the laser energy with the assumption that the pellet design is more efficient with larger drivers. It is not unreasonable if the fraction of the pellet mass in non-DT materials, such as tampers, varies with pellet size.

The pellet designer can also play off coupling efficiency against symmetry or isentrope, as required by the physics of laser-target coupling.

Analysis of Gain Figures

1. High pellet gain is not necessarily related to successful ignition. The predicted laser energy requirements for ignition and breakeven can rise or fall without affecting the predicted gain of a multi-megajoule system, and vice versa. Ignition, scientific breakeven, and high gain are all only predictable with a knowledge of the critical elements. Therefore all implosion experiments should include an evaluation of these elements. And some fraction of implosion experiments should be aimed at optimizing and learning how to scale these elements.

2. Pellet ignition requires a definite ρR. Choosing ignition as a first goal can be expensive, since

$$\rho R = \rho^{2/3}(\rho R^3)^{1/3} \sim \rho^{2/3} E_L^{1/3}$$

A factor of 3 in laser energy only increases the ρR by a factor of 1.44.

3. There are minimum values for four of the critical elements, if high gain is to be achievable. These are:

- Coupling efficiency, $\eta > 3\text{-}4\%$
- Cold Fuel Isentrope, $\mathscr{E}_c/\mathscr{E}_f < 8$
- Implosion Symmetry, $R_h/R_0 < 4\%$
- Ablation Pressure, $P_a \sim 5\text{-}40$ Mbar

The previous set of equations allows one to calculate the upper bound on pellet gain for any given set of these critical elements (and the other four parameters.) If these four critical elements are themselves functions of the laser energy, then small laser systems may perform poorly while large laser systems may produce high gain. Or vice versa.

4. When one has a physics basis for scaling the critical elements to a large system, one can logically proceed directly to propagating burn studies, using a Single Pulse Test Facility. Such a facility would probably put about a megajoule of energy on a pellet.

IV. WHAT LASER-TARGET INTERACTION PHYSICS CAN AFFECT THE CRITICAL ELEMENTS OF GAIN?

Four of the five critical elements are direct functions of the laser-target interaction, and they depend upon the laser's intensity, wavelength, pulse length, bandwidth, and spatial uniformity.

At low laser intensities the laser-target coupling is collision-dominated. There are no plasma instability effects and the coupling is rather innocuous. But at too low an intensity the laser cannot provide sufficient ablation pressure or sufficient implosion symmetry. At too high an intensity the various plasma physics effects reduce the coupling and raise the isentrope. Pellets will therefore operate within some window in intensity, limited both from above and below.

At shorter laser wavelengths the laser-target coupling again becomes more collisional, thereby raising the threshold for plasma effects. But at too short a wavelength, as we shall note below, the implosion symmetry deteriorates. Thus there will also be a window in laser wavelength.

Finally, a multi-line laser can help control the deleterious plasma instabilities. If the laser energy is divided into many distinct wavelengths, then there is less energy available to drive each plasma instability mode. A multi-line broadband laser raises the threshold for plasma instability effects.

Many of the plasma physics effects are also in the category of "convective instabilities," which means that their growth depends upon the radial extent of the plasma corona around the pellet. Reactor-sized pellets will have dimensions of several millimeters, and associated laser pulse lengths of tens of nanoseconds. But these long laser pulses require substantial laser energy, and therefore the pulse length effect has only begun to be addressed experimentally in the last few years.

The following sections briefly address some of the underlying laser-target physics issues that control each of the critical elements. Again, this is not a general survey article. Such an article might include hundreds of references.

Coupling Efficiency

The efficiency of laser-fuel coupling can be written as the product of three distinct efficiencies.

$$\eta = \eta_a \eta_h \eta_t. \tag{22}$$

The laser energy is first absorbed onto the pellet with an *absorption efficiency* η_a. This absorbed thermal energy is then converted, by the rocket ablation process, into kinetic energy of the imploding shell with a *hydrodynamic efficiency* η_h. When the imploding shell converges to the center of the pellet, this kinetic energy is converted into compression and heating of the fuel with a *transformation efficiency* η_t. The third conversion varies with the pellet size and pellet design. The first two, which are functions of the laser-target coupling, will be reviewed in the next sections.

Absorption Efficiency

The most efficient way to absorb laser energy is via inverse bremsstrahlung (collisions). Absorption efficiencies of 80% to 90% have been measured at the lower laser intensities and shorter laser wavelengths, and are probably due to this mechanism. As one changes to higher intensity and longer wavelength, collisions become less important and the absorption comes primarily from plasma processes such as resonant absorption, enhanced ion-acoustic fluctuations, and the various decay instabilities. Short-pulse experiments show that this combined absorption efficiency is usually in the range of 30% to 50% at the higher intensities and short pulse lengths.

Opposing this absorption is the process of stimulated Brillouin scatter, which can enhance the reflectivity of the laser energy. See Fig. 9. Like the above plasma processes, this scattering mechanism tends to increase with higher laser intensity and longer wavelengths (except perhaps for the CO_2 laser wavelength). Stimulated Brillouin scatter is usually a "convective" instability and therefore the amount

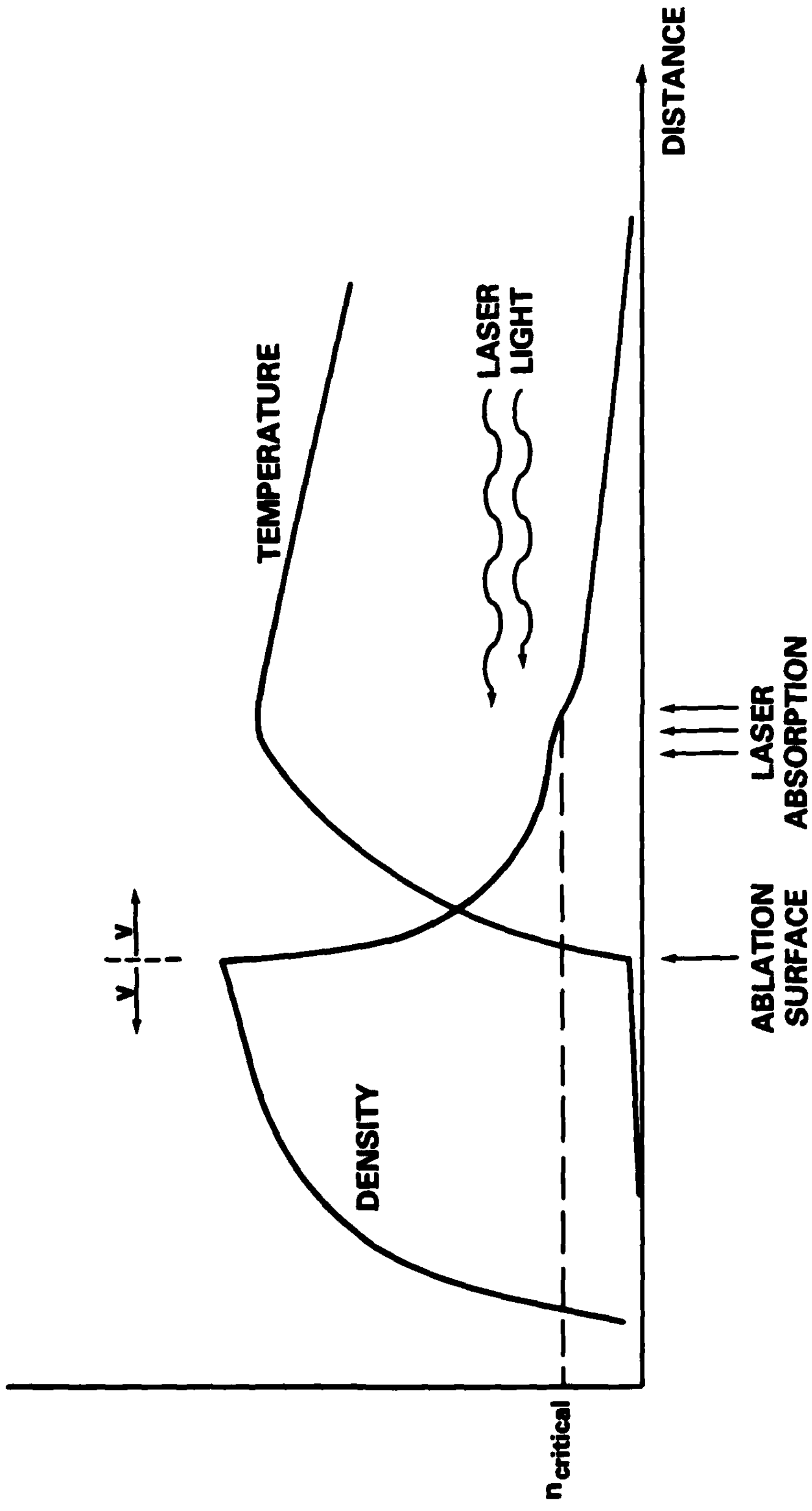

Fig. 9 — Typical density and temperature profiles at one moment during the implosion

of scatter depends upon the physical size and profile of the plasma, which in turn depends upon both the laser pulse length and the size of the target. The scatter will be limited by various mechanisms. (Perhaps the most important of these are the plasma's velocity gradient and the nonlinear limits on the density fluctuations.)

Very few experiments have yet been done with millimeter-sized plasmas and/or multi-nanosecond laser pulses, so that it is not yet possible to estimate the amount of backscatter for various reactor-sized pellet concepts. For higher laser intensities and reactor-sized plasmas, theoretical predictions of stimulated Brillouin backscatter vary from about 30% to 90% of the incident light. (The current high absorption efficiency of shorter wavelength radiation by inverse bremsstrahlung was predictable. The problem of interest remains with longer pulse-lengths and larger plasmas appropriate to reactor-size pellets.)

At the lowest laser intensities ($\sim 10^{13}$ W/cm^2), NRL[15] has measured absorptions of about 80%-90%. As the laser intensity increases, the absorption will drop to 10%-40%, depending on the still unknown level of backscatter. Ripin, et al. of NRL[16] have shown that the early "shaped pulse" pellets were particularly sensitive to high backscatter. Current pellet concepts such as the "double shell" use lower laser intensities, operating in the transition region between collision-dominated and plasma-dominated physics.

Hydrodynamic Efficiency

The efficiency of a rocket is a function, basically, of the velocity of the exhaust. The greatest efficiency occurs when the exhaust leaves the rocket at the rocket's own speed. The exhaust then has no velocity or kinetic energy in the Earth's frame of reference. In the same way, the hydrodynamic efficiency of a spherical implosion is optimized when the ion blowoff velocity is comparable to the implosion velocity.

The plasma density profile is as important for evaluating hydrodynamic efficiency as it is for evaluating absorption efficiency. The absorption depends upon the size and profile of the *underdense* plasma, where the laser light penetrates. But the ion blowoff velocity depends primarily on the size and profile of the *overdense* plasma, from the absorption region to the thermal front (or ablation surface). See Fig. 9. It has been shown by several computer codes that it takes at least a nanosecond to set up a quasi-steady-state overdense profile. Experiments with pulses shorter than a nanosecond do not produce a meaningful blowoff velocity or hydrodynamic efficiency.

Higher laser intensities also tend to produce a longer overdense plasma. This longer plasma is appropriate to a larger reactor-sized target, where the spherical divergence does improperly shorten the density profile. Combining higher laser intensities with larger targets and multi-nanosecond pulses means that rather large lasers will be needed to explore all of this physics.

At lower laser intensities NRL[15] has measured hydrodynamic efficiencies on flat targets at these lower intensities as high as 20% ($I = 10^{13}$ W/cm^2; $\lambda_L = 1\,\mu$m; $\tau_L = 3.5$ nsec). Using this low intensity multi-nanosecond data, the net coupling efficiency becomes

$$\eta_a \eta_h \eta_t \lesssim .8 \times .2 \times \eta_t \leqslant 16\%.$$

The prototype pellet in Part II had a 15% overall coupling efficiency. In the next few years experiments with larger-sized plasmas and with longer pulse lengths will give a foundation for predicting the maximum laser intensity that one can use to efficiently drive a pellet.

Cold Fuel Isentrope

The isentrope of the cold fuel can increase due to unwanted shocks in the pellet, or due to fast electrons whose mean-free-path is comparable to the pellet shell thickness. Some of this heating will occur prior to the compression, and some will occur during the compression.

Using the Second Law of Thermodynamics, we assume that there is some heating during the compression process, and that this heating is proportional to the compressional energy;

$$dQ = -\xi\, pdV$$

so that

$$dU = -(1 + \xi)\, pdV.$$

Combining this equation with the energy-pressure relation $U = 3/2\ pV$ (good for both Fermi-Dirac and ideal-gas statistics), one can derive the energy requirement to compress the fuel:[17]

$$U = U_0 \left(\frac{\rho}{\rho_0} \right)^{2/3(1+\xi)} . \tag{23}$$

Fast electrons and shocks can preheat the fuel by raising U_0, or they can continuously add heat via a nonzero ξ. (The variable $U = m\mathscr{E}_c$.)

For example, if the DT fuel is raised initially to just 7 eV, then the compressional energy will be about 8 times its value for a cold fermi-degenerate system. (Cold solid-density DT has a 5 eV fermi temperature.)

Alternatively, if the heating occurs during the compression phase, then a $\xi = 15\%$ will produce a factor of two energy increase during a thousandfold compression. If the pellet is of reactor size with a negligible heat load on the ignitor, the continuous preheat energy can be related to the laser energy:

$$dQ = -\xi\ pdV \approx \xi\ \eta\ dE_L . \tag{24}$$

Therefore the allowable energy in fast electrons is only $\xi\eta$ times the incident laser energy. In our example, if $\xi = 15\%$ and $\eta = 15\%$, the energy in fast electrons is limited to only about 2% of the incident laser energy.[17]

Some plasma instabilities which generate fast electrons are "convective" instabilities, so that the number of fast electrons will increase with plasma size, and therefore laser pulse length. But perhaps more importantly, for long laser pulselengths the laser light can *filament* in the plasma. If the laser intensity is slightly higher in some regions of the pellet, then the plasma can be pushed out of these regions. The lower plasma density has a higher index of refraction, producing a positive lens effect, which then leads to still higher laser intensities, and the process bootstraps. This filamentation or self-focusing effect can increase the intensity of the laser light, and therefore also enhance the generation of fast electrons. While enhancing the fast electrons, the channeling due to the filamentation might also reduce the stimulated Brillouin scatter. (Recent NRL measurements of emitted X-rays and light harmonics provide strong evidence for this filamentation.)

There are two ways to move the plasma aside. In the first, called ponderomotive self-focusing, the pressure of the intense laser light itself pushes the plasma. In the second, called thermal self-focusing, the laser energy locally heats the plasma, and the hotter plasma then expands. The first mechanism tends to occur at higher laser intensities, the second at lower laser intensities.

Asymmetric Implosions

The number of ways of destroying the symmetry of an implosion are limited only by one's imagination. But if the designer is careful, and the pellet is made very symmetrically, then there are two chief causes of asymmetry: the nonuniformities in the laser beams, and the Rayleigh-Taylor instability. See Fig. 10.

Laser Asymmetry

To achieve high pellet gain, the symmetry of an implosion must be better than $\pm 4\%$. How will realistic laser asymmetries compare with these implosion asymmetries? Unfortunately, there is a paucity of detailed optical designs for uniform illumination in a reactor-sized system. It should be possible, in principle, to balance the different laser beams to a few percent. And from the laws of optics, it is theoretically possible to have each beam uniform to a few percent. But it is unlikely that in realistic systems each separate laser beam can produce a uniformity in the target plane of much better than about $\pm 20\%$. Therefore, one should probably either overlap a large number of beams, or find some physics mechanisms which can smooth each laser beam by about a factor of ten, from laser asymmetry to implosion asymmetry.

Thermal diffusion is such a mechanism. By analogy, if one looks up in the sky on a cloudy day, one cannot discern where the sun is.[5]

If the distance between the absorption region and the ablation surface is d, and if the wavelength of the laser intensity perturbation is λ_p, then the temperature nonuniformities will be reduced by roughly the factor $\exp(-2\pi d/\lambda_p)$ from the absorption to ablation surface. (This relation is only

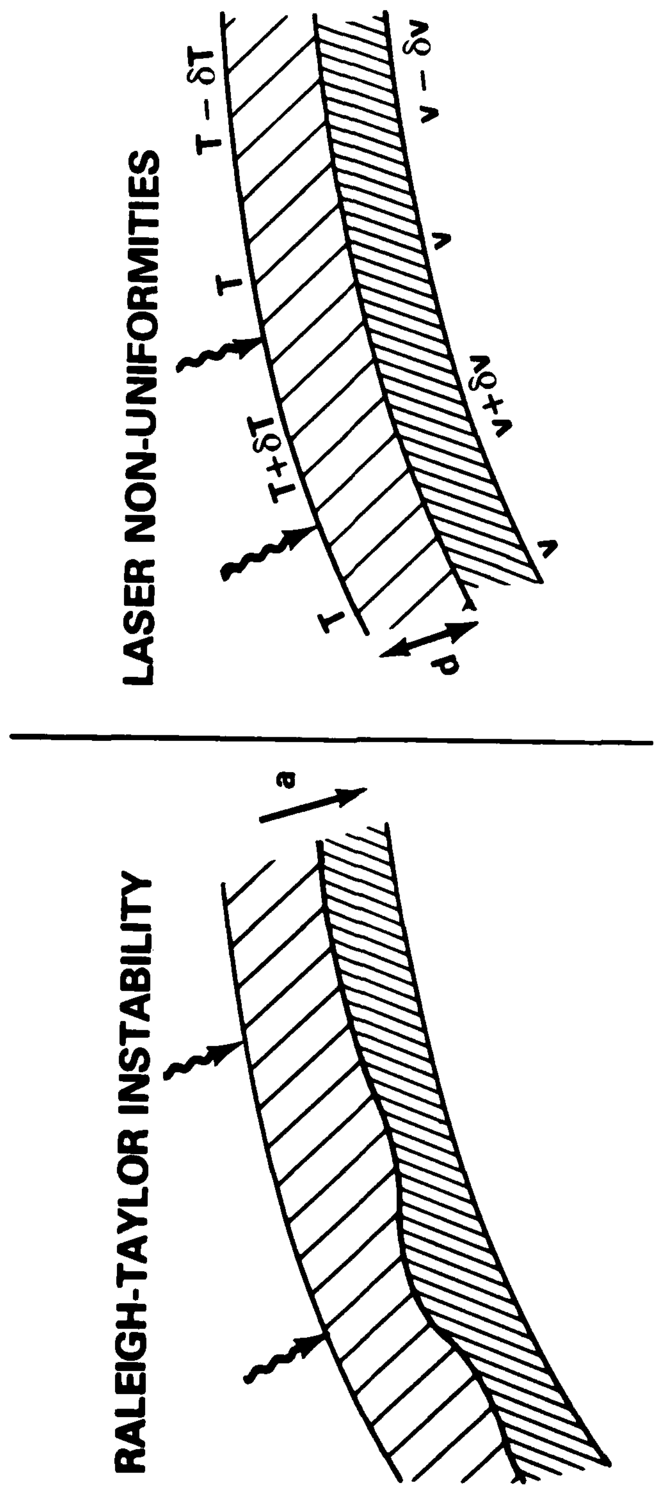

Fig. 10 — Two sources of nonuniform implosions. The lower region represents the dense imploding shell. The outer region represents the hit.

approximate.) The maximum λ_p for a 20 beam laser will be approximately equal to the laser radius R_0. Therefore the separation distance d should be at least 1/3 R_0. [exp $(-2\pi/3) = .12$.] For pellets with small R_0, d can be small. But for a reactor-sized pellet, with R_0 in the range of 3-10 mm, the separation distance d should be at least 1-3 mm.

Although the distance d is not stationary during an implosion, there is a quasi-stationary value if the laser pulse length is longer than a few nanoseconds. This quasi-stationary value is a function of the laser intensity, the laser wavelength, and the target size. Recent calculations at NRL by J. Gardner, M. Emery, and the author show that d is approximately proportional to $I_L \lambda_L^3$. For realistic intensities I_L, d is in the millimeter range only when the laser wavelength is in the infrared. Therefore this uniform-illumination laser fusion concept requires *infrared lasers.* (If the laser light is first converted to X-rays, visible-to-UV lasers can be used. This is the LLNL approach.)

In experiments at NRL, a low intensity laser beam has been used to illuminate a millimeter spot on a foil target with $\delta I_L / I_L = 40\%$. This foil has then been accelerated, on a low isentrope, with a velocity nonuniformity of only $\pm 5\%$.[18]

Rayleigh-Taylor Instability

At the ablation surface, a hot low-density plasma pushes a cold high-density shell inward. See Figs. 9 and 10. This system will have a lower energy state if the high density shell breaks through the low density plasma. This interchange is the infamous Rayleigh-Taylor instability. For a small growth of the instability, there will be an enhanced asymmetry in the implosion. For a large growth, the shell will actually break up into droplets.

In the simplest two-fluid version of this instability, with large differences in the fluid densities, the growth rate γ equals $\sqrt{kg}$, where g is the acceleration of the shell, and k is the wave number of the disturbance. With constant acceleration, the total growth of this mode is $\gamma t \cong \sqrt{kgt^2}$. If the shell is constantly accelerated for half the radius, then $gt^2 \cong R_0$. Therefore the amplitude of a disturbance is, roughly,

$$\delta A = \delta A_0 \, e^{\gamma t} \cong \delta A_0 \, e^{\sqrt{kR_0}}. \tag{25}$$

This instability will grow exponentially until its amplitude approaches the wavelength of the disturbance. Then it will grow quadratically—a much slower rate. For wavelengths less than the shell thickness ΔR, the slower quadratic growth begins before the full shell is penetrated. Therefore the most dangerous wavelength, the largest k which always grows exponentially, has $k \, \Delta R_0 \cong \pi$. For this fast-growing mode,

$$\delta A \cong \delta A_0 \, e^{\sqrt{\pi R_0 / \Delta R_0}}. \tag{26}$$

(The coefficient of π in the exponent is not too accurate.) This crude but popular derivation is shown here to illustrate the basic concept: thinner shells with higher aspect ratio may have more e-foldings of the Rayleigh-Taylor instability.[5]

Happily, this simplest version of the Rayleigh-Taylor instability is not generally valid. A number of physical mechanisms have been proposed that may reduce or perhaps even eliminate this instability.

The first mechanism is called "fire-polishing," (or thermal conduction). If part of the high density shell moves out radially, towards the higher-temperature absorption region, then that part of the shell will ablate faster and recede back to its quasi-stationary value. There is a minimum wavenumber for this effect, which is a function of the laser intensity and laser wavelength. This has not yet been thoroughly explored by calculations; in 1977 J. Boris of NRL[19] found a strong stabilization, at low laser intensities, for wavelengths up to about $50 \, \mu$m.

Second, there is the possibility of dynamic stabilization, proposed by J. Boris of NRL.[20] By oscillating the laser intensity at the right frequency, one can stabilize a band of wavenumbers. (The common analog here is the balancing of a broom upside down by moving your palm up and down periodically. The mathematical analog is the Mathieu equation.) This oscillation will drive another band of wavenumbers even more unstable, but Boris suggests that these could be stabilized by the fire-polishing effect. This dynamic stabilization mechanism has been evaluated in simple planar geometries; it has not yet been incorporated into any pellet design. Critics have suggested that the oscillating laser intensity will drive in shocks which raise the fuel isentrope, but planar calculations so far show that oscillations with a half nanosecond period do not produce strong shocks.

Finally, imploding shells fundamentally differ from the simple heavy-fluid-on-light-fluid analogy because the ablative-convective process produces subtle changes in the pressure profile and very steep gradients in the density. Fine-grid one-dimensional computer codes with piggy-back instability models predict less Rayleigh-Taylor growth than coarse-grid two-dimensional codes.[21] But most Rayleigh-Taylor calculations have been performed with the two-dimensional computer codes.

Experimental studies of the Rayleigh-Taylor instability are just beginning, with some claimed experimental evidence actually dominated by laser asymmetries, not instabilities. Experiments at NRL[18] with 4 nsec pulses have so far shown strong evidence of stabilization for perturbations less than or of order 50 μm.

Ablation Pressure

Lower laser intensities tend to have a better coupling efficiency and drive the fuel with a lower isentrope. Lower laser intensities also produce a lower ablation pressure, and Eq. (21) shows that this implies thinner pellet shells. But thinner pellet shells may produce more growth of the Rayleigh-Taylor instability, as seen in Eq. (26). Thus there are vaguely defined upper and lower bounds on the ablation pressure, and therefore also the laser intensity.

At lower laser intensities ($I \lesssim 10^{14}$ W/cm^2), there is good agreement between the experimentally measured $P_a(I)$, analytic theory, and hydrodynamic codes.[22] (Experiments at NRL find pressures of 5-10 Mbar at 5×10^{13} W/cm^2 with a 1 μm laser.)[23] But at higher intensities the absorbed energy can flow into non-useful forms, via fast electrons, fast ions, and inhibited heat flow. There is not yet a currently satisfactory theory or data for $P_a(I)$ at the higher intensities.

Intensity — Wavelength Window

From 1972 to 1977 the NRL laser fusion group, along with many other labs, used high laser intensities and short sub-nanosecond pulses to investigate the coupling physics associated with the "shaped pulse" pellet concept. Since 1977, NRL has been using multi-nanosecond laser pulses ($\tau_L \cong 3.5$nsec, $\lambda_L = 1\,\mu$m) at low intensities ($I_L \sim 5 \times 10^{12}$ w/cm^2 to $I_L \sim 5 \times 10^{13}$ w/cm^2) to study the coupling and the ablation physics associated with relatively unshaped pellet concepts, such as the "double-shell" design.

More recently, we have compared some of our accumulated experimental data with our 1-D and 2-D hydrodynamic computer programs. The surprisingly good agreement between experiment and calculation has made us venturesome enough to extrapolate the calculations to somewhat higher laser intensities and to other laser wavelengths. Figure 11 summarizes some of the results of this study, appropriate to a reactor-sized pellet, $R_0 = 0.5$ cm.[24]

There is a barrier at low intensities associated with the requirement that the ablation pressure exceed 5 Mbar. The diffuseness of the barrier is intended as an indication of the inherent limitations of any hydrodynamic calculations.

There is also a barrier at short laser wavelengths, associated with the requirement that the ablation-to-absorption distance be greater than a millimeter. This should smooth the inherent laser nonuniformities. Again, the diffuse nature of the boundary is in indication of the inherent limitations of a hydrodynamic code.

These two barriers (due to the pressure and symmetry critical elements) limit the opening in the intensity-wavelength window to *infrared* lasers of at least moderate intensity. But two of the other critical elements (coupling efficiency and isentrope) are sensitive to the plasma instabilities. These plasma effects place another barrier against the use of high intensities and long wavelengths. As indicated earlier, this plasma instability barrier has not yet been studied experimentally with multi-nanosecond pulses, and therefore its location as more speculative. A barrier with $I_l \sim \lambda_l^{-2}$ is shown in Figure 12.

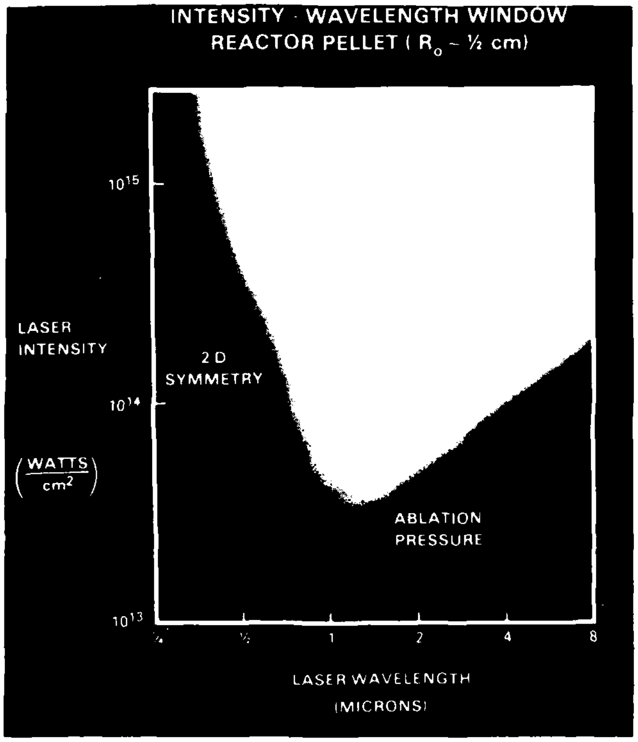

Fig. 11 — Symmetrization requirements place an effective barrier against the use of short laser wavelengths. Pressure requirements place a lower bound on the laser intensity.

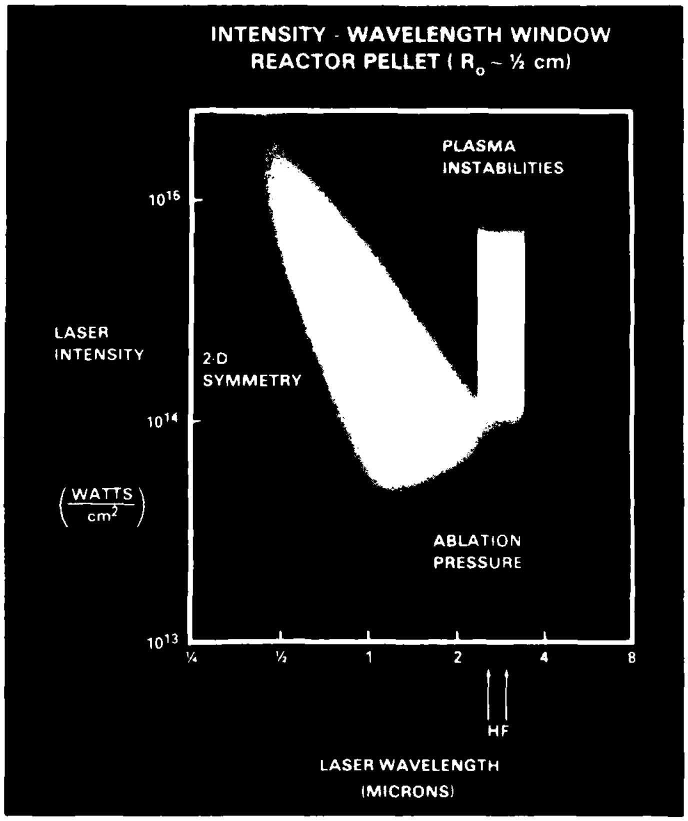

Fig. 12 — The coupling and isentrope critical elements place another barrier against the usage of high laser intensities and long laser wavelengths. The broad bandwidth of the HF laser may raise this barrier.

This figure also shows an alternate plasma instability barrier for a very broadband laser. In practice, there is only one high-efficiency near-infrared laser: HF. It laser on about 20 strong lines between about 2.6 μm and 3.1 μm, plus a large number of weaker lines. Based on current theory and microwave experiments, a factor of ten increase in the plasma instability threshold is not unreasonable.

There is another way to open up the intensity-wavelength window: one can first convert the laser energy to X-rays, and then use these X-rays to implode the pellet. This eliminates the symmetrization barrier; short wavelength lasers are then clearly superior. This is the LLNL approach.

There are thus two different laser fusion concepts. The direct illumination approach uses infrared lasers. The X-ray coupling approach uses visible to ultraviolet lasers. In the opinion of this author, the direct illumination approach is as viable as the X-ray coupling approach. In the next few years we should be able to judge both of these approaches.

SUMMARY

There is a set of parameters that determines the maximum possible gain of a pellet. Some of these parameters, called the critical elements, can form a basis for evaluating laser fusion concepts. By analytically varying four of these critical elements, one can obtain a set of criteria for a high pellet gain. Other milestones have been suggested before, such as scientific breakeven, ignition, and compression. Although these latter are necessary for high gain, they are not sufficient. Critical elements form a superior basis for evaluating laser fusion concepts. The five critical elements are:

(1) laser-to-fuel coupling efficiency

(2) cold-fuel isentrope

(3) implosion symmetry

(4) ablation pressure

(5) high-gain ignition concept

The first four of these depend upon uncertain laser-target coupling physics, which in turn depends upon laser parameters (such as intensity, wavelength, pulselength, and bandwidth), and upon target parameters (such as scale size and material). To simultaneously reach the maximum intensity, pulse-length, and scale size of interest implies rather large and costly laser facilities. How much can we reduce the laser size, and still obtain scalable data that allows us to realistically evaluate the critical elements for a high gain system? This question is a proper subject for discussion by the scientists in the program.

Ion beam drivers have the potential of much higher driver efficiency, and they therefore can be used with simpler lower-gain pellets, with relaxed criteria on the critical elements. But these ion drivers must still satisfy the ablation pressure requirement ($\sim 10^{14}$ W/cm^2) at the high driver efficiency. These simultaneous goals are under development, but have not yet been achieved.

Interestingly, there are existing lasers which may be scalable to the reactor size and at the same time satisfy all of the pellet physics requirements. For the X-ray coupling approach, the laser is KrF, at 0.25 μm. The short wavelength may inhibit most, or perhaps all, of the deleterious plasma effects. For the direct illumination aproach, the laser is HF, at 2.6-3.1 μm. Since it is in the infrared, it can provide the necessary symmetrization around a reactor-sized pellet. Since it lases on a large number of lines,[25] it may be possible to use a high enough laser intensity to provide the necessary ablation pressure, and still avoid excessive preheat and backscatter.

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