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LA-5789-MS  
Informal Report

UC-20  
Reporting Date: October 1974  
Issued: November 1974

DT-1124

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UNITED STATES  
ATOMIC ENERGY COMMISSION  
CONTRACT W-7408-ENG. 36

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## TAMPED THERMONUCLEAR BURN OF DT MICROSPHERES

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TAM-100

### ABSTRACT

The thermonuclear yields and gains from highly compressed DT spheres tamped by high-Z shells are calculated for temperatures near and above ignition and for tampers up to 100 times more massive than the DT. It is shown that the dynamic and structural advantages of including pusher-tamper shells need not be significantly diminished by the reduction of total fuel mass in the target.

Much discussion has been given to the laser-driven compression of homogeneous DT pellets.<sup>1-6</sup> Structured laser<sup>6</sup> and e-beam<sup>7</sup> fusion targets are also under consideration in which the DT "fuel" is stored as a gas inside a thin tamper layer of metal or glass, or a shell of DT is frozen onto the inner surface of the tamper. The tamper can provide structural support--eliminating cryogenic concerns, it can ease the laser pulse shaping requirements,<sup>8</sup> and it may serve to shield the DT from superthermal electron preheat.<sup>9</sup> The use of a number of contiguous shells of various low- and high-Z materials in laser and e-beam initiated fusion targets has been under study at the Los Alamos and Livermore Laboratories for many years. The aim of the present work is to examine the effects of tamping on the efficiency of thermonuclear burn.

We assume that a laser or e-beam can be used to bring a tamped pellet core to high compressions and ignition conditions.<sup>10</sup> The DT will generally be hotter than the tamper, since it is compressed from a lower initial density, and since it is heated by a final strong shock,<sup>2,6</sup> or possibly multiple shocks<sup>11</sup> as the tamper inner radius closes to a minimum, while the pulse form

is adjusted to minimize shock heating of the tamping material during implosion. With the increased DT opacity at high density, 3 keV is near the minimum temperature at which ignition and efficient yield production are possible in bare DT microspheres. At 10-keV, burn performance in untamped pellet cores is nearly optimal. These results were spelled out in Ref. 10. We explore this now familiar phenomenology with the addition of tamping.

### Numerical Studies and Results

By computer simulation we have traced the evolution of tamped fuel configurations, such as that shown in Fig. 1. Numerous cases have been calculated with our "3T" hydro-burn code of Ref. 10. Most of the runs were for 10  $\mu$ g of DT fuel  $m_f$  surrounded by from 10  $\mu$ g to 1 mg of tamper material  $m_t$ : thus, the mass ratio  $R_m = m_t/m_f = 1$  to 100, suitable parameters for a 10-J laser. The initial fuel density ranged from  $\rho_f = 1.6$  to 2100 g/cm<sup>3</sup>. Its electron and ion temperatures were taken as initially equal, and either at 3 or 10 keV; the radiation temperature in the DT was started at 1 keV. The tamper density was varied from 4 times the fuel density to the maximum allowed by

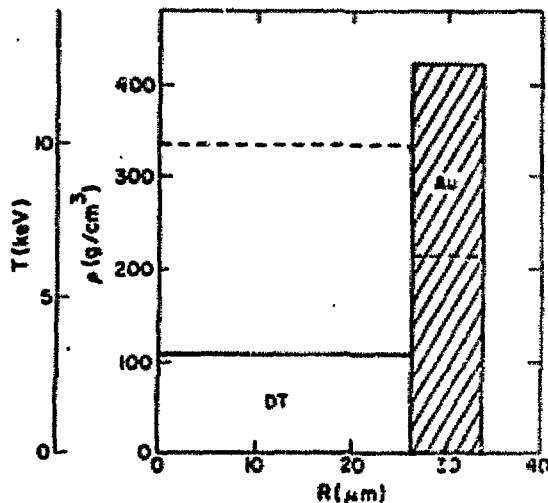


Fig. 1. Sample initial burn configuration. Fuel density  $\rho_f = 105 \text{ g/cm}^3$ , tamper density  $\rho_t = 420 \text{ g/cm}^3$ . Fuel temperature ( $T_f, T_t$ ) 10 keV, gold temperature 6.6 keV.  $n_t/m_t = 10$ .

degeneracy. The electron, ion, and radiation temperatures in the tamper were equal and chosen to establish initial pressure equilibrium between the tamper and the fuel. This was accomplished graphically with the aid of detailed pressure plots of the Fermi-Thomas-Dirac equations of state for the DT, and for the various tamper materials. Calculations were done for tampers of gold ( $Z = 79$ ,  $A = 179$ , normal density  $19.3 \text{ g/cm}^3$ ), nickel ( $28$ ,  $58.7$ ,  $8.68 \text{ g/cm}^3$ ), and glass ( $10$ ,  $20$ ,  $2.2 \text{ g/cm}^3$ ).

Figure 2(a) shows the 3-keV yields  $Y_0$  obtained from 10  $\mu\text{g}$  of DT for various  $\rho_f$  and  $R_m$  values and at  $\rho_t/\rho_f = 4$  for the solid curves. The  $\rho R$  product for the fuel  $\rho R_f$  ( $\int \rho R_f$ ) is also given as a scale. The tamper is of gold. The long dashed,  $R_m = 0$ , untamped yield curve is from Ref. 10, Fig. 7(a). Along it, below  $\rho R_f = 0.3 \text{ g/cm}^2$  we get simple  $Y_0 \sim \rho_f^{2/3} \sim \rho R_f$  yield scaling. Above 0.3 we observe bootstrap heating of the fuel from  $\alpha$ -particle redeposition. (The

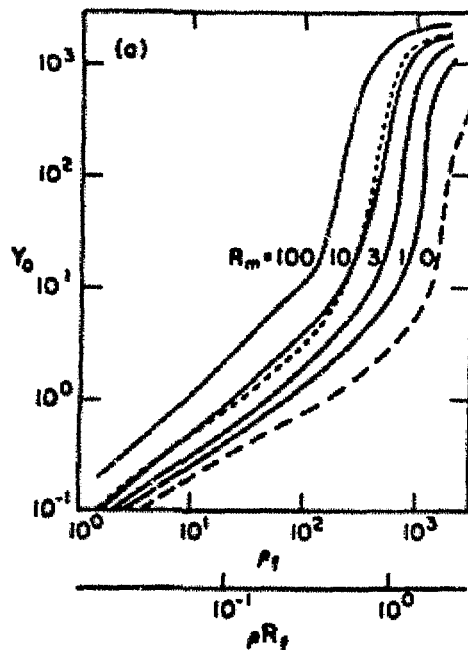


Fig. 2(a). 10  $\mu\text{g}$  of DT at 3 keV, tamped with gold. The gold/DT density ratio generally 4/1; yield in kilojoules vs  $\rho_f$  (or  $\rho R_f$ ) for various tamper/fuel mass ratios.  $R_m = 0$  is  $\rho_t = \rho_f$ .  $\rho_t = \rho_f |_{\text{max}}$  is  $\rho_t = \rho_f |_{\text{max}}$ .

ratio of  $\alpha$ -particle range to the fuel radius is  $0.06/\rho R_f$  at 3 keV.) Reference 10 defined the burn-up fraction to be  $f_{70} = Y_0/(326 \cdot m_f)$  where  $Y_0$  is in kJ and  $m_f$  is in  $\mu\text{g}$ . Beyond  $\rho R_f = 2.0$  there is sufficient confinement time when  $R_m = 0$  to raise the fuel temperature into the 20- to 70-keV range, where  $Y_0 \approx 326 \cdot m_f \cdot \rho R_f / (6.1 + \rho R_f)$ . Going to  $R_m = 1$ , and higher, we observe substantial increases in the yields, especially in the  $\rho R_f > 1.0$  ignition region. Perhaps, more important, as we go from  $R_m = 0$  to 100, the ignition value of  $\rho R_f$  decreases from about  $1.5 \text{ g/cm}^2$  to  $0.3 \text{ g/cm}^2$ . Addressing the tamper density dependence, we point out that the maximum tamper density is limited by degeneracy -- given the constraint of initial pressure equilibrium. At  $\rho_f = 2100 \text{ g/cm}^3$  this limit is  $\rho_t/\rho_f |_{\text{max}} = 4.9$  with gold. At  $\rho_f = 1.6 \text{ g/cm}^3$  we are permitted many more multiples

of the fuel density before the gold becomes degenerate at temperatures well below the fuel value, so  $\rho_t/\rho_f|_{\max} = 217$ . The short dashed,  $R_m = 10$  curve shows the yield obtained at the maximum permissible gold densities. Clearly, at 3 keV the sensitivity to  $\rho_t$  is slight.

Overall burn performance is measured by the gain  $G_0 = Y_0/(mI)$ , in which  $mI$  ( $m_f I_f + k_t I_t$ ) is the total energy invested in the fuel and tamper prior to burn. Figure 2(b) was constructed by dividing the 2(a) yields by internal energies extracted from our equation-of-state tables. The  $R_m = 0$  curve goes through unity at  $\rho R_f = 1.00$  and predicts a 350-fold gain at  $\rho R_f = 4.4$ . With tamping at low  $\rho R_f$  the extra input energy demands outweigh the augmented yield from the extended confinement time. Above  $\rho R_f = 0.1$ , however, bootstrap heating raises the

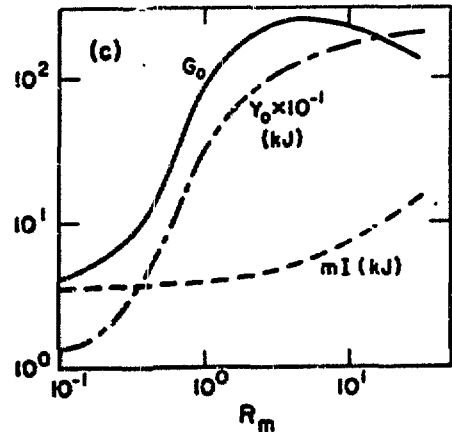


Fig. 2(c).  $Y_0$ ,  $mI$ , and  $G_0$  variations with  $R_m$  for  $\rho_f = 1260 \text{ g/cm}^3$ ,  $T_f = 3 \text{ keV}$ , and  $\rho_t = 7527 \text{ g/cm}^3 = \rho_t|_{\max}$ ,  $T_t = 250 \text{ eV}$ .

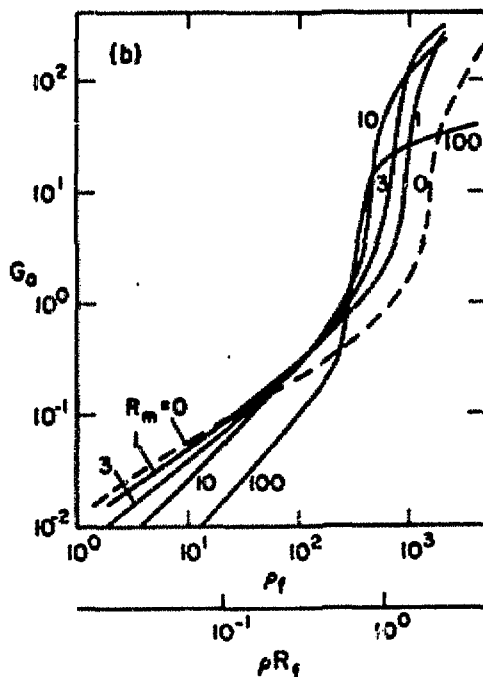


Fig. 2(b). Gain ( $\equiv G_0/mI$ ) vs  $\rho_f$  (and  $\rho R_f$ ) and  $R_m$ .

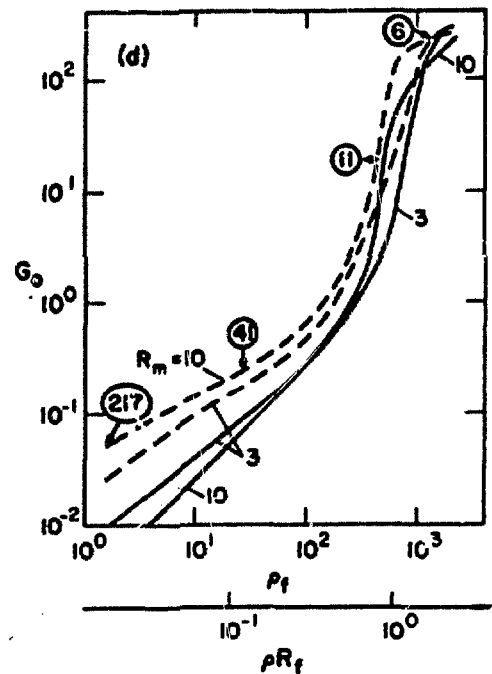


Fig. 2(d).  $R_m = 3$  and 10 gains for  $\rho_t/\rho_f = 4$  — and  $\rho_t/\rho_f|_{\max}$  ---- (maximum density ratio values circled).

DT reaction rate sufficiently so that the extra time can markedly raise the gain. At  $\rho R_f = 1.4$ , for example, both the  $R_m = 3$  and the  $R_m = 10$  tamper give a 50-fold increase in  $G_0$ . With excessive tamping, the added energy requirements again destroy  $G_0$ , as indicated by the  $R_m = 100$  results. Figure 2(c) shows how, typical of the  $\rho R_f > 1$  regime, the ml requirements, and yield saturation from fuel depletion<sup>10</sup> lead at  $\rho R_f = 1.56$  ( $\rho_f = 1260 \text{ g/cm}^3$ ) to a best  $G_0$  ( $\approx 250$ ) and an optimal  $R_m$  ( $\approx 4.5$ ). Figure 2(d) shows that the gain can improve significantly with  $\rho_t \rightarrow \rho_t|_{\text{max}}$ , even though the yield may remain relatively constant. This is a consequence of the tamper fuel pressure equilibrium. The pressure measures energy/volume, so a denser tamper represents less deposited energy -- giving a higher  $G_0$ .

When the 3-keV yield and gain curves are plotted vs the overall confinement parameter  $\rho R_{\text{tot}}$  ( $\equiv \int \rho dr_f + \int \rho dr_t$ ),

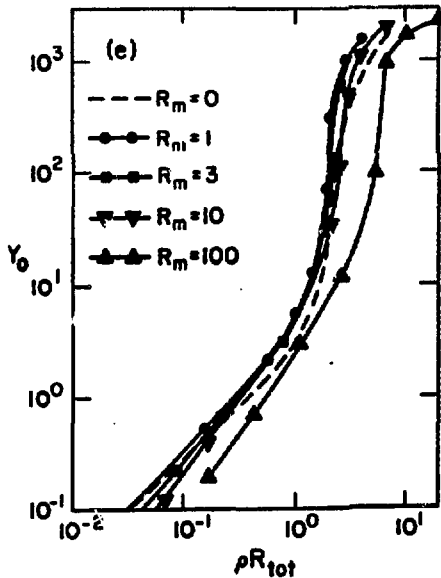


Fig. 2(e). Yield vs  $\rho R_{\text{tot}}$ .

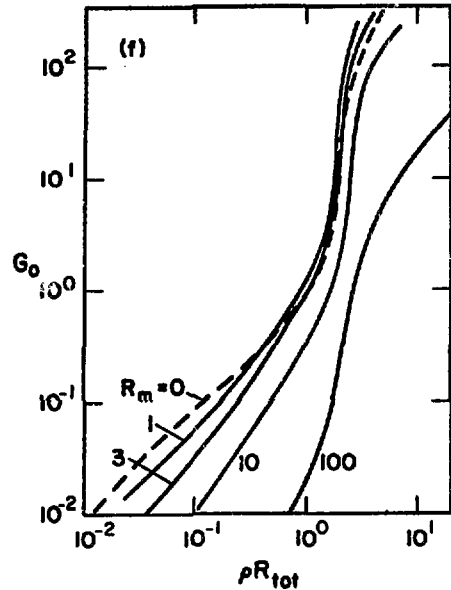


Fig. 2(f). Gain vs  $\rho R_{\text{tot}}$ .

Figures 2(e) and (f), the yield curves are in close coincidence for  $R_m < 10$ , and even the gain curves are nearly coincident for  $R_m < 3, \rho R_{\text{tot}} > 0.5$ . Note that the  $R_m = 1$  to 10 yields slightly exceed the untamped performance in the  $0.3 < \rho R_{\text{tot}} < 2.0$  regime, since the greater tamper opacity aids the burn and ignition.

Figure 3(a) shows that our results readily scale to smaller systems when expressed in terms of burn-up fractions and  $\rho R_{\text{tot}}$ . It shows good agreement as we go from 10  $\mu\text{g}$  to 0.1  $\mu\text{g}$  of DT at 3 keV, keeping  $\rho_t/\rho_f = 4$ , with a gold tamper, and  $R_m = 3$ . Under these conditions at  $\rho R_{\text{tot}} = 1.37$ , for example, there is 3.5 kJ of internal energy in the 10  $\mu\text{g}$  of DT, and 2.7 kJ in the gold. Taking the efficiency of the energy transfer from the laser to the tamper-DT pellet to be 10%, this implies that 62 kJ of laser energy is deposited. Alternatively, the 0.1  $\mu\text{g}$  fuelled core should require only 620 J of laser input energy.

Results for the 10-keV DT are collected in Figs. 3(b) - (d). All of the yields are,

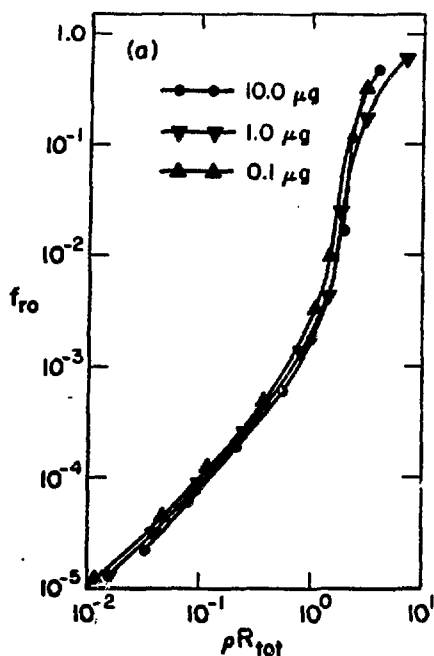


Fig. 3(a). Burn fraction  $f_{ro}$  vs  $\rho R_{tot}$  from 10, 1 and 0.1  $\mu$ g of DT, tamped by gold at  $R_m = 3$  and  $\rho_t/\rho_f = 4.0$ .

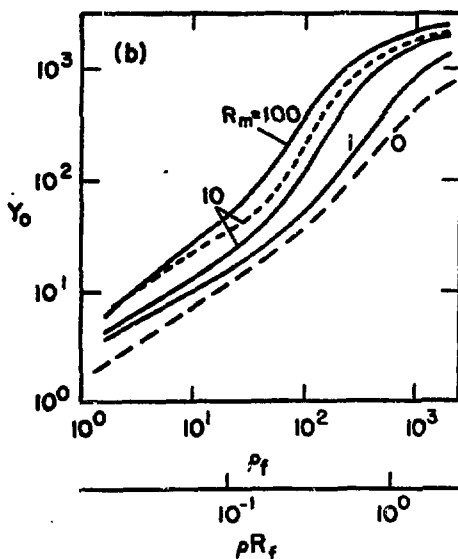


Fig. 3(b) 10  $\mu$ g of DT at 10 keV and gold tampers: yield vs fuel density and  $R_m$ .

of course, higher than at 3 keV because of the  $\langle \sigma v \rangle \sim T^{3.5}$  dependence of the burn rate. Here, when  $\rho_t$  goes from  $4\rho_f$  to  $\rho_t|_{\max}$ , the  $Y_0$  increase is considerable (e.g., 1.6-fold at  $\rho_t = 50 \text{ g/cm}^3$ ). This is because the early heat flow from the 10 keV DT to the much cooler, dense tamper (typically at only 250 eV for its pressure equilibrium in degeneracy) causes the inner surface of the tamper to explode (or, equivalently, ablate) which results in a temporary reduction of the fuel outer radius, increased confinement, and the extra yield. This explosion is too weak to be of consequence when  $\rho_t/\rho_f \sim 4$ , or, in general, at 3 keV. Both the 10-keV yields and gains are down for  $R_m > 1$  when plotted vs  $\rho R_{tot}$ , Figs. 3(c) and (d). This loss of performance does not occur at 3 keV because of the relative increase of yield from ignition is greater than at 10 keV, and tamping aids ignition. Only at  $\rho_t|_{\max}$  do the  $R_m = 10$  gains approach their untamped values.

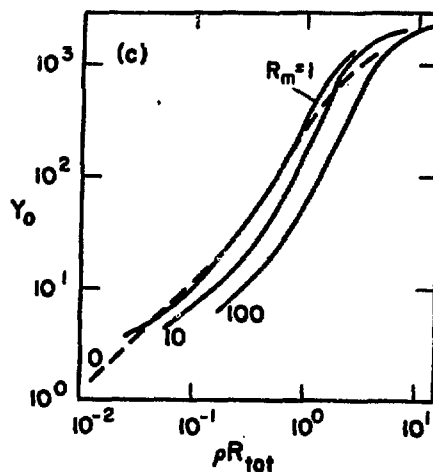


Fig. 3(c). 10  $\mu$ g of DT at 10 keV and gold tampers: yield vs  $\rho R_{tot}$ .

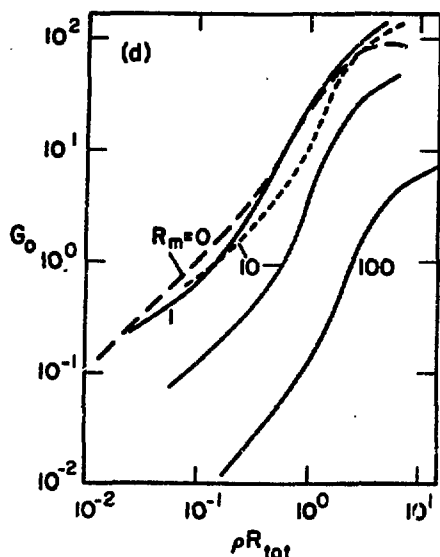


Fig. 3(d). 10  $\mu\text{m}$  of DT at 10 keV and gold tamper; gain vs  $\rho R_{\text{tot}}$ , showing improvements for  $\rho_t \rightarrow \rho_c |_{\text{max}}$  -----.

The relative insensitivity of gain to the choice of tamper materials is demonstrated by 3(e). At low  $\rho R_{\text{tot}}$  the glass is

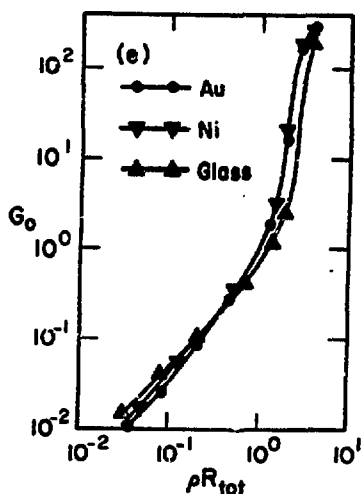


Fig. 3(e). Materials dependence:  $G_0$  vs  $\rho R_{\text{tot}}$  for gold, nickel, and glass.

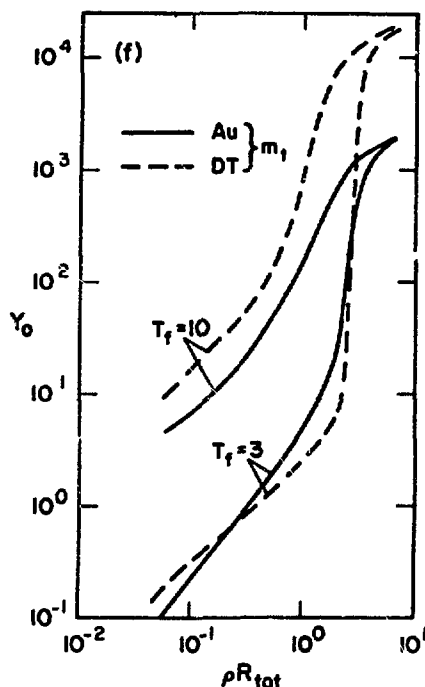


Fig. 3(f). The yield vs  $\rho R_{\text{tot}}$  with first gold, then a "DT tamper" ----- at  $R_m = 10$ ,  $\rho_c/\rho_f = 4$ , and  $T_f = 3$  and "10 keV".

marginally best by requiring less internal energy to establish the pressure equilibrium. For  $\rho R_{\text{tot}} > 1.0$  the situation is reversed, since the glass manifests degeneracy energy needs first.

Of course, if it were possible to replace the cold, inert tamping material with DT at the same temperature and density the results would be better in almost all cases since then the tamper itself could be ignited by propagating burn.<sup>10</sup> Figure 3(f) shows how the use of a "DT tamper" at  $R_m = 10$  leads to up to 10 times the yield production obtainable with the corresponding gold tamper. An exception to this occurs at 3 keV near  $\rho R_{\text{tot}} = 1.5$ , where the  $\rho R_{\text{tot}}$  is too low ( $< 2$ )<sup>10</sup> to encourage good propagation, and the greater gold capacity encourages faster bootstrap heating.



## Conclusions

A fixed amount of fuel gives an increased yield for a given  $\rho R_f$  and ignites at a lower  $\rho R_f$ , if tamping is added. What is more important, however, is that up to some tamper-to-fuel mass ratio (for 10  $\mu\text{g}$  of DT,  $R_m \approx 3$  for 10 keV or  $\approx 10$  for 3 keV), the energy gain and fractional burn-up of a given amount of tamped fuel is very nearly a function of the total  $\rho R$  of fuel and tamper, independent of  $R_m$ , provided that  $\rho R_{\text{tot}} \gtrsim 1$  and  $\rho R_f \gtrsim 0.3$ . Since, in practice, it should be easier to obtain a given  $\rho R_{\text{tot}}$  in a pellet in which the fuel is initially surrounded by a higher Z shell, we conclude that this advantage need not be diminished by reduced thermonuclear burn performance. A guideline for maximizing the gain is therefore:

1. Choose parameters which set the compressed fuel temperature at the minimum value at which ignition occurs, and, if possible, bring just the central fuel region out to  $\rho R_f = 0.3$  to this temperature, with the remainder cooler to encourage propagating burn.

2. Increase the fraction of fuel mass  $f_f = m_f / (m_f + m_t) = 1 / (1 + R_m)$  within other constraints, until just before  $\rho R_{\text{tot}}$  falls just below the ignition value, reflected in  $f_{\text{ro}}$  vs  $\rho R_{\text{tot}}$ , or until 1. is violated. In addition to providing considerable fabrication convenience, the contribution of the shell can be, then, a means for manipulation of the implosion dynamics to bring  $\rho R_{\text{tot}}$  to ignition values which might otherwise be inaccessible, without significantly reducing the amount of fuel that can be raised to optimized thermonuclear burn conditions.

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