Relative energy yield of laser targets with deuterium as fuel

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The results of a numerical and analytic study of the compression and burn of deuterium targets are summarized. The conditions required for an intense burn of deuterium in inertial-confinement-fusion targets are discussed [see Fig. 2 in a previous paper: G. H. Miley, Atomkernenergie **32**, No. 1, 12 (1978)].

1. The advantages of controlled thermonuclear fusion over nuclear (fission) power would be realized fully if it were possible to avoid the use of radioactive materials (tritium) in the fuel of fusion reactors.

Research on the burning of deuterium targets is also of interest from a purely physical standpoint. During the burn of a DT mixture (at the typical temperatures), the energy yield from a single deuteron (or from a single triton) of a $D_{0.5}T_{0.5}$ mixture is essentially the same as the yield in the reaction $^3H(d, n)^4He$, which is 17.6 MeV, since other fusion reactions play only a minor role.[1,2] In the case of pure deuterium as fuel, the relative frequencies of the primary and secondary reactions, the thermonuclear yield which they determine, and also the energy which the fast thermonuclear particles contribute to the plasma depend strongly on the temperature and compression conditions. Calculations for several laser targets with deuterium as fuel have generated curves of $\epsilon_y(T)$ and $\epsilon_a(T)$, i.e., curves of the yield and the contribution to the plasma, per deuteron, versus the temperature reached in the course of the burn (Fig. 1). The ratios of the numbers of primary reactions (n and p) and of secondary reactions (t and g) also depend on the temperature. For example, if a temperature of 140 keV is reached, we would have $n{:}p{:}t{:}g = 0.32{:}0.32{:}0.28{:}0.08$. If a temperature of 280 keV is reached, we would have 0.31:0.31:0.25:0.13. It can be seen that it would be effective to enrich the deuterium with an admixture of helium-3. The reaction $^3He(d, p)^4He$ has the highest yield (18.3 MeV), but its role is always smaller than those of the other reactions, as we see. Furthermore, it would be difficult to expect a greater than 50% contribution of the energy of the fast proton of this reaction at reasonable values of ρR. The replacement of deuterium by the mixture $D_{0.5}{}^3He_{0.5}$ in the calculations increased the burnup by a factor ~ 1.5, while the maximum temperature reached in the course of the burn nearly tripled.

2. The results reported here were calculated by the Diana program.[1] The calculations were carried for a target of the same type as in Ref. 1, but with various values of the ablator aspect ratio A. The use of a shaped laser pulse ($\sim 50\%$ of the energy was in the last 10–20% of the pulse length) in the numerical simulations resulted in an energy deposition ~ 0.7–1.4 MJ/mg in the fuel before the beginning of the burn; the shell moved at a velocity $v \sim 800$–1000 km/s; and the value of the parameter ρR in the fuel was ~ 2-10 g/cm^2. The values of the hydrodynamic efficiency η (the ratio of the

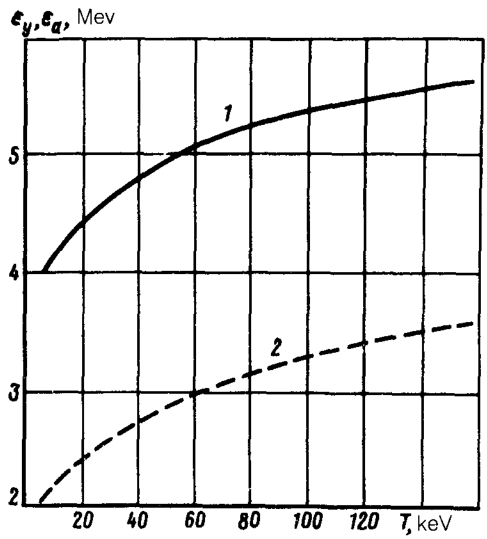

FIG. 1. 1—Yield from a single deuteron, ϵ_y; 2—contribution of the reactions products to the plasma, ϵ_a, versus the maximum temperature reached in the course of the burn.

kinetic energy of the layers accelerated toward the center to the energy absorbed in the target) are described well by the formula $\eta \approx 0.052A^{0.3}$.

3. An analytic study of a model of a uniform burn of the deuterium (the temperature and density of the fuel are independent of the spatial coordinates; see also Refs. 3 and 4) led to an approximate relation between the burnup $\phi = 1 - f_D$ (f_D is the fraction of deuterium nuclei in the target at the end of the burn) to the parameter $\rho \widetilde{R} = \rho R \sqrt{1+\mu_*}$ before the burn, where μ_* is the ratio of the unevaporated mass of

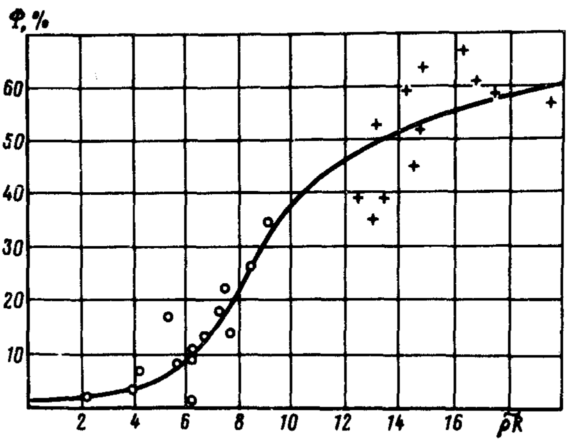

FIG. 2. Solid line—theoretical burnup ϕ (%) versus the parameter $\rho \widetilde{R}$ (g/cm^2) ($T_0 = 15$ keV); o, + — results of numerical calculations.

the ablator to the mass of the fuel (Fig. 2):

$$\phi \approx \begin{cases} K_m^{-1}\, \xi^{-3/2}\,[\,2\exp(\,\xi-1)-(\,\xi+1\,)], & \xi < 5,25, \\ 1-1,07\,[\,\xi - \ln(\,\frac{K_m}{6}\,\xi\,)\,]^{-1/2}, & \xi \geqslant 5,25. \end{cases}$$

Here $\beta = \dot{\rho}\widetilde{R}(\phi^{-1}-1)$; and the deuterium is assumed to be an ideal gas (with a ratio of specific heats $\gamma = 5/3$ in this formula).

One way to check for a nonuniformity of the fuel is to compare the parameter $\beta = \dot{\rho}\widetilde{R}(\phi^{-1}-1)$ found from the calculations with the theoretical value for a uniform model, $\beta_0(T) = s_d^{-1}(T)\sqrt{3km_DT}$, where m_D is the mass of the deuteron, $s_d = s_n + s_p$ is the sum of the rates of the $^2H(d,n)^3He$ and $^2H(d,p)^3H$ reactions, and T is the maximum burn temperature. If $\beta < \beta_0$, we are observing a definitely nonuniform burn. In most of the calculations we found $\beta/\beta_0 \approx 0.95$–$1.10$. The better calculations (in terms of yields) had $\beta/\beta_0 \approx 0.6$.

The calculations show that the condition for a target burn can be evaluated from the simple relation $t_q < t_g$, where $t_q = c_v\rho T_0 G^{-1}(T_0)[q(T_0) - \exp(-\tilde{v}_0/T_0)]^{-1}$, $t_g = R_0\sqrt{(1+\mu_*)/2c_vT_0}$, ρ and T_0 are the density and temperature in the deuterium before the burn, G is the specific power of the volume loss, $\tilde{v}_0$ is the effective screening frequency, and q is the ratio of the thermonuclear energy source to the volume loss ($q \approx 0.33 s_d\epsilon_a/\sqrt{T_0}$, where s_d is expressed in units of 10^{-18} cm^3/s, ϵ_a in MeV, and T_0 in keV). This relation can be rewritten as $5.65\,(\rho R/T_0)[q - \exp(-\tilde{v}_0/T_0)] > 1$, where $\rho\widetilde{R}$ is expressed in units of g/cm^2.

4. The physical-mathematical models used here incorporate several comparatively optimistic assumptions, and this is not an unnatural approach for an exploratory study: to determine whether a DD burn is possible in principle. Analysis of the results of the calculations shows that questions concerning the incorporation of radiation in the plasma energy balance must be examined more thoroughly and more accurately. However, this analysis does not rule out the possibility of an intense burn of deuterium, which is observed in the numerical simulations which have been carried out. For several targets, for example, the ratio of the energy released to the laser energy absorbed was found to have values $K_y = E_{TN}/E_a \approx 18$–$20$. If the greatest possible effect of radiation on the fuel energy balance is incorporated in the model, the values of K_y for these targets decrease to ≈ 9–10.

We note in conclusion that the enrichment of deuterium with an admixture of helium-3 was also considered in Refs. 5–7.

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