Section 1
PROGRESS IN LASER FUSION

1.A ρR Measurements Using Secondary Reactions

A successful high-compression laser-fusion experiment is usually described in terms of achieving a satisfactory value of the density radius product ρR. Over the last several years, a number of techniques have been proposed to determine this product. Most of these techniques use the nuclear reaction products of the DT or DD reactions. One of the earliest proposals[1] to measure ρR noted that in DD reactions, one of the branches gives a triton at 1.06 MeV, which will have a finite probability of interacting with the deuterium fuel [^{3}H(D,n)^{4}He], giving rise to a high-energy neutron. The probability of this reaction occurring is proportional to the number of deuterons interacting with the triton in traversing the compressed fuel. It can be shown that this secondary reaction probability is proportional to the areal density ρR of the fuel. Blue[2] pointed out that the other branch of the DD reaction, which gives rise to a ^{3}He nucleus, would also undergo a secondary reaction ^{3}He(D,p)^{4}He, which gives a high-energy proton that can also escape from a highly compressed core. Since both the triton and the alpha particle are charged, they lose energy, in passing through the hot plasma. As the reaction products lose energy, the probability of a secondary reaction changes, since the interaction cross sections are strong functions of energy. The rate of energy loss is a function of the electron temperature of the plasma, which adds uncertainty to the interpretation of the measurements. Azechi *et al.*[3] pointed out that a simultaneous measurement of the fast-neutron and fast-proton production rates could give a measurement of both the effective electron temperature and the ρR of the compressed core.

Unfortunately, this answer is unique only if there is no mixing of the pusher with the fuel.

If mixing occurs before the time of neutron emission, the mass contributed by the pusher contributes to the slowing down of the reaction products but, naturally, cannot contribute directly to the production of secondary reactions. Thus, in the presence of mixing we have three unknowns: ρR, electron temperature, and mixing ratio. If simultaneous measurements can be made of the fast-neutron and fast-proton ratios with respect to the DD neutron production, and make an independent determination of the electron temperature, it is possible to determine the three unknowns.

For the purposes of this discussion, we will define the mixing ratio to be the fraction of the electrons in the compressed-fuel mixture that are contributed by the pusher material. If the pusher material has a Z/A equal to 1/2, then this definition gives the same value as what would be obtained by just using the mass ratio itself.

It is a straightforward procedure to calculate the expected ratio of the DT neutrons to the DD neutrons, and the ratio of the ^3He proton to the DD neutrons, for particular experimental conditions. A postprocessor has been added to the *LILAC* and *ORCHID* codes to make these predictions for specific simulations. An alternative approach is to assume a hot-spot emission model in which the DD reactions are produced in a very small region in the center of the fuel and the products proceed out radially through the rest of the fuel. The probability of producing the secondary reactions can be calculated as a function of the electron density, the electron temperature, the deuteron density, and the radius of the compressed core. In the situation of constant Z/A for all materials in the core, the product of electron density and core radius is linearly proportional to the total ρR of the fuel mixture. To calculate the energy loss in the plasma, we have used the expression given by Longmire[4]:

$$\frac{dE}{dX} = - \frac{N_e \, 4\sqrt{\pi} \, z_1^2 z_2^2 e^4 \ln\Lambda \; m_1/m_2 \left[\int_0^{\alpha} e^{-y^2} dy - \left(1 + \frac{m_2}{m_1} \right) \alpha e^{-\alpha^2} \right]}{E} , \quad (1)$$

where m_1 is mass of the fast particle; m_2 is mass of the electron; z_1 is charge of the fast particle; z_2 is charge of the electron;

$$\ln \Lambda = 24 - \ln \, (n_e^{0.5}/T_e)$$

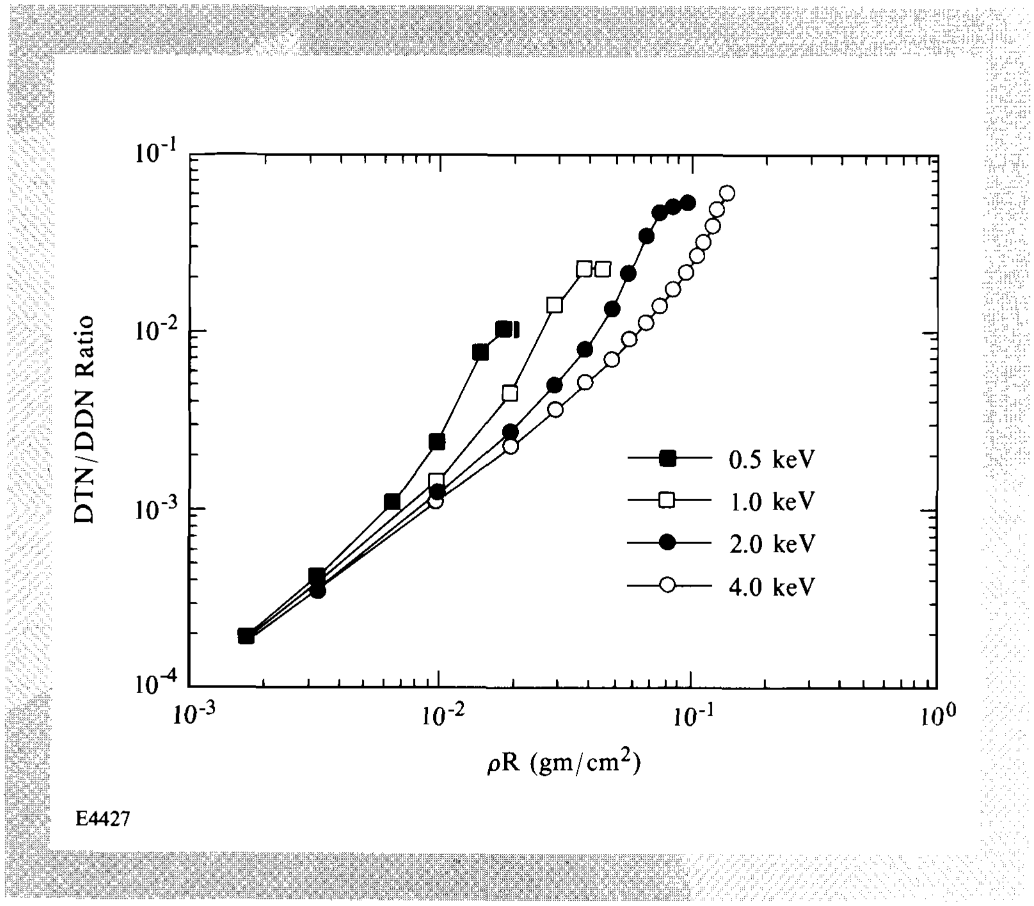
is the coulomb logarithm; N_e is the electron density

$$\alpha^2 = \frac{m_2}{m_1} * \frac{E}{\kappa T} \; ;$$

and E = energy of the fast particle.

To carry out the computer calculation, the secondary triton is initiated at its energy of creation and propagated through a region of constant electron and deuterium density. At each step, the energy loss to the triton and the probability that a ^{3}H(D,n)^{4}H reaction will occur is computed. This differential probability is equal to $N_D * s(E) * Dx$. One then sums up the total probability for passing through a given mass of deuterium. These calculations are summarized in Fig. 32.1, which shows the predicted ratios of DT neutrons to DD neutrons as a function of ρR in gm/cm^2, with the electron temperature as a parameter. These curves assume no mixing, i.e., the electron density is equal to the deuterium density. Figure 32.2 shows the results for the ^{3}He proton production. It is interesting to note the difference between the two sets of curves. The fast-proton ratio curves are smooth, with the first derivative always falling. This results from the fact that the peak in the cross section of the ^{3}He-D reaction occurs at a larger energy than the 0.8-MeV maximum in this experiment. Also note that the ^{3}He particles have a relatively short range in the plasma and thus, for moderately large ρR – i.e., values greater than 10 mg/cm^2 – the proton/neutron ratios are more sensitive to the temperature than to ρR. The tritons, being charge one, have a much larger range than the ^{3}He particles; thus, the fast- to slow-neutron ratios depend on both the temperature and the ρR. The peak of the triton reaction occurs at much lower energy than the 1.06 MeV the triton is born with. This leads to an increase in the slope of the probability curves near the end of the triton range. In the absence of mixing, the two measurements together give a unique prediction for the fuel temperature and the ρR.

Fig. 32.1
Calculated probability of the production of fast neutrons from the ^{3}H(D,n)^{4}He reaction versus ρR (gm/cm^2), with electron temperature as the parameter. These calculations assume a hot-spot model, i.e., that all the DD neutrons are produced near the center of the compressed core.



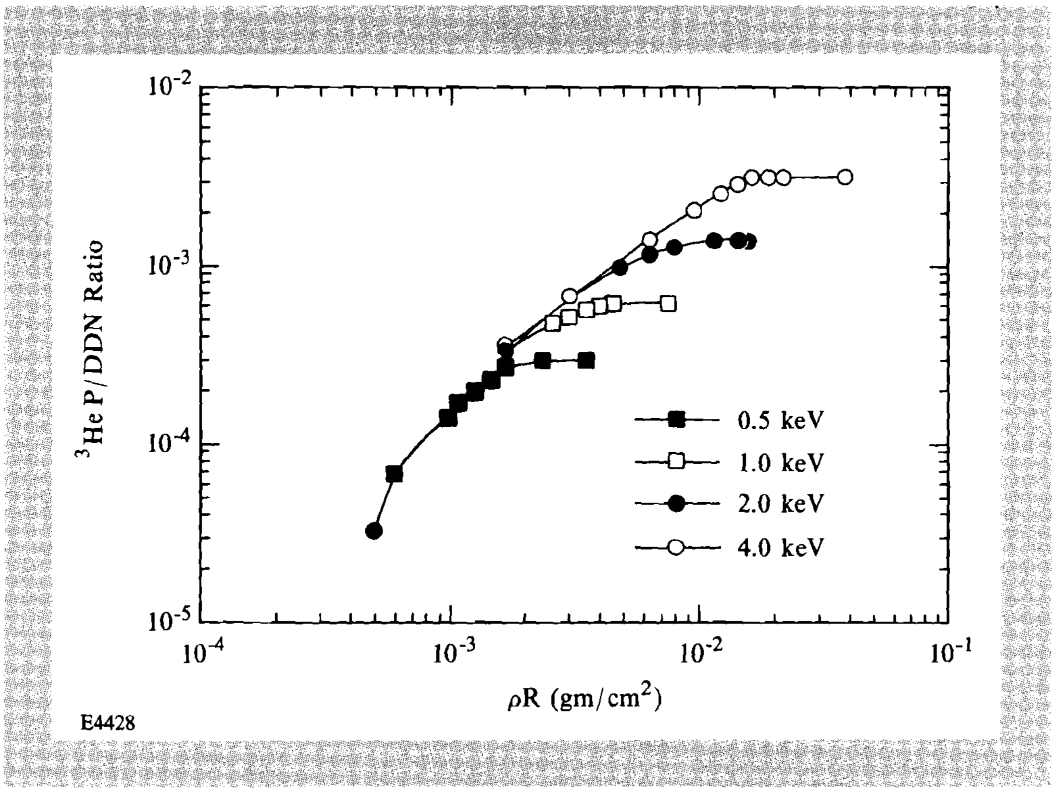


Fig. 32.2
Calculated probability of production of fast protons from the $^3He(D,p)^4He$ reaction, with electron temperature as the parameter.

In the presence of mixing, an independent measurement or estimate of the core electron temperature is needed. The effect of mixing is to change the ratio of electron density to deuteron density. The effect on the ^3He secondaries is simple, i.e., the range of the fast particle is determined by the total $(\rho R)_T$; however, the secondary probability is given by the $(\rho R)_F$, which is the areal mass of the deuterium alone. It was noted earlier that the $^3He(D,p)^4He$ peaks at the highest energy; thus, the extra stopping power of the high-Z mixed materials can only reduce the number of secondaries. The situation for the tritons' reactions is more complicated because the peak of the cross section occurs at relatively low energy. For the experiments of current interest, in which the expected electron temperature is less than 3 keV, the fast-proton measurement will determine a mixing ratio almost independent of the fast-neutron result, provided the total ρR is greater than 5 mg/cm^3. This becomes clearer if we take a hypothetical experimental result.

Assume that a simulation predicts that the nonburning fuel should be at 0.5 keV and a proton/DD neutron ratio of 1.0×10^{-4} and a DTN/DDN ratio of 2.1×10^{-3} are observed. The predicted proton ratio at 0.5 keV is 3.0 for a ρR greater than 3 mg/cm^2. It can therefore be concluded that the mixing ratio = predicted/measured proton value was 3 for this illustration. Returning to the fast-neutron measurements, we note that the number of fast neutrons would have been three times larger if the tritons had passed through deuterium alone. We therefore look up the effective $(\rho R)_T$ by looking up the predicted value at a ratio of $3 \times 2 \times 10^{-3}$, which for this case is 13.7 mg/cm^2. The deuterium $(\rho R)_F$ is equal to 13.7/3 = 4.6 mg/cm^2.

This analysis makes no assumptions about the total ρR, and thus is independent of the simulations except possibly for estimating the electron temperature. In summary, the total ρR, the fuel ρR, and the mix ratio can be deduced from the knowledge of the two secondary ratios and the electron temperature.

A note concerning the laboratory measurements of the secondary ratios: For many of the experiments on OMEGA, the number of secondary reactions is small; therefore, detectors with large solid angles are required. Currently, we are using plastic scintillators with a 1×10^{-3} fractional solid angle to detect the fast neutrons, and CR-39 solid-state detectors with a $>1 \times 10^{-2}$ fractional solid angle to detect the 14.7-MeV protons.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy Office of Inertial Fusion under agreement No. DE-FC08-85DP40200, and by the Laser Fusion Feasibility Project at the Laboratory for Laser Energetics, which has the following sponsors: Empire State Electric Energy Research Corporation, General Electric Company, New York State Energy Research and Development Authority, Ontario Hydro, and the University of Rochester. Such support does not imply endorsement of the content by any of the above parties.

REFERENCES

1. E. G. Gamali *et al.*, *JETP Lett.* **21**, 70 (1975).
2. T. E. Blue and D. B. Harris, *Nucl. Sci. Eng.* **77**, 463 (1981).
3. H. Azechi *et al.*, *Appl. Phys. Lett.* **49**, 555 (1986).
4. C. Longmire, *Elementary Plasma Physics* (Wiley, New York, 1963), pp. 196–197.