LA-5603-MS

Informal Report

UC-20
Reporting Date: April 1974
Issued: May 1974

c.3

Burn Characteristics of Marginal Deuterium-Tritium Microspheres

by

Dale B. Henderson

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

In the interest of prompt distribution, this LAMS report was not edited by the Technical Information staff.

Printed in the United States of America. Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $4.00; Microfiche $1.45

BURN CHARACTERISTICS OF MARGINAL DEUTERIUM-TRITIUM MICROSPHERES

by

Dale B. Henderson

ABSTRACT

Existing studies of the thermonuclear burn of DT microspheres have assumed complete Maxwellian distributions in the reactivity $<\sigma v>$. Under marginal conditions, $\rho R < 10^{-2}$, we find long mean-free-paths for ions in the tail of the distribution may quench the burn. This missing factor appears to explain the lack of success in laser-fusion experiments conducted to date.

The thermonuclear burn of laser-fusion pellets may be usefully studied by consideration of the burn of hot compressed microspheres.[1] Such microspheres may be thought of as being the inner core of DT droplets which have been compressed and heated by laser-driven ablation of the outer region of the pellet.[2-4] From such studies we know that the fractional burn-up f_{ro} may be expected to follow from the fusion reactivity $<\sigma v>$ as[1]

$$f_{ro} = \left(\frac{<\sigma v>}{8C_s M_i}\right) \rho R \tag{1}$$

for conditions in which $f_{ro} << 1$. In evaluating the expressions in equation 1, the density ρ, radius R, and sound speed $C = (2\gamma T/M_i)^{1/2}$ are evaluated at the initial conditions. We use $\gamma = 5/3$ and M_i is the ion mass. For $<\sigma v>$ we use the average over the Maxwellian ion distribution f(v), integrated out to infinity[5]

$$<\sigma v>_\infty = \int_0^\infty v\,\sigma(v)\ \ f(v)\ \ v^2\ \ dv. \tag{2}$$

Justification of the integration out to infinity requires that the mean-free-path for test ions at speed v, $\lambda(v)$, be smaller than dimensions of interest over ranges of v important to the integration. Unfortunately the cross section, σ, rises very rapidly with increasing v (below the maximum near 100 keV, deuteron energy) so that important ranges of v in the integration may correspond to energies well above the thermal energy in f(v) and to very long mean-free-paths $\lambda(v)$.

At low energies the cross-section behavior is due mostly to Gamow's barrier penetration formula[6]:

$$\sigma \sim \exp(-v^*/v)/v^2$$

where $v^* = (2\pi)^2\ e^2/h = 1.375 \times 10^9$ cm/sec. It is convenient to actually perform the integrations with a center-of-mass energy variable $E = M_R\ v^2/2$, while experimental data is usually reported in deuteron energy $E_D = M_D v^2/2$. Thus $E_D^* = 1.97 \times 10^6$ eV $= (1.403 \times 10^3)^2$ eV, while an empirical best fit[7] is $(E_D^*)^{1/2} = A = 1.453 \times 10^3\ (\text{eV})^{1/2}$. Using this last value and $E_D = (M_D/M_R)E$, we obtain

$$\sigma \sim \exp(-\sqrt{3/5}\ \ A/\sqrt{E})/E. \tag{3}$$

Then changing integration variable from dv to dE, the integrand in equation (2) is proportional to

$$K(E) = \exp(-\sqrt{3/5}\ \ A/\sqrt{E})\ \exp(-E/kT)$$

which has its maximum at

$$E_M = [0.5\ \sqrt{3/5}\ \ A\ kT]^{2/3}, \tag{4}$$

which for $kT = 1$ keV, is 6.8 keV.

The mean-free-path for 90-degree deflection for a test ion, on the other hand, is [8]

$$\lambda = M_i^{\,2} v^4 / 8\pi\, n\, e^4\, \ell n\, \Lambda .$$

Substituting $E_c = M_i v^2/2$ and $n = \rho/M_i$, this expression can be evaluated as

$$E_c = 559.\ \mathrm{keV}\ (\ell n\, \Lambda/10.)^{1/2} (\rho\lambda)^{1/2},$$

where $\ell n\, \Lambda = 10.$ is typical, applying to a 1.0 μg microsphere of DT at $\rho R = 10^{-4}$, and $kT = 1$ keV. Thus if we consider that test ions with $\lambda \sim R$ ought to quickly diffuse out of the hot compressed core and be lost to the thermonuclear burn, we would expect, in this case to lose ions above about 5.6 keV, while the maximum in the integral for $< \sigma v >$ is found to be at 6.8 keV. Thus, significant quenching is expected.

Rather than follow test-ions in a Monte Carlo process, we have adopted $\lambda = R$ as the criteria for lost ions, and have truncated the Maxwellian tails at the corresponding cut-off E_c's in performing the $< \sigma v >$ integration. A better treatment would also include reactions in-flight by the lost ions, but our criteria appear to be adequate to estimate this important and over-looked factor in standard treatments. The cut-off E_c's obtained are shown in Figure 1 for a 1.0 μg microsphere. The weak temperature dependence (in $\ell n\, \Lambda$) is indicated; the still weaker mass (or density in $\ell n\, \Lambda$) dependence is insignificant for 0.1 to 10.0 μg masses.

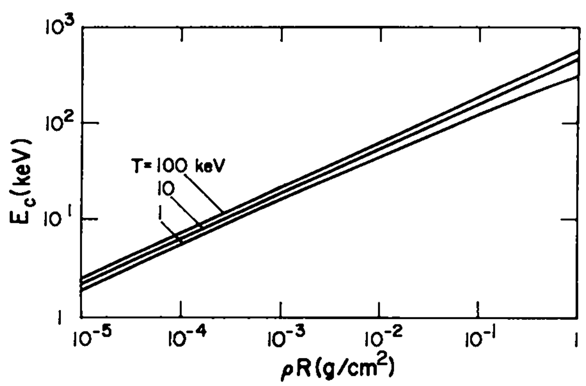

Fig. 1. Cut-off energy E_c for ion loss vs. areal mass density ρ P.

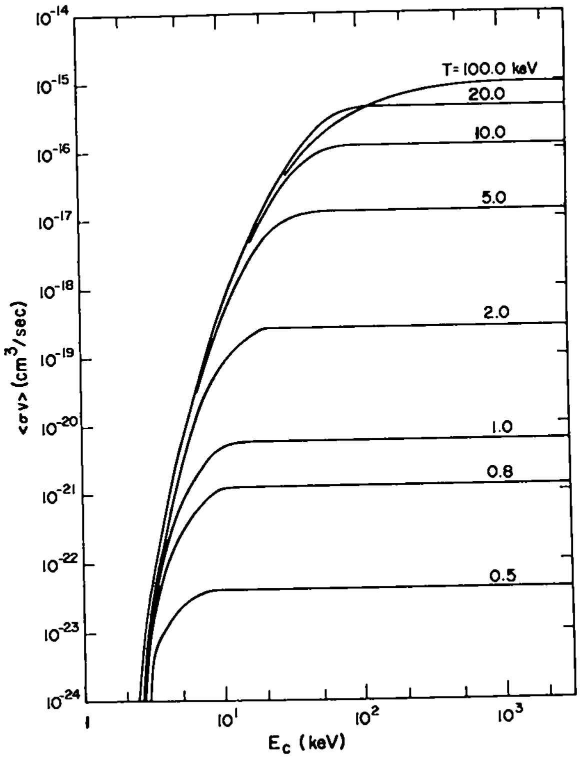

Fig. 2. Fusion reactivity $< \sigma v >$ integrated to cut-off energy E_c for various values of temperature T.

Using a best fit[7] to empirical data [5] for the cross section σ, we have numerically integrated $< \sigma v >$ up to various cut-off energies. The resulting $< \sigma v >$ curves are plotted in Figure 2. It is

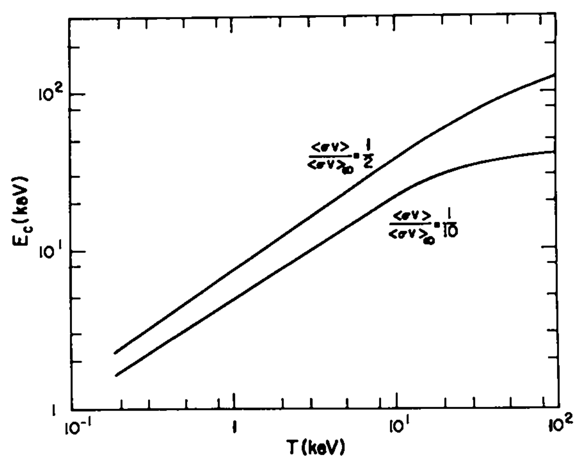

Fig. 3. Cut-off E_c required to reduce the reactivity $< \sigma v >$ to 0.5 and 0.1 of its asympotitic value vs. temperature T.

observed that at high E_c the several curves saturate to the traditional $< \sigma v >_\infty$ values, while at smaller E_c they fall rapidly and become approximately independent of temperature. This approximate temperature independence is a remarkable and important result. In order to get a better understanding of the important values of E_c, than simply that from Eq. (4), we have plotted the E_c which reduces $< \sigma v >$ to 0.5 and to 0.1 of its asymptotic value in Figure 3. The $(kT)^{2/3}$ - dependence for small temperatures is apparent.

In Reference 1, it is shown that the burn-up fraction f_{ro} may be expected to be one-half the characteristic expansion time $\tau_e = R/4C_s$ where $C_s = (2\gamma T/M_i)^{1/2}$ divided by the characteristic burn time $\tau_r = 1/n < \sigma v >$. We have therefore plotted the ratio (τ_e/τ_r), for 1.0 µg microspheres, in Fig. 4.

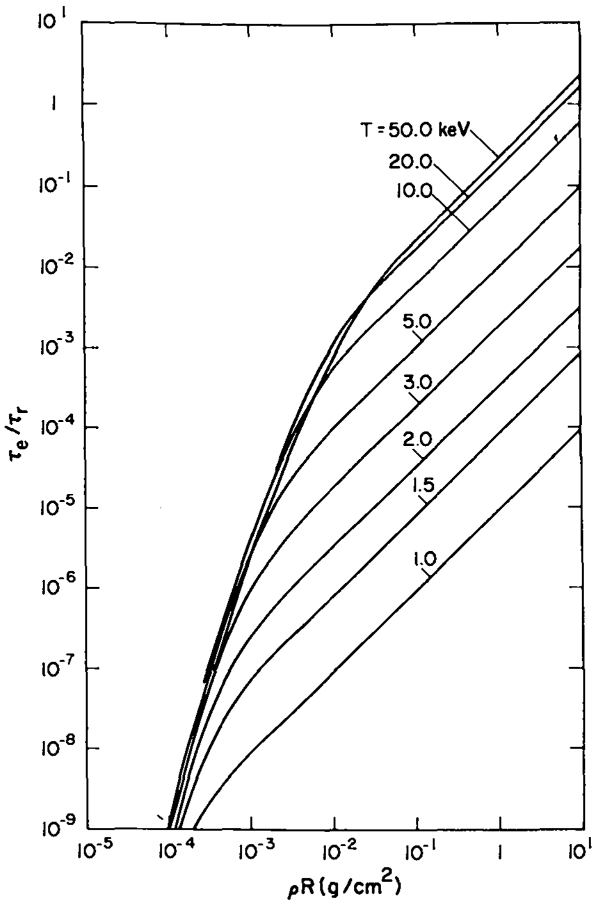

Fig. 4. Ratio of characteristic burn and expansion rates (τ_e/τ_r) vs. areal mass density ρR for various temperatures T, for a 1.0 µg sphere of DT.

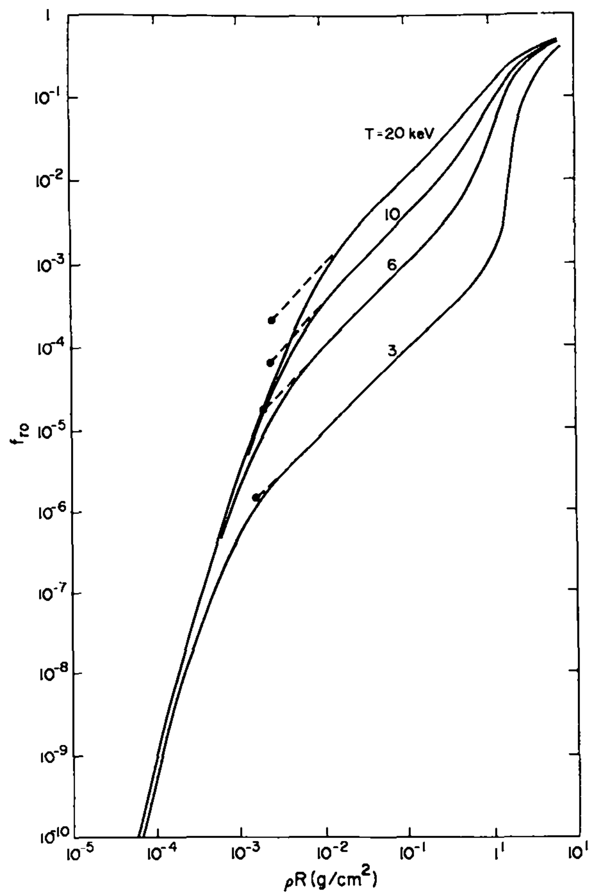

Fig. 5. Fraction burn-up f_{ro} of a 1.0 µg sphere of DT vs. areal mass density ρR for various temperatures T. This is a composite of Fig. 4 and one from Reference 1.

It is seen that the upper straight-line parts of the curves agree with Fig. 8 in Reference 1. The small ρR convergence to an approximate temperature-independent part is due to the lost ion cut-off.

Finally we have taken the data in Fig. 4 and joined it onto the complete burn study result from Fig. 10a of Reference 1. In some cases a small (1.0 to 1.1 x) multiplicative adjustment was made in order to join the two. (The computer simulation data in Reference 1 followed the dashed lines and terminated as shown.) In the composite figure, Fig. 5, we see that below $\rho R \approx 10^{-2}$, we have a weakly temperature-dependent, fast ion loss regime. From $\rho R \approx 10^{-2}$ to 1.0 gm cm^{-2}, we have scaling as predicted in Eq. (1). Above $\rho R \approx 1.0$ gm cm^{-2}, we have boot-strap heating to higher burn-up. That the lost-ion regime is separated from the non-linear burn regime by a factor of 100 in ρR is important in the justification of the analysis done here.

To date there have been no true thermonuclear neutrons observed in experiments[9], which in some cases has been hard to reconcile with Eq. (1). The faster-than-linear small ρR fall-off of f_{ro} in these marginal experiments is adequate and probably a correct explanation. We should note that above $\rho R \approx 10^{-2}$ this difficulty goes away, and so our new results do not provide any obstacle in the path of useful laser-fusion applications. There is also a bright side to the present marginal ρR experimental difficulty: when true thermonuclear neutrons are observed from small microspheres, they will serve as proof-of-compression; an important milestone to laser fusion.

ACKNOWLEDGMENT

Dr. E. Linnebur provided helpful comments during this work as well as performing some of the initial computations.

REFERENCES

1. G. S. Fraley, E. J. Linnebur, R. J. Mason, R. L. Morse, "Thermonuclear Burn Characteristics of Compressed Deuterium-Tritium Microspheres," Los Alamos Report LA-5403-MS, and to appear in Physics of Fluids.

2. J. S. Clarke, H. N. Fisher, and R. J. Mason, Phys. Rev. Lett. 30, 89 (1973) and 30, 249 (1973).

3. J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, Nature (London) 239, 139 (1972).

4. J. Nuckolls, J. Emmett, and L. Wood, Physics Today, 26, no. 8, p. 46 (August, 1973).

5. J. L. Tuck, Nucl. Fusion 1 202 (1961).

6. G. Gamov, C. L. Critchfield, "Theory of Atomic Nucleus and Nuclear Energy Sources," (Oxford, Claredon Press, 1951), ch. X.

7. B. H. Duane, "Fusion Cross Section Theory," in the Pacific Northwest Laboratory Annual Report on Controlled Thermonuclear Reactor Technology-1972, ed. by W. C. Wolkenhave, p. 75, Battelle PNWL Report BNWL-1685 (1972).

8. L. Spitzer, Physics of Fully Ionized Gases, (New York, Interscience, 1956).

9. G. H. McCall, F. Young, A. W. Ehler, J. F. Kephart, and R. P. Godwin, Phys. Rev. Letters, 30, 1116 (1973).