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**Existence and Lifetime of  
Laser Fusion Pellets Containing Tritium**

University of California



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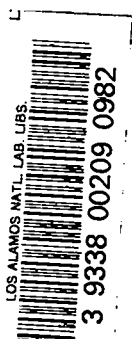
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# Existence and Lifetime of Laser Fusion Pellets Containing Tritium

Joseph J. Devaney



# EXISTENCE AND LIFETIME OF LASER FUSION PELLETS CONTAINING TRITIUM

by

Joseph J. Devaney

## ABSTRACT

Cryogenic pellets containing significant amounts of solid tritium cannot be maintained in a pure vacuum for longer than (typically) some tens of seconds because radiative cooling at low temperatures is inefficient. The steady state temperatures in typical one- and two-shell pellet designs both in vacuum and with external cooling, as well as the lifetimes of pellets following cooling removal, are calculated.

## I. INTRODUCTION

This report examines whether laser fusion pellets containing tritium can be kept cool enough to avoid structural damage, and calculates their lifetime away from refrigeration. Some typical theoretical pellet designs are not physically realizable. Universally, others have limited lifetimes away from a cooling source. One class of pellet design can only survive in a limited range of cooling bath temperatures. Paradoxically, too much cooling of these pellets will cause melting and consequent destruction of the pellet.

We deal here with pellets containing solid 50:50 at.% DT or solid  $T_2$ , for which significant melting leading to change of shape of the solid hydrogen is considered to have destroyed the pellet. Because a mixture of DT invariably contains considerable  $D_2$  (46 to 31 at.%),<sup>1</sup> the  $D_2$  triple point temperature,<sup>1,2</sup> 18.71 K, is a conservative temperature at or below which we may regard the DT mixture to be a solid. At higher pressures than that of the triple point (17 130 Pa for  $D_2$ )<sup>1</sup> solid  $D_2$  does exist at yet higher temperatures, but below the triple point temperature the only possible phases are of course gas and solid.

Although the beta radioactivity of tritium is exceedingly weak with a 12.26 year half-life<sup>3</sup> and a mean beta particle energy of only 5.7 keV,<sup>3</sup> cooling is difficult when trying, as in our case, to keep a heat source at an extremely low temperature at which radiative heat transfer is extremely small because it is proportional to temperature to the fourth power. Both the thermal conductivity and the heat capacities are also extremely small, going rapidly to zero with decreasing temperature. In fact, radiation cooling is so weak that typical pellet designs containing tritium within a vacuum cannot exist at all as we next proceed to show. We will then examine the effect of gaseous conduction in cooling the inner shell structure of a multiple-shell pellet, calculating the inner shell's response as a function of outermost shell temperature. Last we give the lifetime of various pellets upon cooling surcease.

## II. PELLET NON-EXISTENCE

One pellet design, representative of a class of designs, contains  $6.1 \times 10^{-4}$  g of solid 50:50 at.% DT in a spherical shell of inner radius 0.165 cm and outer radius 0.173 cm, in turn surrounded by a shell of polyethylene doped with tungsten oxide to a density of  $1.26 \text{ g/cm}^3$ , and having a

mass of  $5.167 \times 10^{-3}$  g, and an outer radius of 0.182 cm. This inner shell structure is surrounded by vacuum. To make our "non-existence" point even stronger in this first steady state calculation below, we omit the insulating value of the doped plastic and also assume the surroundings are at 0 K temperature. We ask for the steady state temperature of the DT under the above conditions. The mass of tritium in 50:50 at % DT is,

$$M_T = 0.6 M_{DT} . \quad (1)$$

The heat production in tritium is 0.325 J/s·g.<sup>3,4</sup> We thus have a heat production of  $6.1 \times 10^{-4}$  g  $\times$  0.6  $\times$  0.325 J/s·g = 1.19  $\times$  10<sup>3</sup> erg/s. The radiative heat loss is

$$e = dE/dt = \epsilon \sigma A T^4 , \quad (2)$$

where the emissivity,  $\epsilon$ , of plastic at low temperature is 0.85<sup>5</sup>; the Stefan-Boltzman constant,  $\sigma = 5.6696 \times 10^{-5}$  ergs/cm<sup>2</sup>·s·K<sup>4</sup>; the area, A is  $4\pi(0.182 \text{ cm})^2$ ; and T is the equilibrium temperature which is to be determined. Equating Eqs. (1) and (2) we find that the DT temperature must rise to 87.8 K, well above the melting point for DT.

If we replace the inner shell of 0.61 mg DT with a shell of 0.999 mg of pure T<sub>2</sub> the shells must then rise to a temperature of 113 K in order to radiate away their total energy.

It is thus clear that any appreciable amount of tritium cannot be kept in the solid state within a vacuum without direct cooling. Of course real pellets contain support structures which may possibly allow some additional continuous cooling. More effectively, if hydrodynamically allowed, a small amount of hydrogen or helium gas will nicely conduct away the radioactive heat as we discuss below. However, the coolant temperature of such a system must not be allowed to be too low or too much of the gas will condense and leave too little gas for efficient conduction. Thus, paradoxically, the inner structure will overheat and melt if cooling is excessive. Also the inner pellet structure itself may be cooled directly. We will discuss below the lifetime of these structures following cooling removal.

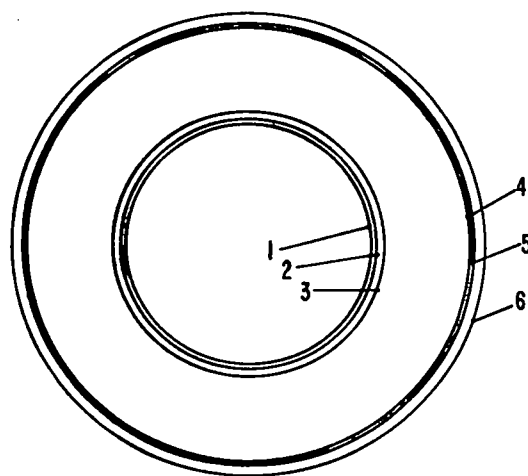


Fig. 1. Two-shell pellet.

### III. MULTISHELL PELLETS EXISTENCE

A second generic class of laser pellets consists of two shells of DT and plastic. For example consider the design of Fig. 1 and Table I. The inner shell structure is identical to that discussed in Sec. II. Added are an outer shell of DT surrounded by a shell of tungsten-oxide doped polyethylene. We suppose that the radius  $r_6$  is kept at a temperature  $T_6$  and examine cooling of the shells by radiation, conduction, and convection. In general in this report a temperature  $T_i$  refers to the temperature at radius  $r_i$  (Fig. 1). Although we deal with spherical shells, they are thin enough so that one dimensional calculations are suitable where advantageous.

We first establish that convection is generally negligible except possibly at very high accelerations. For a spherical shell of gas the effective conductivity including convection,  $k_e$ ,

TABLE I  
TWO-SHELL PELLETS CONSTRUCTION

No.	Radius, cm	Material	Density, g/cm <sup>3</sup>	Mass, g
1	0.165	DT	0.2125	6.10(-4)
2	0.173	Plastic, W	1.26	5.167(-3)
3	0.182	VOID		
4	0.3016	DT	0.2125	3.00(-4)
5	0.3028	Plastic, W	1.26	2.32(-2)
6	0.32			

divided by the pure conductivity,  $k$ , is,<sup>6</sup>

$$(k_e/k) = 1 + m \left[ \frac{N_{Ra}^r}{(N_{Ra} + n)} \right], \quad (3)$$

which is suitable for laminar flow;  $m$ ,  $r$ , and  $n$  are constants.  $N_{Ra}$  is the Rayleigh number and is equal to the product of the Grashof number times the Prandtl number. In the British system the Rayleigh number for hydrogen is,<sup>6</sup>

$$N_{Ra} = 3.73 \left[ 1 + (129/T) \right]^2 / (T/100)^4 p^2 \delta^2 \Delta T, \quad (4)$$

with units of  $\text{ft}/\text{lb}^{20}\text{R}$ ,  $^{\circ}\text{R}$  being degrees Rankine.  $\delta$  is the spacing or width of the spherical gas shell in feet,  $p$  is the pressure in  $\text{lb}/\text{in}^2$ , and  $\Delta T$  is the temperature difference between surfaces in  $^{\circ}\text{R}$ . Equation (4) is only valid when the thermal conductivity, the dynamic viscosity, and the specific heat are not functions of pressure, that is when the gas mean free path is less than  $\delta$ .

The vapor pressure of DT gas in equilibrium with DT solid is given by,<sup>2</sup>

$$\ln P = - (A/T) + B \ln T + C, \quad (5)$$

where  $P$  is in torr, and

$$\begin{aligned} A &= 151.5 \\ B &= 2.349 \\ C &= 5.667. \end{aligned}$$

There are two principal regimes in the behavior of a gas, that for mean free paths less than container distances, and that for paths greater than container distances. In the former, for example, the conductivity is pressure independent because decreased pressure, although proportionately reducing the heat carriers, i.e., the density, inversely increases the mean free path, so the effective rate of molecular energy exchange remains unaltered. When the mean free path becomes of the same order, or less than, the distance separating the surfaces in question, heat exchange is effected by molecules proceeding directly from the hot to the cold surface. The number of carriers, hence the pressure then is important. One must

then determine the pressure and, hence, the temperature at which the molecular mean free path is that of the "void spacing,"  $r_4 - r_3 = 0.1196$  cm. For our purpose it is amply good enough to take all the molecules identical; the mean free path is then given by:<sup>7</sup>

$$\lambda = 1/(\pi n d^2 \sqrt{2}); \quad (6)$$

$\lambda$  is the mean free path,  $n$  the molecular density, and  $d$  the molecular diameter,  $2.968\text{\AA}$ .<sup>7</sup> Using

$$P = nkT \quad (7)$$

and Eqs. (3) and (4) we find that the temperature for a mean free path of  $\delta = r_4 - r_3$  is 8.9 K. Above this temperature one expects no strong pressure dependence of the heat conductivity between  $r_4$  and  $r_3$ . Thus, for our circumstances, we shall expect formula (4) to be accurate above 8.9 K. Below this temperature, convection ceases to exist or to have meaning.

Let us therefore make a trial calculation at 10 K or  $18^{\circ}\text{R}$ . Substituting  $T = 18^{\circ}\text{R}$  in Eq. (4) and  $T = 10$  K in Eq. (5) to determine the pressure which in  $\text{lb}/\text{in}^2$  is in turn substituted in Eq. (4) we find

$$N_{Ra} = 4.38 \times 10^{-5} \Delta T (^{\circ}\text{R}), \quad (8)$$

and choosing  $\Delta T = 6$  K or  $10.8^{\circ}\text{R}$  we substitute Eq. (8) and the values,<sup>6</sup>

$$\begin{aligned} m &= 0.119 \\ n &= 1.45 \times 10^4 \\ v &= 1.270, \end{aligned} \quad (9)$$

which are appropriate for outward heat flow across a spherical shell, into Eq. (3) to find,

$$(k_e/k) = 1 + 4.9 \times 10^{-10}, \quad (10)$$

from which we conclude that for our circumstances, free convection is an extremely small perturbation on conductive heat losses which we now proceed to calculate.

To determine the DT conductivity above 8.9K we use the values measured for H<sub>2</sub><sup>8</sup> at: 20K (0.0155 W/m K); at 60K (0.043W/m K); and (as a check) at 80 K (0.0565 W/m K), ignoring the slight ortho-para hydrogen differences, to find the power law

$$\lambda_{H_2} = 0.0155(T/20)^{0.9287} \text{ W/m}\cdot\text{K} . \quad (11)$$

We then extrapolate the ratios of conductivities<sup>8</sup> of deuterium to protium measured at 60, 80, and 100 K down to the range 8.9 to 18.71 K to get the law

$$\lambda_{D_2} = \lambda_{H_2} (M_H/M_D)^{0.2383} , \quad (12)$$

which we apply to DT to find

$$\lambda_{DT} = \lambda_{H_2} \left[ \frac{2M_H}{(M_D + M_T)} \right] = 0.8043 \lambda_{H_2} , \quad (13)$$

together with Eq. (11) we then have,

$$\lambda_{DT} = 1246.6(T/20)^{0.9288} \text{ erg/cm}\cdot\text{K}\cdot\text{s} , \quad (14)$$

$$T > 8.9 \text{ K} .$$

For temperatures enough below 8.9 K so that the bulk of heat transfer is direct from hot to cold surfaces without intermolecular collision, the molecule is assumed to take up the temperature of each wall at its last collision, and the rate of heat energy transfer per unit area, the heat energy flux, is given by,<sup>9</sup>

$$(d^2E/dtdA) = (3/8)P \sqrt{3R/MT} \cdot (T_3 - T_4) , \quad (15)$$

where P is the pressure, R the gas constant, M the molecular weight, T the mean gas temperature, and,  $\Delta T = T_3 - T_4$  the temperature difference between the walls. Note that there is no dependence on the spacing  $\delta = r_4 - r_3$ . Because we cannot allow  $T_3 - T_4$  to be large (else the pellet melts) and because  $\sqrt{T}$  is a slowly varying function we take T to be  $T_4$  and use Eq. (5) to obtain for DT void gas,

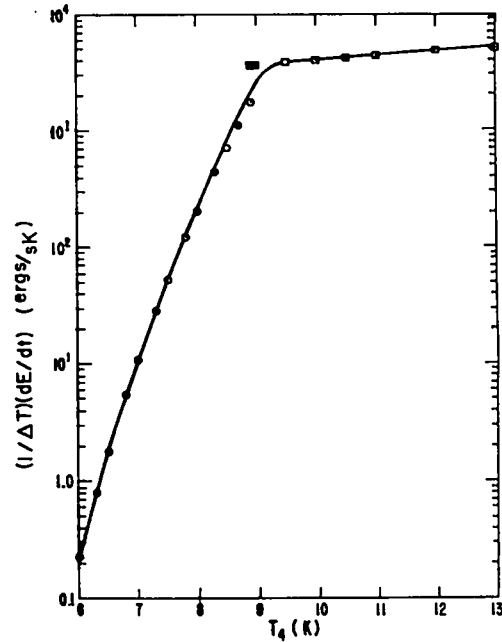


Fig. 2. Saturation DT vapor conductivity divided by the temperature difference (across 0.7347 cm<sup>2</sup> area, 0.1196 cm spacing) ( $\Delta T^{-1} dE/dt$ ) versus temperature of solid DT in vapor equilibrium ( $T_4$ ). (Square points are based on Eq. 14; circular points are based on Eq. 16. The mean free path equals the spacing at 8.9 K).

$$e \equiv dE/dt = 2.587 \times 10^6 T_4^{-1/2}$$

$$\cdot \left\{ \exp \left[ \left( -A/T_4 \right) + B \ln T_4 + C \right] \right\} (T_3 - T_4) \text{ erg/s} , \quad (16)$$

$$T_4 < 8.9 \text{ K} ,$$

where we have used the mean radius  $r_{34} \equiv (r_3 + r_4)/2$  in the area formula

$$4\pi r_{34}^2 = 0.7347 \text{ cm}^2 . \quad (17)$$

Figure 2 gives the energy transmission through the "void"  $r_3$  to  $r_4$  by conduction divided by the temperature difference  $\Delta T = T_3 - T_4$ . The square points are obtained from Eq. (14) multiplied by the mean area 0.7347 cm<sup>2</sup> and divided by the spacing  $r_4 - r_3 = 0.1196$  cm. The encircled points are from Eq. (16). The transition between the curves occurs when the mean free path is about equal to the spacing  $r_4 - r_3$  which we compute to be at about 8.9 K, see above. The smooth curve indicates only the estimated transition behavior and contains no physics beyond the above asymptotic behaviors and the transition temperature.

TABLE II  
POLYETHYLENE THERMAL CONDUCTIVITIES  
(0.971 g/cm<sup>3</sup>)

Temperature, T(K)	4	10	20
Conductivity, $\lambda$ (mW/cm K)	0.26	1.5	4.65

Having now the conductivity of the "void,"  $r_3$  to  $r_4$ , as a function of temperature, we turn to the conductivities of the plastic and of the DT solid. The conductivity of high-density (0.971 g/cm<sup>3</sup>) polyethylene at low temperatures is given in Table II.<sup>10</sup> The values of Table II are fit (to  $\pm 3\%$  in the range 10 to 20 K) by

$$\lambda = 303.2 T^{1.6826} \text{ erg/s}\cdot\text{cm}\cdot\text{K} . \quad (18)$$

In the doped plastic we regard the pure plastic plus oxygen as having the net conductivity of polyethylene and the W as being, in effect, of infinite (relative) conductivity.<sup>8</sup> Differences are negligible (temperature changes would be only several nK) as we shall see, and the conductivity of tungsten oxide at these low temperatures is hard to come by. The effective thickness of the DT loaded plastic between radii  $r_1$  and  $r_2$  of Fig. 1 and Table I, which we label plastic-23, is then,

$$\Delta r_{23}(\text{effective}) = 0.008854 \text{ cm} , \quad (19)$$

and of the plastic-56 is,

$$\Delta r_{56}(\text{effective}) = 0.014757 \text{ cm} . \quad (20)$$

The conductivity of H<sub>2</sub>, which we use for DT and T<sub>2</sub> ranges from 200 W/m·K at 4 K to 3 W/m·K at 10 K. From  $r_4$  to  $r_5$  these conductivities lead to maximum temperature differences of from about 0.45  $\mu$ K at 4 K to 30  $\mu$ K at 10 K so we can ignore temperature differences across solid DT or T<sub>2</sub> also. Our picture then can be usefully simplified to a heat source of 1190 erg/s at  $r_2$ , a conductivity given by Eq. (18) over a distance given by Eq. (19), a conductivity given by Fig. 2 between  $r_3$  and  $r_4$ , a heat source of 585 erg/s at  $r_5$ , a conductivity between  $r_5$  and  $r_6$  given by Eq. (18) over a distance given by Eq. (20), and finally a set temperature T<sub>6</sub> at  $r_6$ .

Our method of calculation is to choose a temperature T<sub>4</sub> then use the usual plane conduction equation with the appropriate mean radius  $\hat{r}$ , conductivity  $\lambda$ , and spacing  $\Delta r$ , to determine the temperature  $\Delta T$  of successive shells in both direction seriatim, thus we use

$$T = (\lambda 4\pi \hat{r}^2)^{-1} \Delta r \sum_i e_i , \quad (21)$$

where  $e_i$  denotes the various sources within the particular largest radius of the shell under consideration. Following the model described above Eq. (22) yields little temperature change T<sub>4</sub> to T<sub>6</sub> running about 0.001 to 0.007 K (at 17 to 6 K respectively), and the little temperature change T<sub>1</sub> to T<sub>3</sub>, again only of the order of a few thousandths Kelvin. As expected, the major temperature drop occurs across the gas of the "void." The conductive and radiative losses are there matched to equal the total heat flow through the "void." The result of these labours is plotted in Fig. 3 in which we plot the cooling temperature, T<sub>6</sub>, on the outside of the outer shell structures as the independent variable with the resulting DT temperature, T<sub>1</sub> (or T<sub>2</sub>) as dependent variable. As noted before, too much cooling condenses so much DT vapor between the inner and middle shell structures that there is not enough gaseous thermal conduction and the DT temperature, therefore, rises to the radiative limit. Because D<sub>2</sub> constitutes a large component of DT, the integrity of the DT shell cannot be guaranteed above the D<sub>2</sub> triple point temperature of 18.71 K.

Two curves are shown, the lower for the DT shells as described above, the upper for replacing the inner DT with 0.999 mg of T<sub>2</sub> and replacing the outer DT with a trace amount of ordinary hydrogen (i.e., 0.1  $\mu$ g protium - but arbitrarily keeping the same vapor pressure and conductivity of the DT mixture for comparison purposes. The cooling is thus not strictly correct for this case).

The minimum cooling temperatures at  $r_6$  that will keep the inner hydrogen shell just at 18.71 K is T<sub>6</sub> = 7.75 K for DT and 8.16 K for T<sub>2</sub>. The maximum permissible temperatures are T<sub>6</sub> = 18.54 K for DT and T<sub>6</sub> = 18.23 for T<sub>2</sub>. The minimum inner



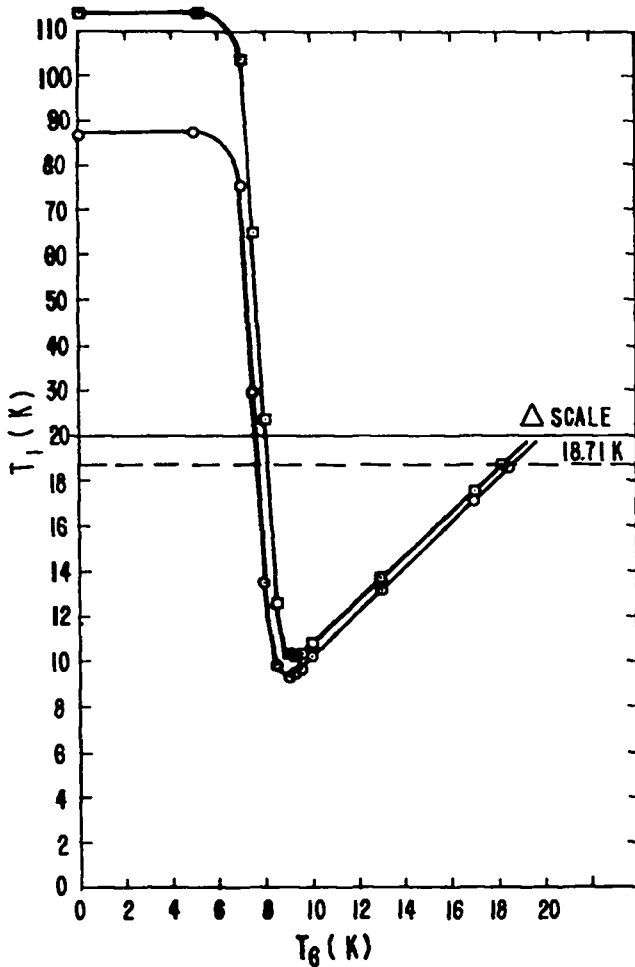


Fig. 3. Inner hydrogen shell temperature ( $T_1$  or  $T_2$ ) versus plastic temperature ( $T_6$ ). The upper curve,  $\blacksquare$ , is for the inner shell composed of .999 mg  $T_2$ . The lower curve,  $\bullet$ , is for the inner shell composed of 0.61 mg DT.

DT shell temperatures achievable are  $T_1 = 10.2$  K at  $T_6 = 9.25$  K for  $T_2$  and  $T_1 = 9.48$  K at  $T_6 = 9$  K for DT of our example.

For a number of reasons it may be possible to do better in a real pellet than the above calculations show. The support structure of the inner shells may provide highly effective additional cooling. (The use of very low density plastic or aluminum for example, but "poisoning" the radiative properties of the plasma can occur by higher Z materials). Higher gas pressures may be allowed in the "void" with consequent higher melting points than the triple point, but the hydrodynamics of the implosion may be adversely affected. Indeed use of the  $D_2$  triple point for DT may be

needlessly conservative; one might be able to go to the  $19.71$  K<sup>1,2</sup> triple point of DT itself. In fact, one might even take advantage of fractionation or so construct the pellet that the void gas is solely  $D_2$  with a higher conductivity and vapor pressure than the DT I have used plus mostly (or more)  $T_2$  in the solid with a triple point ( $T_2$ ) approaching  $20.62$  K.<sup>1,2</sup> Further, one can imagine using both different designs and different materials  ${}^6\text{LiD}$  is a possibility, or mixtures thereof, with DT. The consequent radioactive heating is zero or at least less. There are penalties in yield, but at present it is clear that we have many options open for future study. Last, one may even directly cool the inner shell structure prior to laser illumination. The time between cooling termination and pellet melting is the subject of the next section.

#### IV. PELLETT HEAT CAPACITIES: PELLETT LIFETIMES FOLLOWING COOLING SURCEASE

This section determines the lifetimes of pellets after cooling has ceased. The plastic shells are so thin that even at 4 K their net conduction is sufficiently great in times of a few seconds or greater that we can consider each shell structure as one heat capacity unit. (The temperature difference needed to continuously transmit all the inner tritium heat across the inner plastic is 0.008 K at 4 K and is less at higher temperatures and for less heat conducted.)

Because of the paucity of data at low temperatures we are forced to use the specific heat of the plastic, polyethylene-terephthalate [PET, mylar,  $-(C_{10}H_8O_4)_n-$ ], rather than that of polyethylene itself. For simplicity, we lump the oxygen with the PET and determine the specific heat of tungsten separately. Based then on the specific heat of PET<sup>11</sup> of 0.07 J/g·K at 10 K and of 0.11 J/g·K at 20 K (and 0 at 0 K) we made the fit

$$C_p(\text{plastic}) = 0.0085 T - 0.00015 T^2, \text{ J/g}\cdot\text{K} \quad (22)$$

which is usable between 0 and 20 K. For tungsten we match the measured values<sup>12</sup> by the equations,

$$C_p(W) = 2.34 \times 10^{-6} T^2, \text{ J/g}\cdot\text{K}, 4 \text{ to } 10 \text{ K} \quad (23)$$

$$C_p(W) = 3.723 \times 10^{-5} T - 5.63 \times 10^{-6} T^2 + 4.247 \times 10^{-7} T^3, \text{ J/g K, } 10 \text{ to } 25 \text{ K.} \quad (24)$$

For DT we extrapolate the measured specific heats of H<sub>2</sub> and D<sub>2</sub> to get the relations,<sup>8</sup>

$$C_p(DT) = 0.00042 T^3, \text{ J/g K, } 0 \leq T \leq 10 \text{ K,} \quad (25)$$

$$C_p(DT) = 1.29 + 0.171 T, \text{ J/g K, } 10 \text{ K} \leq T, \text{ (solid only)} \quad (26)$$

The heat capacity or energy gain from a temperature change T<sub>1</sub> to T<sub>2</sub> of a number of masses, M<sub>i</sub>, is given by

$$\Delta E = \int_{T_1}^{T_2} \sum_i M_i C_{pi} dT. \quad (27)$$

Note that a power T<sup>n</sup> in any C<sub>pi</sub>, after integration, will become

$$(T_2^{n+1} - T_1^{n+1}) / (n+1). \quad (28)$$

Using the masses of Fig. 1 and the fractionation of plastic described above we obtain for the inner shells' masses,

$$\begin{aligned} M_{DT}(\text{inner}) &= 6.10 \times 10^{-4} \text{ g} \\ M_{\text{plastic}}(\text{inner}) &= 4.05 \times 10^{-3} \text{ g} \\ M_W(\text{inner}) &= 1.118 \times 10^{-3} \text{ g,} \end{aligned} \quad (29)$$

and for the outer shell masses,

$$\begin{aligned} M_{DT}(\text{middle}) &= 3.00 \times 10^{-4} \text{ g} \\ M_{\text{plastic}}(\text{middle}) &= 1.743 \times 10^{-2} \text{ g} \\ M_W(\text{middle}) &= 5.77 \times 10^{-3} \text{ g.} \end{aligned} \quad (30)$$

Applying Eqs. (21) through (30) we obtain the values displayed in Table III. These values the pellets can withstand under slow warming (temperature equilibrium). The mode of failure is softening of D<sub>2</sub> for DT solid, or the same temperature for T<sub>2</sub> for comparison. The pellet can withstand much higher energy deposition from rapid external warming because the plastic can take much higher temperatures. Table III also includes the energy

TABLE III  
ENERGY CAPACITIES OF PELLET STRUCTURES  
(Joules)

	For Temperature Changes	
	4.22 to 10 K	10 to 18.71 K
Inner shells	0.00185	0.00938
Outer shells	0.00614	0.0222
Total	0.00799	0.0316

needed to raise the pellet temperature from boiling helium temperature (4.22 K at SP) to 10 K.

Without any heat loss (radiation, conduction or conversion) the time it takes pure DT to begin to soften (18.71 K) starting at 10 K is obtained by dividing the mean DT heat production (0.6 gT/g DT 0.325 J/s gT),<sup>5,7</sup> into the capacity (10.148 J/g) to obtain 52.04 s. Similarly the time for DT without losses to warm from 4.22 K to 10 K is 5.215 s. In the pellet the plastic serves as a heat sink leading to longer lifetimes as we now calculate.

We consider the self-heating lifetime of the inner shell structures in vacuum, the surrounding being at 4.22 K. Equation (2) gives the radiative heat loss and Sect. II the radiative heat production. At temperatures below 19 K the radiative losses are negligible compared to the heat production (0.2 to 0.07% at 19 K, less at lower temperatures) so we may immediately determine the inner shell lifetime from Table III and the heat production rates to be as given in Table IV. Thus upon losing all cooling, the inner shell has only 26 s to live, if originally at 10 K and composed of T<sub>2</sub>, but it has 94 s to live if initially at 4.22 K and if composed of a lesser mass of DT.

TABLE IV  
LIFETIMES OF SELF-HEAT OF THE INNER SHELL  
STRUCTURE (Seconds)

	For Temperature Changes	
	10 to 18.71 K	4.22 to 10 K
0.61 mg DT inner shell	78.9	15.5
0.999 mg T <sub>2</sub> inner shell	26.2	4.9

Next we calculate the lifetimes of the pellet when initially only the outer shell structure is (optimally) cooled (Fig. 3) so as to give minimum inner-shell temperatures, and then cooling is stopped. By balancing heat flow and the heat capacities of the two shell structures, we determine that the temperature of the outer shell structure is 18.67 K when the inner shell DT has reached the threshold of destruction at 18.71 K. Figure 3 gives the minimum initial temperatures of 9.48 K for  $T_1$ , the inner DT temperature, and 9.0 K for  $T_6$ , the outer plastic temperature. Using the masses of Eqs. (29) and (30) and formulas (22) and (23) to (28) we calculate the heat capacities of  $9.67 \times 10^4$  erg for the inner shell structure and  $2.35 \times 10^5$  erg for the outer shell structure. Using Eqs. (28) and (30) together with a heat production of  $3.25 \times 10^6$  erg/s  $gT^{5,7}$  times the mass fraction of tritium in 50:50 DT of 0.6 we get the energy production values of Table V. Dividing the sum of the above capacities by the total DT heat production of Table V gives the lifetime of the pellet from the moment cooling ceases to the beginning of inner DT melt. That lifetime is 118 s or 1.96 min. The isolated inner shell structure lifetime under the same temperature changes as used above is 81 s.

For a  $T_2$  composed inner shell, balancing heat flow and capacities leads to an outer shell temperature of 18.39 K when the inner  $T_2$  has reached 18.71 K. Figure 3 gives the minimum initial temperatures of 10.2 K for  $T_1$ , the inner  $T_2$  temperature, and of 9.26 K for  $T_6$ , the outer plastic temperature. Proceeding as before, but with the inner DT replaced by  $T_2$ , we calculate an inner shell structure heat capacity of  $8.75 \times 10^4$  erg and an outer shell capacity of  $1.99 \times 10^5$  erg. The lifetime of the pellet after cooling surcease is 57 s or 0.95 min. The isolated inner shell structure would have a lifetime of 26 s. These results are summarized in Table VI.

TABLE V  
TRITIUM ENERGY PRODUCTION (erg/s)

0.61 mg DT, $r_1$ to $r_2$	1190
0.999 mg $T_2$ , $r_1$ to $r_2$	3247

TABLE VI

PELLET LIFETIMES TO ONSET OF MELTING OF HYDROGEN CAUSED BY TRITIUM RADIOACTIVE HEAT  
( $T_1 = 18.71$  K)  
(Initially at minimum inner temperature achievable by cooling outer shell)

	Complete Pellet	Isolated Inner Shell Structure <sup>a</sup>
0.61 mg DT	118 s	81 s
0.999 mg $T_2$	57 s	26 s

NOTE:

<sup>a</sup>DT: 9.48 to 18.71 K;  
 $T_2$ : 10.2 to 18.71 K.

Thus if one cools only the outer shell structure to the lowest possible inner DT temperature, the lifetime of the pellet after cooling stops is 118 s for our DT case, and 57 s for our  $T_2$  case.

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