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EFFECT OF FUSION REACTION PRODUCTS HEATING ON THE VOLUME IGNITION OF DT AND D^{3}He FUEL PELLETS

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Abstract

Laser fusion simulations are carried out for DT and D-^{3} He pellets by using a hydrodynamic code including heating from all charged reaction products and neutrons. It is shown that the inclusion of the side reactions and heating from all reaction products in the fuel pellets have an appreciable effect on the plasma temperature, the ICF drive energy requirement, fusion gain and the ignition conditions. The total input energy is decreased and the burn efficiency and total gain are increased compared to the results of simple volume ignition calculations.

Introduction

Since it has been internationally decided to reduce carbon dioxide emission before the year 2005 in order to avoid the greenhouse catastrophy of the earth's atmosphere, and since there is an urgent need for energy, especially in the developing countries, there is now a strong demand for alternative energy sources. While the established low cost energy production by light water nuclear fission reactors could be a solution for a period of transition (limited by resources of the light uranium isotope), fusion energy is of interest for large scale energy production while renewable sources will be able to meet a part of the increased energy demand.

The advantages of using advanced fuels for fusion have been recognized for a number of years. We can look forward to this long-range goal, which would enable fusion to fulfill its ultimate potential as a very clean and efficient energy supply. The classical deuterium-tritium (D-T) mixture is the premier candidate for a fusion fuel on account of its outstanding energy gain [1].

$$D+T \rightarrow n(14.1\text{ MeV}) + {}^4He(3.5\text{ MeV}) \qquad (1)$$

However, because of its neutron production, it certainly can not be considered as an ideal long-term option. It is preferable to avoid the use of radioactive tritium and the undesired radioactivity generated by the neutrons (most of which will be absorbed and used for breeding in the lithium surrounding the reactor). An ideal reaction is the H-^{11}B reaction, in which less radioactivity is emitted per unit of energy produced [1] than the two parts per million of uranium given off in the dust that is released from burning coal. It is very difficult, however, to make H-^{11}B reaction and the results currently available suggest that inertial confinement fusion (ICF) operation with this clean fuel must be postponed to much later stages.

Another "clean" reaction that can be considered is the D-^{3} He reaction [2]:

$$D + {}^3He \rightarrow P(14.7\text{ MeV}) + {}^4He\ (3.6\text{ MeV}) \qquad (2)$$

Because of the absence of uncharged reaction products (neutrons), this obviously is a desirable reaction. There remains the problem of the competing reactions

$$D + D \rightarrow n(2.4\text{ MeV}) + {}^3He\ (0.8\text{ MeV}) \qquad (3)$$

and

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$$D + D \rightarrow P(3.0\ \text{MeV}) + T\ (1.0\ \text{MeV}) \qquad (4)$$

which represent a source of radioactivity.

It has been shown that reaction (2) can dominate up to 95% by application of spin polarization [3] and hence can be still considered as relatively clean. A detailed inclusion of these complex influences for the sake of completeness has recently been done for both reactions of type (1) and (2) using a detailed volume ignition model. Therefore, the problem of the secondary reaction, due to two different D-D nuclear reactions taking place at the same time in the D-^{3}He and D-T pellets [4,5], has been solved. The results of calculations for D-^{3}He show that the effect of secondary reactions cannot be ignored. Inclusion of the D-D reactions in the D-^{3}He pellet has an appreciable effect on the driver energy requirements for both ignition conditions and fusion gain.

Although the n/D-^{3}He ratio depends on volume and density, this ratio is small and nearly the same for different pellet volumes and pellet concentrations for conditions where pellet ignition occurs. The inclusion also increases the fusion gain and further reduces the reaction ratio [5]. One of the main advantages of the inclusion of the D-D reactions in the D-T pellet is that the exact ratio $R = \frac{DD}{DT}$ can be calculated. Since the fuel depletion and the reaction ratio is known, the true value of the neutron flux can be used in any DT reactor design. Before considering any approach for inclusions of other possible nuclear reactions in the D-T and D-^{3}He pellets, we point out here that laser engineering at Osaka University [7-9] demonstrated that the best fusion gains from laser-irradiated pellets result when central shocks are avoided and an ideal volume compression is achieved. The advantages of volume compression and volume ignition of laser-irradiated fusion pellets against spark ignition have been reviewed in the literature [10-12]. Thus, the experimental success of volume compression led us to use the simple original model of volume ignition [13] with possible improvement in the model for D-T and D-^{3}He fuel pellets fusion calculations.

Volume compression and ignition to clean fusion have been applied to the D-^{3}He reaction [4,10,11,14,15] and the D-T reaction [5,10-12,15], but the role and relative magnitude of all secondary reactions at the same time i.e. D-D and T-T in the D-T reaction, D-D and ^{3}He-^{3}He in the D-^{3}He reaction with heating by the fusion neutrons, have been ignored. After having studied the volume ignition of D-D fuel [16], with the inclusion of the D-D reactions in the D-^{3}He reaction [4] and the D-T reaction [5] with encouraging success, we are now able to carry out fusion gain calculations for D-^{3}He and D-T pellets with all the secondary reactions and the neutron heating included.

In our simulation, the effects of all charged reaction products from the D-T, D-D and T-T reactions and neutrons from the D-T reaction for D-T fuel pellet and from the D-^{3}He, D-D and ^{3}He-^{3}He reactions for D-^{3}He fuel pellet, fuel depletion and bremsstrahlung losses for both pellets have been included.

From our calculations, compared with (D-^{3}He)+(D-D) case [4], the inclusion of the (^{3}He-^{3}He)+(D-D) reactions in the D-^{3}He fuel pellet results in up to a 10% reduction in the input energy, and the increase in the fusion gain by about 10% maximum plasma temperature is also increased by about 2%.

Unlike the D-^{3}He case, the inclusion of the D-D and T-T reactions in the D-T fuel pellet with respect to different fusion parameters is not considerable, but taking together all reactions allows us to consider a fusion reactor operating with realistic parameters in the volume ignitions mode and then ignore the effect, if any, of the T-T reaction. Although our calculation for a D-T fuel pellet with neutron interaction included is in its preliminary stage, the first results show that the neutrons which are produced in a D-T plasma with energy 14.1 Mev can not be ignored in the volume ignition mode.

Adiabatic Volume Compression and Volume Ignition Calculations

The calculation of the nuclear fusion gain G from laser compressed D-T or D-^{3}He plasmas

$$G = \frac{\text{nuclear reaction energy}}{\text{input energy } E_o} \qquad (5)$$

is very sensitive to the parameters chosen as initial volume V_o, temperature T_o, and density n_o. Also of vital importance is the model chosen for the slowing down rate of the charged reaction products within the reacting plasma, causing reheat and eventually ignition and self-burning. A further parameter to be included is the radiation loss by bremsstrahlung and the depletion of the nuclear fuel by the reaction itself, while the expansion of the plasma, determined by inertial confinement and adiabatic cooling follows the hydrodynamic equations [13]. For the fusion gain calculation in this model [9-16], we consider a spherical plasma of volume V_o and radius R_o and an initial density n_o. By unspecified mechanisms, the plasma has been heated by a laser (or particle beam) of energy E_o to an initial temperature T_o. We calculate the fusion reaction energy during the subsequent expansion and adiabatic cooling.

If the energy produced per fusion reaction of one nucleus i with another nucleus j is E_{ij}, the very simplified gain, equation 4, is given by

$$G = \frac{E_{ij}}{E_o} \int_0^\infty dt \int_{R_0}^\infty d^3r \frac{n^2{}_i}{A} < \sigma v> \qquad (6)$$

where n_i is the ion density with a constant A= 4 for binary reactions (otherwise, A= 2). The velocity-averaged fusion cross section $<\sigma v>$ for a thermalized plasma of temperature T and an average mass m of the nuclei is given by

$$< \sigma v > = \frac{\sqrt{m}}{2[\pi\ (KT)^{3/2}]^{1/2}} \times \int^\infty \frac{m}{2} v^2\sigma(v) \exp\left(\frac{mv^2}{KT}\right) dv^2 \qquad (7)$$

Thus, from Eqs. (5) and (6), gains depending on the initial volume, density, and input energy can be calculated. Using Eq. (5) and including fuel depletion, bremsstrahlung loss, the reheating due to charged reaction products and the effect of secondary D-D reactions, the gain for D-^{3}He and D-T reactions [4,5] has been calculated previously for D-^{3}He and D-T pellets, but because of the complexity of the calculation, the effect of other side reactions has been neglected.

In the light of dramatic changes following the D-D reaction in the D-^{3}He gain efficiency predictions [4], we felt that it would be worthwhile to carry out fusion-gain calculations for D-^{3}He and D-T pellets using our recently extended code [4,5,15] to fully include all possible side reactions. Thus, in addition to the D-D reactions we included the ^{3}He-^{3}He reaction

$$^3He + {}^3He \rightarrow P + P + {}^4He + 12.86\ MeV \qquad (8)$$

in the (D-^{3}He) + (D-D) reactions and the T-T reaction

$$T + T \rightarrow n + n + {}^4He + 11.33\ MeV \qquad (9)$$

in the (D-T) + (D-D) reactions by the simultaneous calculation of Eq. (5) for the pellets.

In general our model algorithm includes all nuclear reactions, all direct temperature changing elements, the adiabatic cooling T_{ad} (due to the thermodynamic expansion process), the temperature change due to bremsstrahlung losses T_{br} and all charged reactions products reheating of all nuclear reactions, the α particle reheat T_α, the proton reheat T_p, the neutron reheat T_n and so on ($T_{cp} = T_\alpha + T_p + T_n + \ldots$). The change in temperature during a time interval of the simulated dynamics follows hence as

$$\Delta T = T_{cp} - T_{ad} - T_{br} \qquad (10)$$

and the initial temperature for the following time step is then essentially

$$T_{n+1} = T_n + \Delta T, \qquad T_0 = T_0(E_0) = \frac{E_0}{2n_0V_0K_B} \qquad (11)$$

This is a very interrelated and highly non-linear mathematical description. It can be stated in principle that the reheat contributions are always positive, they can never really interfere negatively and the added charged reactions products and neutrons reheat (reaction 7,8 and neutron from reaction 3) and are therefore not likely to significantly change the qualitative appearance of the process only its quantitative patterns.

As in our previous calculations [4,5,14-16] the same method [17] was used for reabsorption of the bremsstrahlung, and again the collective model for stopping power [13] was adopted in calculating reheat by the charged fusion products.

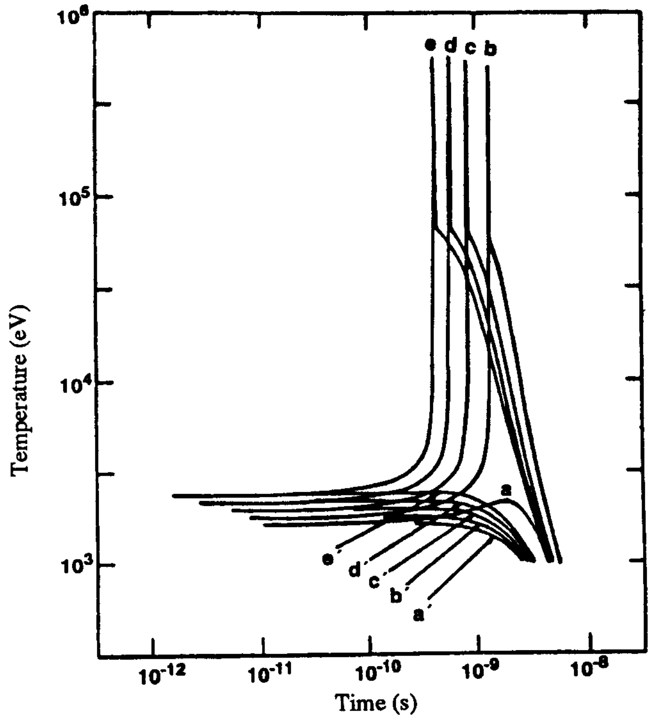
Results

In order to test the results with regard to our recent simulation, Figure 1 shows the time dependence of the plasma temperature T for the case of an initial density of 3×10^3 times the solid state density, $n_s = 5.8\times10^{22}$ cm^3, and an initial volume of 10^{-1} cm^3. Five cases are given in Figure 1 where the input laser energy is 172.3, 189.0, 207.3, 227.4 and 249.5 GJ respectively. The plasma temperature dependence of the D-^{3} He and D-^{3} He + D - D reactions is not the same. For cases with the D-^{3} He reaction alone, the fuel does not ignite. The exact values of the input parameters and the results of calculations of gains, maximum plasma temperatures, and fuel depletions of the D-^{3} He and the D-^{3} He + D-D reactions are given in the figure captions.

In contrast to the D-^{3} He fusion reaction our application of volume compression and ignition to the D-T pellet including the D-D reactions shows that the effect of the inclusion of the D-D reactions on the fusion gain is so small that it will have no appreciable effect in any fusion reactor. However, the inclusion of the secondary reactions in the calculation enables us to calculate the n/D-^{3} He and n/D-T neutron to reaction ratio, and therefore true neutron flux, which is an important factor in any reactor design. The ratio not only has an input energy dependence but also has a pellet volume and density dependence.

An example of our computations of fusion gain and the time dependence of the plasma temperature for a D-^{3} He fuel pellet with an initial density of 4×10^3 times the solid state density n_s is shown in Figure 2. Figure 3 shows the result of similar computations for a D-T fuel with an initial density of 5×10^3 n_s and initial volume of 10^{-1} cm^3.

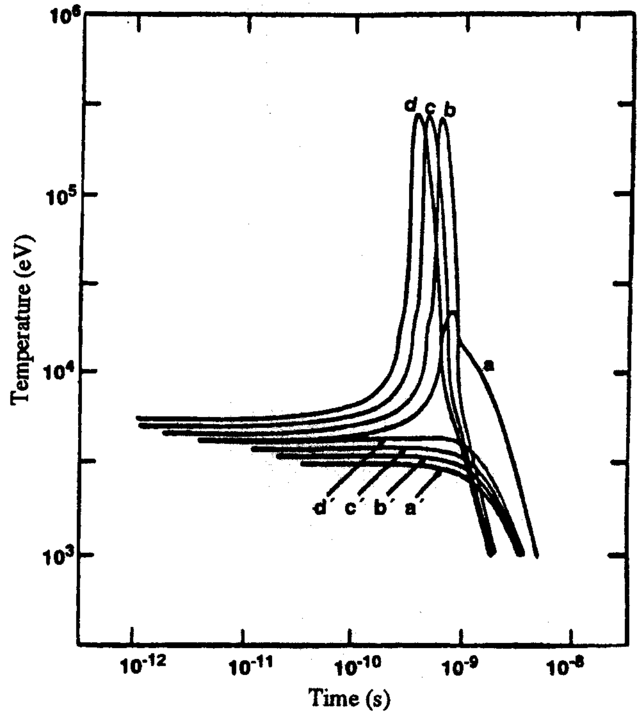
From Figure 2, the inclusion of the D-D reaction in the D-^{3}He also has an appreciable effect on the plasma temperature and fusion gain, but the inclusion of the ^{3}He-^{3}He reaction as well, has a small effect on the fusion parameters. The exact values of the input parameters and



Input Energy Eo (GJ)	Initial Temperature (KeV)	Curve[*]	Fusion Gain G	Fuel Depletion (%)	Maximum Plasma Temperature (KeV)
172.3	1.650	a	0.414	0.265	2.137
		á	0.003	0.0002	1.640
189.0	1.810	b	1167	94.0	512.3
		b′	0.007	0.0005	1.890
207.3	1.98	c	1077	95.0	534.1
		c′	0.013	0.0011	1.987
227.4	2.178	d	986.3	95.4	557.2
		d′	0.026	0.0023	2.184
249.5	2.389	e	898.1	95.5	545.6
		é	0.051	0.0050	2.412

[*] Curves without primes indicate calculations with the D-D reactions included; curves with primes indicate calculations without the D-D reactions included

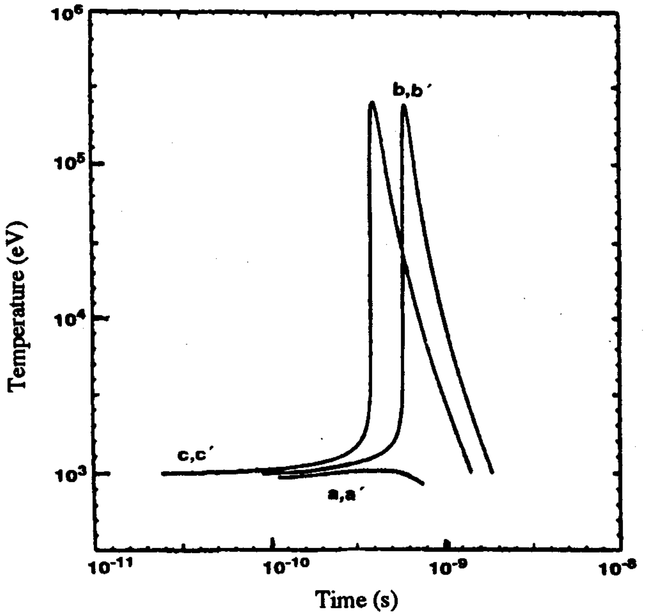
Figure 1. Dependence of the temperature of a D-^{3}He pellet on time at initial compression of 3×10^3 times the solid state density and an initial volume of 10^{-1} cm^3



Input Energy Eo (GJ)	Initial Temperature (KeV)	Curve[a]	Fusion Gain G	Fuel Depletion (%)	Maximum Plasma Temperature (KeV)
42.97	3.087	*	2.05	0.856	22.96
		a	1.16	0.709	22.35
		á	0.02	0.003	3.094
47.14	3.386	*	347.4	80.3	275.1
		b	512.1	78.1	270.6
		b′	0.045	0.006	3.408
51.71	3.715	*	493.9	80.9	279.6
		c	472.7	79.2	276.3
		c′	0.083	0.012	3.779
56.72	4.075	*	464.2	82.1	283.8
		d	433.0	79.5	279.5
		d′	0.167	0.028	4.272

[a] Curves without primes indicate calculations with the D-D reactions included; curves with primes indicate calculations without the D-D reactions included. Values with* indicate calculation with (D-D)+(^{3}He-^{3}He) reactions included

Figure 2. Dependence of the temperature of a D-^{3}He pellet on time at initial compression of 3x10^3 times the solid state density and an initial volume of 10^{-1} cm^3



Input Energy Eo (GJ)	Initial Temperature (KeV)	Curve*	Fusion Gain G	Fuel Depletion (%)	Maximum Plasma Temperature (KeV)
127.1	0.913	a	1.81	0.057	1.044
		á	1.75	0.055	1.039
131.9	0.947	b	2504.0	83.28	245.1
		b′	2559.0	82.89	239.2
139.9	0.983	c	2471.0	85.37	255.9
		c′	2537.0	85.25	250.7

*Curves without primes indicate calculations with the (D-D) + (T-T) reactions included; curves with primes indicate calculations with only D-D reactions included.

Figure 3. Dependence of the temperature of a D-T pellet on time at initial compression of 5×10^3 times the solid state density and an initial volume of 10^{-1} cm^3

the results of calculations of different parameters of the D-^{3}He, D-^{3}He + D-D and D-^{3}He + D-D + ^{3}He-^{3}He are also given in the figure captions.

Figure 3 shows the results of the same computations, as in Figure 2, for the D-T pellet. This figure shows that the effect of the D-D + T-T reactions included in the D-T pellet and the D-D reactions included in the D-T pellet is the same and so small that we can ignore all side reactions in the calculation. But a preliminary calculation of different fusion parameters for the case of inclusion of the fusion neutrons of the D-T pellet indicates that the reheating of the neutrons should not be ignored.

A detailed inclusion of these complex influences is on its way, and work on this topic in general is in progress at Urumia University.

Conclusion

The effects of the side reactions due to different nuclear reactions taking place at the same time in a D-^{3}He and in a D-T pellet are now known. The results of our calculation for the D-^{3}He pellet show that the inclusion of the ^{3}He-^{3}He reaction in the D-^{3}He + D-D reactions reduces the input energy E_0 up to 10% and increases fusion gain and maximum plasma temperature up to 10% and 2% respectively. Our calculations show that there is no distinguishable difference between gains with and without the inclusion of the D-D and D-D + T-T reactions in the D-T pellet. This is because a small amount of fusion energy is carried out by the charged reactions products. Our preliminary results show that the effects of the fusion neutrons interaction with the D-T plasma in the D-T reaction should be taken into account.

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