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Thermonuclear burn of DT and DD fuels using three-temperature model: Non-equilibrium effects

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Abstract

Conditions for thermonuclear ignition are determined by three parameters: fuel density, temperature and hot-spot size. A simple three temperature model is developed to calculate the critical burn-up parameter or the minimum ρR product. Extensive results obtained are compared with earlier one temperature model for DT and DD fuels. While the two approaches are found to provide similar results for DT fuel except at low temperature regime (~10 keV), three temperature modeling is found to be necessary for DD fuel. This is argued to be due to the lower fusion reactivity and energy production in DD reactions.

Keywords: Bremsstrahlung radiation; Compton-scattering; Critical burn-up parameter; Fusion reactivity; Thermonuclear burn-up; Three-temperature model

1. INTRODUCTION

Compressed deuterium-tritium (DT) fuel is of interest in inertial confinement fusion schemes as thermonuclear (TN) ignition occurs at temperatures about 4 to 5 keV. There are two approaches to establish TN burn, viz., volume ignition and hot-spot ignition. In the former scheme, the entire fuel pellet is heated and ignition occurs over the whole mass. In the second scheme, a central hot-spot is heated to ignition conditions and a TN burn wave propagates to the outer fuel (Brueckner & Jorna, 1974; Kidder, 1976). This concept is more attractive as it leads to higher energy gains (Brueckner & Jorna, 1974; Fraley *et al.*, 1974; Gus'kov *et al.*, 1976; Kidder, 1976, 1979; Meyer-ter-vehn, 1982; Tahir & Long, 1983) as only the hot-spot has to be ignited. However, it requires that energy released in the burn zone exceeds losses via heat conduction and radiation. Critical burn-up parameter or minimum areal density — defined as product of initial fuel density and minimum hot-spot radius — is generally used to characterize TN burn in various fuels.

The first estimates of TN burn parameters in DT target was obtained using self-similar solutions (Brueckner & Jorna, 1974; Gus'kov *et al.*, 1976). More detailed calculations done later (Fraley *et al.*, 1974; Kidder, 1976) to determine the hot-spot parameters, have established (Basko, 1990) that ignition of pure DD fuel is much more difficult than DT fuel. Recently, Frolov *et al.* (2002) calculated the critical burn-up parameter in isochoric DT, DD and deuterides of some light elements using a simple burn model (Avrorin *et al.*, 1980; Frolov, 1998; Frolov *et al.*, 2002), which assumed same temperature (1-T) for ions, electrons and radiation.

Aim of the present paper is to extend Frolov's approach to include a three temperature (3-T) description (Atzeni, 1986; Tahir *et al.*, 1986). In addition, accurate calculations of fusion reactivity, inclusion of Compton scattering and black-body radiative losses are also accounted. While the 3-T scheme is less important in determining the critical burn-up parameter for DT, except for low temperatures, it plays a crucial role for DD fuel.

The paper is organized as follows. In Section 2, we recall the fusion reactions of DT and DD fuels. Section 3 describes 3-T burn model. A brief description of 1-T model is given in Section 4. Results of 3-T burn model are discussed in Section 5 and the paper is concluded in Section 6.

2. FUSION REACTIONS

Though there are a number of fusion reactions of interest, DD and DT reactions are the most important (Duderstadt & Moses, 1982). DD reaction takes places via two channels with equal probability:

$$_1\mathrm{D}^2 + {}_1\mathrm{D}^2 \rightarrow {}_1T^3 + {}_1p^1 + 4.03\ \mathrm{MeV},$$

$$_1\mathrm{D}^2 + {}_1\mathrm{D}^2 \rightarrow {}_2\mathrm{He}^3 + {}_0n^1 + 3.27\ \mathrm{MeV}.$$

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The tritium ($_1T^3$) produced in p-channel or obtained by external sources, can react with D at a much faster rate in the following manner:

$$_1D^2 + _1T^3 \rightarrow _2He^4 + _0n^1 + 17.6\ \text{MeV}.$$

Due to the large cross-section at relatively lower temperature range, it is taken as the scheme of choice for all inertial confinement fusion (ICF) research. The rate of energy release (MJ/vol./s) for reactions of different species is

$$q_0 = n_1\, n_2\, \langle \sigma v \rangle\, Q, \tag{1}$$

where Q is the energy released in a reaction. Here, $\langle \sigma v \rangle$ is fusion reactivity defined as the probability of reaction per unit time per unit density of target nuclei (cm^3/s). Among the three reactions, Q is largest (17.6 MeV) for DT.

3. THREE TEMPERATURE MODEL

For efficient burning, the net energy produced in the hot-spot should be positive, i.e., the energy produced within the hot-spot should exceed all possible energy losses. Energy loss inside the hot-spot is due to electron-ion collisons, Compton-scattering, bremsstrahlung radiation, and radiative loss. If net energy generation rate within the hot-spot is negative then the burn wave will die out. For DT fuel at solid density (0.23 g/cc), energy balance occurs around 4 keV. At higher densities requirement of ignition temperature comes down. For DD fuel, minimum ignition temperature is about 30–40 keV. Our aim is to determine the minimum hot-spot size for a specified initial temperature and density. We have evaluated the burn-up parameter for both DT and DD reactions in the temperature range 4–50 keV.

We consider the 3-T description of the plasma, i.e., with different ion, electron, and radiation temperatures. The initial spherical hot-spot has radius r_0 and volume V_0. Its other parameters are initial temperature T_0 and density ρ_0. The total internal energy of ions in the hot-spot at time t is:

$$E_i = \rho_0 V\, C_{Vi} T_i, \tag{2}$$

where C_{Vi} is the ionic specific heat, T_i is the ion temperature, and V is the volume at time t. Rate of change of E_i can be expressed as

$$\frac{dE_i}{dt} = V\tilde{q}_i(r, T_i, T_e), \tag{3}$$

where $\tilde{q}_i$ is the net energy production rate of ions in unit volume. It depends on hot-spot radius r at time t, ion temperature T_i and electron temperature T_e. The classical values of specific heats of ions and electrons are

$$C_{Vi} = \frac{3}{2}\frac{k_B}{\bar{m}_i}\ ,\ C_{Ve} = \frac{3}{2}\frac{\bar{Z}k_B}{\bar{m}_i}, \tag{4}$$

where k_B is the Boltzmann's constant, $\bar{m}_i$ is the average ion mass, and $\bar{Z}$ is the average atomic number. It is assumed that the plasma is fully ionized and electron degeneracy is unimpotant at temperatures of interest in ignition conditions. Expressions for $\tilde{q}_i$ will be discussed below. Using Eq. (2) and $V = \frac{4}{3}\pi r^3$, Eq. (3) reduces to

$$C_{Vi}\frac{dT_i}{dt} = -C_{Vi}\frac{3}{r}\frac{dr}{dt}T_i + \frac{1}{\rho_0}\tilde{q}_i(r, T_i, T_e). \tag{5}$$

This equation specifies the evolution of ion temperature in the hot-spot. It is assumed that T_i is spatially uniform in the hot-spot. In terms of the burn-up parameter $x = \rho_0 r$, Eq. (5) is expressed as

$$\frac{dT_i}{dx} = -\frac{3}{x}T_i + \frac{q_i(x, T_i, T_e)}{C_{Vi}\, U_{max}}. \tag{6}$$

Here we have introduced the hot-spot expansion speed U_{max} and $q_i(x, T_i, T_e) \equiv \tilde{q}_i(r, T_i, T_e)/\rho_0^2$. Expressions for U_{max} are discussed below. Eq. (6) is a simple generalization of 1-T model (Avrorin *et al.*, 1980; Frolov *et al.*, 2002) to include electron temperature, which could be different from ion temperature. In non-equilibrium burning conditions, the hot-spot has to be characterized using three temperatures, viz., T_i, T_e, and T_r. The evolution equation for T_e is given by

$$\frac{dT_e}{dx} = -\frac{3}{x}T_e + \frac{q_e(x, T_i, T_e, T_r)}{C_{Ve}\, U_{max}}. \tag{7}$$

Here, $q_e\ (x,T_i,T_e,T_r)$ denotes the net energy production rate for electrons and depends on temperatures of all three species. Assuming Stefan-Boltzmann law for specific radiation energy, $E_r = (1/\rho_0)(4\sigma_B/c)T_r^4$, where c is the speed of light and σ_B is the Stefan's constant, the evolution equation for T_r is

$$\frac{dT_r}{dx} = -\frac{3}{4x}T_r + \frac{q_r(x, T_e, T_r)}{C_{Vr}\, U_{max}}. \tag{8}$$

The radiation specific heat is given by

$$C_{Vr} = \frac{1}{\rho_0}\frac{16\sigma_B}{c}T_r^3. \tag{9}$$

Eqs. (6), (7), and (8) specify the variations of temperatures with respect to the parameter x, and hence the radius of the hot-spot r at time t. Initial values (initial conditions) of temperatures (T_{i0}, T_{e0}, T_{r0}) at x_0 are used to integrate the ordinary differential equations (ODEs). For given values of ρ_0 and T_0, the initial point x_0 can be determined such that T_i, T_e, and T_r are positive for all x in the interval $x_0 \le x \le x_1$, where $x_1 = \rho_0\, r_1$ corresponds to the outer radius of the pellet. The minimum value of x_0 needed is called the critical burn-up parameter x_c. Thus for $x_0 > x_c$, the entire fuel will burn while for $x_0 < x_c$ the burn will be extinguished leaving unburnt fuel. We have considered x_1 much larger than x_0 so that the results

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are independent of x_1. Solutions of the ODEs can also be obtained by choosing a specified value of x_0 but then treating the initial conditions T_{i0}, T_{e0}, and T_{r0} as variable parameters. The net energy production rates q_i, q_e, and q_r are considered now.

3.1. Net Energy Release Rates

3.1.1. Ions

Net energy release rate for ions is given by

$$q_i(x, T_i, T_e) = S_i - A_{ie}(T_i - T_e), \qquad (10)$$

where S_i denotes the energy deposition rate to ions. For example, S_i for DT reaction is

$$S_{i-\mathrm{DT}} = n_{\mathrm{D}}\ n_T\ \langle\sigma v\rangle_{\mathrm{DT}}(f_{ion} + 4g_n)\ \frac{Q_\alpha}{\rho_0^2}, \qquad (11)$$

where n_{D} and n_T are the number of ${}_1\mathrm{D}^2$ and ${}_1T^3$ nuclei per cm^3 and $Q_\alpha = 3.5$ MeV is the energy of the α-particle. $\langle\sigma v\rangle_{\mathrm{DT}}$ is the fusion reactivity discussed earlier. As the range of α-particle is much smaller than the hot-spot size, all its energy is assumed to be deposited within the hot-spot. However, a part (f_{ion}) of its energy goes to ions and the remaining to electrons. An empirical fit to this fraction is $f_{ion} = (1 + 32/T_e)^{-1}$, which shows that electrons and ions share energy equally at $T_e = 32$ keV (Fraley *et al.*, 1974). For very high density about $\rho_0 = 10^4$ g/cc, equal sharing occurs at $T_e = 24$ keV. Detailed calculations to determine leakage of α-particle energy from the hot-spot are also available (Atzeni, 1995). g_n is the fraction of neutron energy deposited in the hot-spot. Remaining fraction leaks out of the pellet. An empirical fit to g_n is $g_n = x/(x + h_n)$ with $h_n = 20\ \mathrm{g/cm^2}$ (Atzeni, 1995). The factor 4 in Eq. (11) arises because $4Q_\alpha = 14$ MeV is approximately the energy of neutron in DT reaction.

For DD reaction, S_i is given by (Basko, 1990; Frolov *et al.*, 2002)

$$S_{i-\mathrm{DD}} = \frac{n_{\mathrm{D}}^2}{4}\ \langle\sigma v\rangle_{\mathrm{DD}}\ \frac{Q_{\mathrm{DD}}}{\rho_0^2}. \qquad (12)$$

Assuming that ${}_1T^3$ produced via the proton channel of DD reaction will certainly react with another ${}_1\mathrm{D}^2$ nuclei, Q_{DD} can be computed as

$$Q_{\mathrm{DD}} = [2.45g_{n2} + 14.1g_n + (3.02 + 1.01 + 3.5)\, f_{ion}] + 0.82. \qquad (13)$$

Here $g_{n2} = x/(x + 5.2)$ is the fraction of neutron energy deposited in the hot-spot from DD_n channel. The factor 14.1 g_n features total neutron energy from DT reaction. The remaining numbers (0.82, 3.02, 1.01, and 3.5) denote energy deposited by ${}_2\mathrm{He}^3$, proton, ${}_1T^3$ and α-particle, respectively. The heavier charged particle ${}_2\mathrm{He}^3$ delivers all its energy (0.82 MeV) to the ion component. This estimate of Q_{DD} is adequate because the reactivity $\langle\sigma v\rangle_{\mathrm{DD}}$ is much smaller than $\langle\sigma v\rangle_{\mathrm{DT}}$ so that DT reaction can be assumed to follow a DD reaction. However, the possibility of $\mathrm{D_2\ He^3}$ reaction is neglected as its reaction rate is much smaller than that for DD fusion.

The second term in Eq. (10) accounts for energy loss from ions due to ion-electron collisions. $A_{ie} = C_{Ve} \times \nu_{eq}$ where ν_{eq} is the collision frequency of ions with electrons. When $T_i = T_e$, net energy transfer by collisions is zero. The collision frequency is given by (Fraley *et al.*, 1974; Spitzer, 1962):

$$\nu_{eq} = \frac{8\sqrt{2\pi}}{3}\ \sqrt{m_e}\ e^4 N_A^2\ \frac{\bar{Z}^2}{\bar{A}^2}\, ln(\Lambda_{ei})\ \frac{\rho_0}{(k_B T_e)^{3/2}} \times \left(1 - \frac{3}{2}\,\frac{T_i}{T_e}\,\frac{m_e}{\bar{m}_i}\right), \qquad (14)$$

where m_e is the electron mass, e its charge, N_A Avgadro's number and $\bar{Z}$ and $\bar{A}$ are the average atomic number and mass number, respectively. The Coulomb logarithm $ln(\Lambda_{ei})$ is obtained using (Spitzer, 1962)

$$ln\Lambda_{ei} = max\left[1,\ \frac{3}{2e^3}\left(\frac{\bar{A}k_B^3}{\bar{Z}\pi N_A \rho_0}\right)^{1/2} T_e^{3/2} \times \left[\bar{Z} + \frac{1}{2\alpha_F}\left(\frac{3k_B T_e}{m_e c^2}\right)^{1/2}\right]^{-1}\right], \qquad (15)$$

where α_F is the fine structure constant.

The number densities n_{D} and n_T in Eqs. (11) and (12) are determined using the rate equations (Martinez-Val *et al.*, 1998)

$$\frac{dn_{\mathrm{D}}}{dt} = -n_D\ n_T\langle\sigma v\rangle_{\mathrm{DT}} - \frac{n_{\mathrm{D}}^2}{2}\langle\sigma v\rangle_{\mathrm{DD}}, \qquad (16)$$

$$\frac{dn_T}{dt} = -n_{\mathrm{D}}\ n_T\langle\sigma v\rangle_{\mathrm{DT}} + \frac{n_D^2}{4}\langle\sigma v\rangle_{\mathrm{DD}}, \qquad (17)$$

and substituting $\rho_0 U_{max}\ dt = dx$. These rate equations take into account the removal of ${}_1\mathrm{D}^2$ and ${}_1T^3$ via DT and DD reactions as well as the production of ${}_1T^3$ in the proton channel of DD reaction.

As the present problem is concerned with propagating burn front, number densities in Eqs. (11) and (12) at the front are assumed to be $n_{\mathrm{D}0}$ and n_{T0}.

3.1.2. Electrons

Apart from energy delivered to electrons directly by charged particles, electron-ion and electron-radiation exchanges also alter electron temperature. Therefore q_e can be written as

$$q_e(x, T_i, T_e, T_r) = S_e + A_{ie}(T_i - T_e) - (A_{er} + A_c)(T_e - T_r). \qquad (18)$$

Here S_e, the direct contribution from charged particles, is

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given by

$$S_{e-\mathrm{DT}} = n_{\mathrm{D}}\, n_T\, \frac{Q_\alpha}{\rho_0^2}\, \langle\sigma v\rangle_{\mathrm{DT}}(1 - f_{ion}), \tag{19}$$

$$S_{e-\mathrm{DD}} = \frac{n_{\mathrm{D}}^2}{4}\, \frac{Q_C}{\rho_0^2}\, \langle\sigma v\rangle_{\mathrm{DD}}(1 - f_{ion}), \tag{20}$$

where $Q_C = (3.02 + 1.01 + 3.5)$ MeV. The factor A_{er}, which determines energy exchange between electrons and radiation via bremsstrahlung, is (Duderstadt & Moses, 1982)

$$A_{er} = 2\left[\frac{2^5}{3}\frac{N_{ion}^2 \bar{Z}^3 e^6 \rho_0}{h m_e c^3}\right]\left(\frac{2\pi k_B}{m_e T_e}\right)^{1/2}, \tag{21}$$

where N_{ion} is the total number of ions per cm^3. Apart from bremsstralung radiation, electrons can transfer energy to radiation by inverse Compton-scattering. The factor A_c in Eq. (18) is given by (Eliezer *et al.*, 2000):

$$A_c = \frac{128}{3}\frac{\pi}{m_e c^2}\sigma_B N_e r_c^2 T_r^4, \tag{22}$$

where N_e and r_c stand for number of electrons per cm^3 and classical radius of electron respectively. σ_B is the Stefan's constant. The unit of the factors A_{ie}, A_{er}, and A_c is MJ/cm^3 s keV.

3.1.3. Radiation

The net rate of energy gain by the radiation component is (Gsponer & Hurni, 1999)

$$q_r(x, T_e, T_r) = (A_{er} + A_c)(T_e - T_r) - \frac{3\sigma_B T_r^4}{\rho_0\, x}. \tag{23}$$

The first two terms denote net photon energy gain via bremsstrahlung processes and Compton-scattering. The last term accounts for radiative loss from surface of the hot-spot, which may be modeled as a black-body (Gsponer & Hurni, 1999). Now we will discuss the speed of expansion of the hot-spot.

3.2. Expansion Speed U_{max}

Specification of the burn model is completed by defining the expansion speed of the hot-spot. The time coordinate of the hot-spot front was converted to its radius or equivalently x, by introducing U_{max}. Depending upon initial temperature, density and radius of hot-spot, the burn-front will propagate either as thermal wave or detonation wave. Thermonuclear burn wave can be compared to chemical detonation wave as the energy liberated in the reaction is used to sustain the propagating wave. However, electron thermal conduction and energy deposition by fusion products (e.g., α-particle) also sustain the wave. The wave speed is determined first by detonation and then by α-particles and electrons when temperature is increased at a specific density (Avrorin *et al.*, 1980). Following Frolov *et al.* (1998, 2002), it is assumed that $U_{max} = max\,(U_{\mathrm{D}}, U_T)$ where U_{D} is detonation wave speed and U_T refers to the thermal wave speed. Assuming the hot-spot plasma to be ideal, U_{D} can be expressed as (Zel'dovich Raizer, 1966)

$$U_{\mathrm{D}}(T_i) = \left[\frac{(\gamma+1)^2(\gamma-1)}{(3\gamma-1)} C_{Vi}\right]^{1/2}\sqrt{T_i}, \tag{24}$$

where $\gamma = 5/3$ is the specific heat ratio of mono atomic ideal gas. For DT and DD reactions, this reduces to $U_{\mathrm{D}}^{\mathrm{DT}} = 3.7 \times 10^{-2}\sqrt{T_i}$ cm/ns and $U_{\mathrm{D}}^{\mathrm{DD}} = 4.1 \times 10^{-2}\sqrt{T_i}$ cm/ns, respectively.

Electrons carry energy from the hot-spot to its surrounding, thus giving rise to an expanding thermal wave. Speed of the thermal wave is given by (Avrorin *et al.*, 1980)

$$U_T(x, T_e) = 2.39\, \frac{k(T_e)}{C_{Ve}\, x}, \tag{25}$$

where the thermal conductivity $k(T_e)$ of the plasma, modeled as a Lorentz gas, is given by

$$k(T_e) = \frac{0.013}{(1 + 0.29\, \bar{Z})}\frac{T_e^{5/2}}{ln(\Lambda_{ei})}. \tag{26}$$

U_{D} and U_T are compared in Figure 1 for DT mixture at $x = 0.1\ \mathrm{g/cm^2}$ for two initial densities $\rho_0 = 1$ and $\rho_0 = 10^4$ g/cc. It is clear that U_T crosses over U_D between 5 to 10 keV.

3.3. Determination of (x_c)

To understand the dependence of the hot-spot temperature profile, i.e., T_i *Vs*. x, the ODEs were integrated for DT fuel for the initial parameters: $\rho_0 = 10$ g/cc and $T_0 = 10$ keV. Three initial values of $x_i = \rho_0 r_0$, viz., 0.37, 0.38, and 0.39 $\mathrm{g/cm^2}$ give the profiles of T_i Vs. x shown in Figure 2. It is clear that if $x_i \leq 0.37\ \mathrm{g/cm^2}$, the burn will be terminated by the time it reaches about $0.9\ \mathrm{g/cm^2}$. However, $T_i(x)$ diverges around $x = 0.8\ \mathrm{g/cm^2}$ for the initial value $x_i = 0.39\ \mathrm{g/cm^2}$. Thus, within the assumptions of the model, the critical value x_c lies between 0.37 and 0.39 $\mathrm{g/cm^2}$.

4. SINGLE TEMPERATURE MODEL

The main assumption here (Avrorin *et al.*, 1980; Frolov, 1998; Frolov *et al.*, 2002) is that the hot-spot is characterized by a single temperature *T*. The effective specific heat of plasma is then given by

$$C_V = \frac{3}{2}\frac{k_B}{\bar{m}_i}(1 + \bar{Z}). \tag{27}$$

The evolution equation for T then becomes (Avrorin *et al.*,

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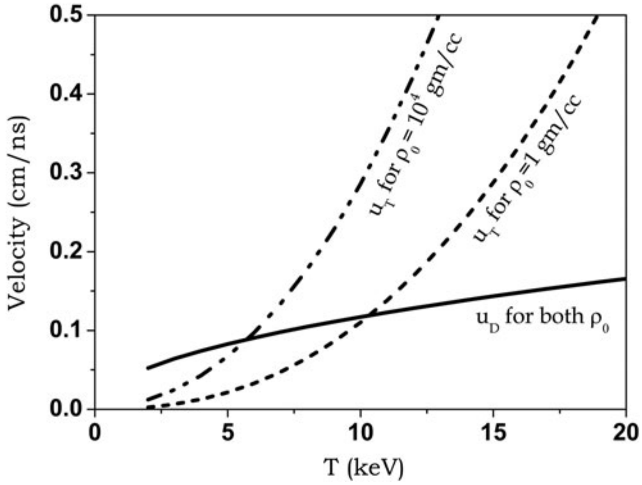

Fig. 1. Detonation speed (U_D) and thermal wave speed (U_T) for DT ($x = 0.1$ g/cm^2).

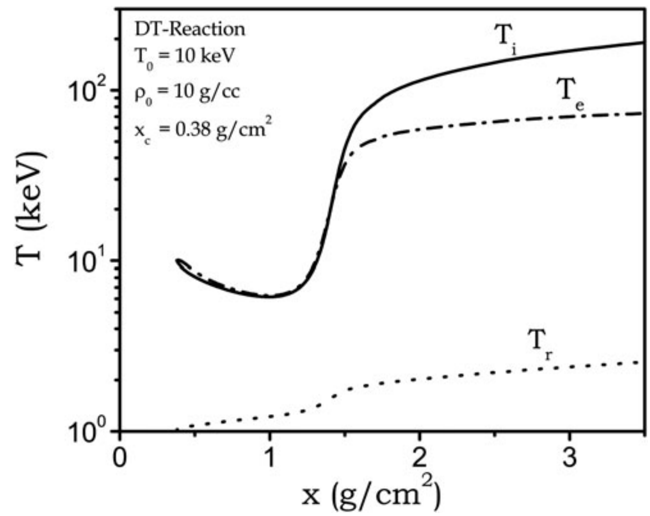

Fig. 3. Ion, electron and radiation temperature profiles for DT fuel at $x_c = 0.38$ g/cm^2.

1980; Frolov *et al.*, 2002)

$$\frac{dT}{dx} = -\frac{3}{x}T + \frac{q(x, T)}{C_V\, U_{max}}. \tag{28}$$

The net energy production rate in the hot-spot, $q(x, T)$, can be expressed as

$$q(x, T) = S - q_L. \tag{29}$$

The production rate S is same as that in Eqs. (11) and (12) for DT and DD reactions. However, $f_{ion} = 1$ as the model does not discriminate between energy deposition to ions and electrons. The energy loss rate q_L is given by Avrorin (Avrorin *et al.*, 1980).

5. RESULTS

Extensive calculations were done by numerically integrating the temperature evolution equations using 3-T models for DT and DD fuels. It is well known that modeling the plasma as a three-component fluid (ions, electrons, and radiation) is necessary to describe non-equilibrium effects, if any. Evolution of T_i, T_e, and T_r with the burn-up parameter, x, is shown in Figure 3 for DT fuel at $T_0 = 10$ keV and $\rho_0 = 10$ g/cc. With these parameters, $x_c = 0.38$ g/cm^2. The initial value T_{r0}, which is not a sensitive parameter, is taken as 1 keV. Temperature profiles of all three species alter due to various production and losses processes and finally attain almost steady values at the burn front. Variation of x_c with starting temperature (T_0) of hot-spot is shown in Figure 4 for $\rho_0 = 10$ g/cc. Results of the 1-T model are also shown

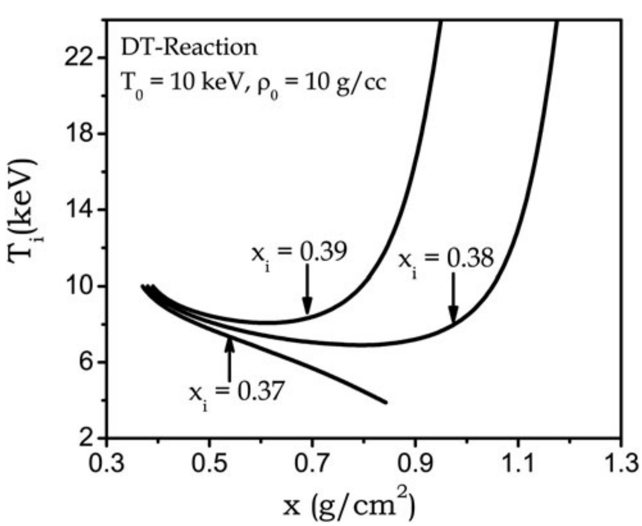

Fig. 2. Determining x_c for DT fuel from $T_i(x)$ curves.

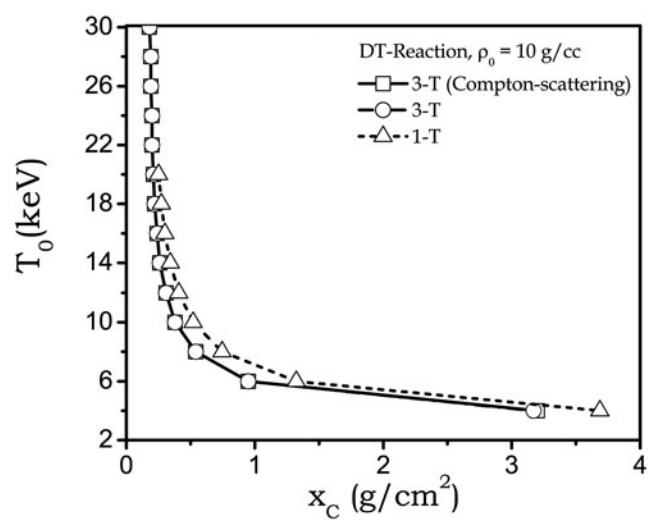

Fig. 4. Comparison of x_c values from 3-T and 1-T models (Frolov *et al.*, 2002) for DT fuel.

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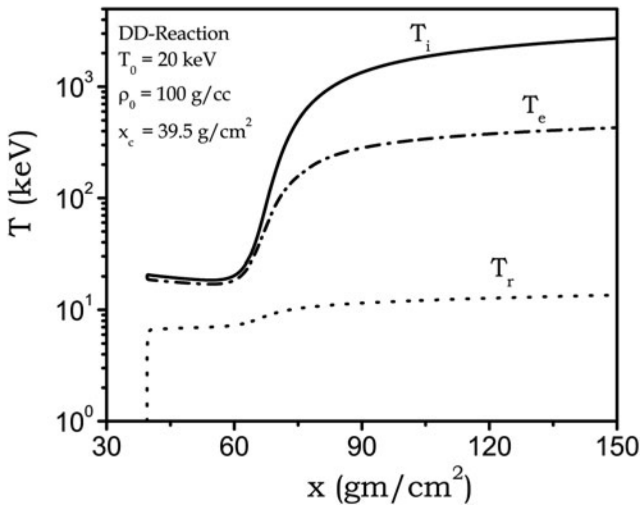

Fig. 5. Ion, electron and radiation temperature profiles for DD fuel at $x_c = 39.5\ \mathrm{g/cm^2}$.

for comparison. For temperatures up to 10 keV, x_c values are higher for 1-T model. However, the resulst are almost same for both models at higer T_0. The main reason for this is the fast equlibration of temperatures of all species behind the front. This figure also compares the effect of including Compton-scattering. Differences in x_c due to the inclusion of this effect are negligible as it becomes important only after about 60 keV for DT fuel (Gsponer & Hurni, 1999).

Evolution of temperatures vs. x are shown in Figure 5 for DD at $\rho_0 = 10^2$ g/cc. Variation of x_c with T_0 is given in Figure 6 at the same density. These results for DD fuel are without the inclusion of Compton-scattering. Addition of this mode of energy exchange, within the present model, does not lead to sustained burning. We find that the main reason for this is the lower rate of energy production in DD fusion. In fact, burn propagation does occur if fusion reactivity is just about doubled.

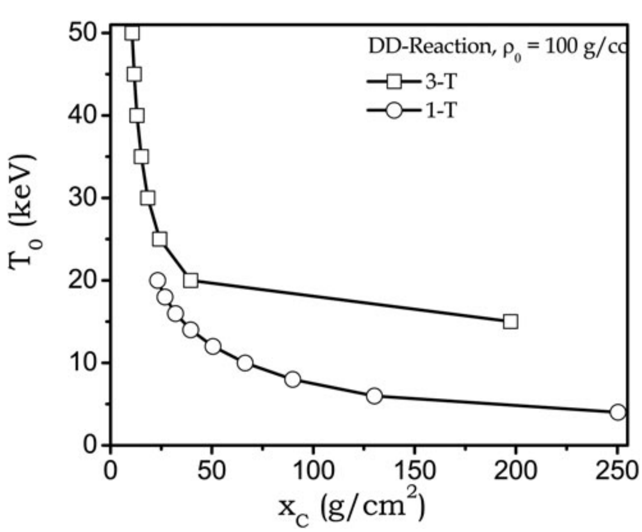

Fig. 6. Comparison of x_c values from 3-T and 1-T models (Frolov *et al.*, 2002) for DD fuel.

CONCLUSION

In this paper we have developed a three temperature model (ions, electrons, and radiation) for describing propagation of thermonuclear burn in DT and DD fuels. Extensive numerical results were obtained and compared with results of 1-T model. Compton scattering was not found to be important in determining the critical burn-up parameter in DT fuel. However, the models we have employed here for various processes showed that propagating burn wave is not possible in DD fuel with Compton-scattering.

One of our main conclusions is that 3-T modeling has a role in determining the critical burn-up parameter for DT fuel at low temperatures. However, at higher temperatures, the 1-T description provides good estimates of this parameter. This finding does not imply that all the three components of the fluid are in equilibrium at the burn front. Burn propagation in DD fuel needs 3-T description because effects like Compton scattering can not be included otherwise.

Several aspects like inclusion of electron conduction, better modeling of Compton scattering and radiation loss are currently under study and new results will be reported separately.

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REFERENCES

Atzeni, S. (1986). 2-D Lagrangian studies of symmetry and stability of laser fusion targets. *Comp. Phys. Commn.* **43**, 107–124.

Atzeni, S. (1995). Themonuclear burn performance of volume-ignited and centrally ignited bare deuterium-tritium microspheres. *Jpn. J. Appl. Phys.* **34**, 1980–1992.

Avrorin, E.N., Feoktistov, L.P. & Shibarshov, L.I. (1980). Ignition criterion for pulsed fusion targets. *Sov. J. Plasma Phys.* **6**, 527–531.

Basko, M.M. (1990). Spark and volume ignition of DT and D_2 microspheres. *Nuclear Fusion* **30**, 2443–2452.

Brueckner, K.A. & Jorna, S. (1974). Laser-driven fusion. *Rev. Mod. Phys.* **46**, 325–367.

Duderstadt, J.J. & Moses, G.A. (1982). *Inertial Confinement Fusion*. Wiley-Interscience Publication.

Eliezer, S., Henis, Z., Martinez-Val, J. & Vorobeichik, I. (2000). Effects of different nuclear reactions on internal tritium breeding in deuterium fusion. *Nucl. Fusion* **40**, 195–207.

Fraley, G.S., Linnebur, E.J., Mason, R. & Morse, R.L. (1974). Thermonuclear burn chracteristics of compressed deuterium-tritium microsperes. *Phys. of Fluids* **17**, 474–489.

Frolov, A.M. (1998). The thermonuclear burn-up in deuterium-tritium mixtures and hydrides of light elements. *Plasma Phys. Control. Fusion* **40**, 1417–1428.

Frolov, A.M., Smith Jr., V.H. & Smith, G.T. (2002). Deuterides of light elements: low-temperature thermonuclear burn-up and applications to thermonuclear fusion problems High-energy ions produced in explosions of superheated atomic cluster. *Can. J. Physics* **80**, 43–64.

Gsponer, A. & Hurni, J.P. (1999). Comment on "Deuterium-tritium fusion reactors without external fusion breeding" by S. Eliezer et al. *Physics Letters A* **253**, 119–121.

Gus'kov, S.Y., Krokhin, O.N. & Rozanov, V.B. (1976). Similarity solution of thermonuclear burn wave with electron and α-conductivities. *Nucl. Fusion* **16**, 957–962.

Kidder, R.E. (1976). Energy gain of laser-compressed pellets: A simple model calculation. *Nucl. Fusion* **16**, 405–408.

Kidder, R.E. (1979). Laser-driven isentropic hollow-shell implosions: The problem of ignition. *Nucl. Fusion* **19**, 223–234.

Martinez-Val, J.M., Eliezer, S., Henis, Z. & Piera, M. (1998). A tritium catalytic fusion reactor concept. *Nuclear Fusion* **38**, 1651–1664.

Meyer-ter vehn, J. (1982). On energy gain of fusion targets: The model of Kidder and Bodner improved. *Nucl. Fusion* **22**, 561–565.

Spitzer, L. (1962). *Physics of fully ionized gases*. Interscience, New York.

Tahir, N.A. & Long, K.A. (1983). Numerical simulation and theoretical analysis of implosion, ignition and burn of heavy-ion-beam reactor-size ICF targets. *Nucl . Fusion* **23**, 887–916.

Tahir, N.A., Long, K.A. & Laing, E.W. (1986). Method of solution of a three-temperature plasma model and its application to inertial confinement fusion target design studies. *J. Appl. Phys.* **60**, 898–903.

Zel'dovich, Y.B. & Raizer, Y.P. (1966). *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*. Academic Press, New York, Volume-I.