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Laser Interaction and Related Plasma Phenomena

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Abstract: Computations are to be performed using the laser driven inertial fusion energy option based on volume ignition with the natural adiabatic self-similarity compression and expansion hydrodynamics [1]. The numerical work includes the establishing of a multi-branch reaction code to be used for simultaneous fusion reactions of D-D, D-T D-He3 and mutual nuclear reaction products. This will permit the studies of neutron lean reactions as well as tritium-rich cases. The D-T reactions will stress the recent new results on one step laser fusion [2] as an alternative to the two-step fast ignitor scheme whose difficulties with new physics phenomena at petawatt laser interaction are more and more evident [3].

Key words: Low Temperature, Inertial Confinement Fusion

INTRODUCTION

Nuclear fusion is a process involving the nuclei of atoms. A process in which two small nuclei (below iron, element 26 in periodic table) join together to produce a larger nucleus, with an increase in binding energy and consequently a release of energy. The process has been known about since the 1920's and the performed collision experiments with deuterons in 1934 [4]. These experiments mark the beginning of the study of nuclear fusion. Indeed during Project Manhatten, the building of the fission A-bomb, Edward Teller urged J. Robert Oppenheimer to let him pursue the "super bomb" or H-bomb.

The energy is obtained by a conversion of mass into energy and hence, a decrease in the equivalent mass. The amount can be calculated using Einstein's famous $E = \Delta mc^2$, Δm the charge in mass from constituent parts to total mass. By a choice MeV units for energy and not Joules, as well as binding energy $(B.E)$ per nucleon; the calculation is simplified. For example, taking the final step in a series of fusion reaction which occurs in stars, one could have taken any of 51 listed by [5].

$$ {}_1^3H + {}_1^2H \rightarrow {}_2^4He + {}_0^1n + 17.6\ MeV \qquad (1)$$

There is more energy to be harvested via fusion than fission. The problem is one of controlling the process and using it with temperatures that are obtainable and manageable on Earth. The reaction cited above takes place at 10^8 K.

Bigger and better lasers are always being built; there is a great deal of commercial and military impetus there. Hence, the focus of this paper has been the plasma and what conditions are the best for fusion. The next obvious question is what energy gains can be hoped for? This is energy gained over and above that used by the laser in initiating and maintaining the process. It is no use having a reaction that produces just enough energy to sustain itself.

Nuclear Fusion Reactions: The stars exhibit two basic reactions, the carbon-nitrogen cycle and the proton-proton cycle. These are confined by massive gravitational forces. These are out of our reach [3].

$$\begin{aligned} D + D &\rightarrow 50\% \quad {}_2^3He + n + 3.27\ MeV \\ D + D &\rightarrow 50\% \quad {}_1^3T + p + 4.03\ MeV \end{aligned} \qquad (2)$$

and

$$D + T \rightarrow {}_2^4He + n + 17.6\ MeV \qquad (3)$$

The tritium being bred from ${}_3^7L_i$ by neutrons from equations (3) or (2), [6]. It is noted that magnetic confinement uses reaction (3). This leads to reactor damage caused by the neutrons; it is hence radioactive. The containment vessel wall can lose a centimetre a day [7]. The exposure of this information caused problems and goes to illustrate the problem of vested interests hampering scientific progress. Among the many possible fusion reactions, those utilising the heavy hydrogen isotope, deuterium (D) combined with the even heavier isotope of hydrogen, the radioactive tritium (T). [8] states

$$D+T \rightarrow n(14.1\ MeV)+{}_{3}^{4}He(3.5\ MeV) \quad (4)$$

This one is marked for best economic fusion energy, but has this high energy, compared to α particle, radioactive neutron. With inertial confinement fusion a better reaction to use is

$$H+{}_{5}^{11}B \rightarrow 3{}_{2}^{4}He(2.88\ MeV) \quad (5)$$

The burning of coal releases more radioactivity per unit of energy via the amount of uranium released [8, 9]. This is still under investigation. In the same vein the reaction

$$D+{}_{2}^{3}He \rightarrow H(14.7\ MeV)+{}_{2}^{4}He(3.6\ MeV) \quad (6)$$

Is a candidate for clean electrical energy production. The 50% each, competing reactions (detail of equation (2))

$$\begin{aligned} D+D &\rightarrow n(2.4\ MeV)+{}_{2}^{3}He(0.8\ MeV) \\ D+D &\rightarrow H(3.0\ MeV)+T(1.0\ MeV) \end{aligned} \quad (7)$$

are viable but radioactive. Further, nuclear spin polarisation can suppress this reaction. This aside, fusion gain calculations with *D-T* reaction are pursued; as are the D_2^3He reactions and $H_5^{11}B$. The reactions are to be ideal, with adiabatic compression. The plasma composition will vary according to three types listed. The parameters will be spherical volume V_0, hence radius R_0, T_0, velocity v_0 of pellet radius, with a linear velocity profile into the centre of the pellet. From this *G*, or fusion gain can be calculated, given as

$$G = \frac{\text{Reaction energy}}{\text{Input energy}} = \frac{\varepsilon_{xy}}{E_0}\int dt \int dr^3 \frac{n_i^2}{A} < \sigma v > \quad (8)$$

x, y being the constituents of the plasma. $< \sigma v >$ velocity averaged fusion cross-section. $A=4$ for binary reaction, or 2 for cases like DD [8].

It needs to be noted that reactions take time to run their course, so often the independent variable against which temperature or alike is plotted. It takes time to start and after a certain time it is finished; hence a range is used. At the beginning of this section the point was made about the high temperatures involved. This causes the constituents to be moving very fast, so efforts are made to keep the particles together to fuse. For example, a *DT* plasma, needs a density $n \approx 10^{16} cm^{-3}$, at $T = 10^9$K; a sufficiently long time τ is required within a set volume within the thermonuclear reactor [3]. The time involved in this case is determined by the energy content *Q* of the plasma, energy losses *W* (this is energy lost through heating the walls, electron bremsstrahlung, neutron emission, etc).

$$\tau = Q/W \quad (9)$$

The smaller the losses, allows a longer confinement time. The reaction's intensity is $n\tau$ given by the confinement parameters like higher density; shorter the time to required for a given number of nuclei to interact. For example, $n\tau = 10^{14} cm^{-3}$ sec for temperature near 10^8, using minimum time and density [6]. For energy released in a thermonuclear reactor to exceed energy consumed, the criterion above must be satisfied. This is known as Lawson's criterion [6]. It involves a definite combination of the confinement parameter $n\tau$ and temperature T [5, 10].

For ICF the time it takes for the pellet to fly apart, τ_D "disassembly time" is important, it relates to the time it takes for a sound wave to traverse the pellet. So the speed of sound in a $10keV$, *D-T* plasma is $10^8 ms^{-1}$, $\tau_D \approx 1ns$ hence fuel density in excess of $n = 10^{14}/\tau_D \sim 10^{23} cm^{-3}$ about liquid state density. If a small, liquid density *D-T* pellet can be heated to thermonuclear temperature before it can expand. $\approx 10^{-9}$s, $E \approx 1$MJ or 0.28 kWh, (enough to run the television for the night) is delivered in 1 ns: power level reaches $10^6/10^{-9} = 10^{15} W$. So the energy of fusion can be viewed as [11]

$$\begin{aligned} E_{fusion} &= E_{thermal} + E_{radiation} \\ E_{fusion} &= n_0 n_\tau < v\sigma > W_\tau = \frac{n^2}{4} < v\sigma > W_\tau \end{aligned} \quad (10)$$

Where:

$< v\sigma >$ = Maxwellian averaged reaction rate parameter

W = energy released per fusion reaction, eg for *DT, 17.6 MeV*

τ = Confinement time

n = ion density number $n_0 - n_T = \frac{n}{2}$

If ideal gas behaviour is considered

$$E_{th} = \tfrac{3}{2}nkT_i + \tfrac{3}{2}nkT_e = 3nkT, T_i = T_e \quad (11a)$$

Taking $E_{rad} \sim 0$, $T = 4keV$, fusion energy release exceeds bremsstrahlung radiation loss, for ICF 20 to

100 *keV*; magnetic fields can be ignored, cyclotron radiation is of little concern.

$$E_{Fusion} \approx E_{Thermal}$$

$$\frac{n^2}{4}\langle v\sigma\rangle W_\tau = 3nkT \quad (11b)$$

Solve for density times confinement time

$$n\tau > \frac{12kT}{<v\sigma>W} \quad (12)$$

at $10keV\ DT, 100keV\ DD$ – Lawson's criteria urges *DT* reaction.

Vital for ICF is an alternative expression of Lawson's criteria. Here the interest is in fuel density ρ, which is radius *R* dependant, rather than $n\tau$. The disassembly time is the pellet radius *R* divided by the speed of sound, taken from exterior to interior center.

$$\text{Fuel disassembly time} = \tau_d \sim \frac{R}{v_s} \quad (13)$$

The thermonuclear reaction time as inverse of the reaction rate can be offered as:

$$\text{Thermonuclear reaction time} = \tau_b \sim \left[\left(\frac{\rho}{m_i}\right)<v\sigma>\right]^{-1} \quad (14)$$

These two rates offer an estimate of the efficiency of thermonuclear burn

$$f_b = \frac{\tau_d}{\tau_b} = \left(\frac{<v\sigma>}{m_i v_s}\right)\rho R \quad (15)$$

This gives an idea of the fraction of the fuel consumed.

$$v_s = \left(\frac{kT}{m_i}\right)^{1/2} \sim T^{1/2} \quad (16)$$

As expressed *DT* fuel operate at efficient temperatures of 20 to 80 keV [11], this gives:

$$\frac{<v\sigma>}{m_i v_s} \sim const \sim 1 \quad (17)$$

The burn fraction can be expressed as:

$f_b \sim \rho R$ in grams per square centimetre (18)

As stated in reaction (C), the alpha particle gets 3.5 MeV, hence the fuel rise must exceed the alpha particle. This gives for *DT*, a *20keV*, $\rho R \approx 0.5g\ cm^{-2}$, efficient self-heating could occur.

In a fusion reaction binary collision occur, the fusion reaction itself plus collisions, which slow down charge particle production and energy deposition (or self-heating). Such processes depend on ρ^2; so to increase the density by 10^3, decreases the collision rate by 10^6.

$$\text{Rate of} \begin{Bmatrix} thermonuclear\ burn \\ energy\ deposition\ by\ chraged\ particles \\ electron-ion\ energy\ exchange \end{Bmatrix} \sim \rho^2$$

As inertial confinement time ~*R*, each major process for ICF can be expressed per unit mass. This includes burn efficiency, self-heating and burn propagation; all ~ ρR. For *DT* $\rho R \approx 3g\ cm^{-2}$, as will be used a bit further on; Lawson criterion gives $n\tau > 10^{14} s\,cm^{-3}$, a new aim for ICF is $\rho R > 3g\,cm^{-2}$.

Briefly the relationship between the ρR and $n\tau$ criteria will be examined [5, 10, 11].

Taking a freely expanding sphere of *R*

$$\tau_d \sim R/4v_s \quad (19)$$

In a spherical fuel pellet, half the mass is beyond 80% of the radius.

$$\text{Number density } n = \rho/m_i \quad (20)$$

$$n\tau = \frac{\rho R}{4v_s m_i} \quad (21)$$

Using some appropriate numbers

$$\rho R = 3g\,cm^{-2} \Rightarrow n\tau = 2\times 10^{15} scm^{-3} \quad (21a)$$

For an efficient thermonuclear burn, $n\tau$ must be well in excess of Lawson criterion, $10^{14} s.cm^{-3}$. It is noted here that MCF, working close to this burns a small fraction of the fuel. This is not good. Looking at depletion effects as accounted for by burn fraction f_b. The rate equation for tritrium fuel density.

$$\frac{dn_T}{dt} = -n_D n_T <v\sigma> \quad \sigma\ being\ for\ DT \quad (22a)$$

Using equimolar densities $n_D = n_T = n/2$

$$\frac{dn}{dt} = -\frac{n^2}{2} < v\sigma > \quad (22b)$$

Integrating from $t=0$ to $t = \tau_d$

$$\frac{1}{n} - \frac{1}{n_0} = \frac{1}{2} < v\sigma > \tau_d \quad n_0 = \text{Initial fuel number density} \quad (22c)$$

Defining the burn fraction f_b now as:

$$f_b = \frac{n_0 - n}{n_0} = 1 - \frac{n}{n_0} \quad (23)$$

Taking as a disassembly time $\tau_d = \frac{R}{4v_s}$ and $\rho = nm_i$

$$\rho R = \left(\frac{8m_i v_s}{< v\sigma >}\right)\frac{f_b}{1 - f_b} \quad (24)$$

Or

$$f_b = \frac{\rho R}{\left(8m_i/\langle v\sigma\rangle + \rho R\right)}$$

Evaluating the denominator for DT fuel are $20keV$

$$\frac{8m_i v_s}{< v\sigma >} \sim 6.3 g\, cm^{-2} \quad (25)$$

Allowing for fuel depletion, f_b for DT becomes

$$f_b = \frac{\rho R}{6.3 + \rho R} \quad (26)$$

$\rho R \sim 3 g\, cm^{-2}$ gives burn fraction of $f_b = 0.30$, that is a burn of some 30% of the fuel. Now it is required that an explanation of the $< v\sigma >$ be offered, in terms of a fusion reaction. Using

$$R = n_1 n_2 < \sigma v > \quad (27)$$

$$< \sigma v > = \left(\frac{m_1}{2\pi kT}\right)^{3/2}\left(\frac{m_2}{2\pi kT}\right)^{3/2} \iint d^3 v_1 d^3 v_2 \sigma(v) v \exp - \frac{MV^2 + \mu v^2}{2kT} \quad (28)$$

$$= \frac{2}{\sqrt{\mu}}\left(\frac{1}{2kT}\right)^{3/2}\left(\frac{\mu}{m_1}\right)^2 \int_0^{\infty} E_K \sigma(E_K) \exp - \frac{\mu}{m_1}\frac{E_K}{kT} dE_K$$

Where:

$\mu = \frac{m_1 m_2}{m_1 + m_2}$ the reduced mass.

$E_K = \frac{1}{2} m_1 v^2$ bombarding energy of particle one for the reaction.

The value $\sigma(E_K)$ can be found experimentally or theoretically, then $< \sigma v >$ can be calculated. For low energies the approximate formula:

$$\sigma(E_K) = \frac{A}{E}\exp\left(-\frac{B}{\sqrt{E_K}}\right) \quad (29)$$

is used; A and B being constants. Various authors [6, 8, 10, 11] have made graphs for values of $< \sigma v >$ having dimensions $cm^3 \sec^{-1}$.

There are variations on the $< \sigma v >$ formula. For example [5]:

$$< \sigma v > = \frac{4}{(2\pi\mu)^{1/2}(kT)^{3/2}} \int_0^{\infty} \sigma(E_r) E_r xp - E_r/kT\, dE_r \quad (30)$$

$E_r = \frac{1}{2}\mu v_r^2$, v_r being the relative velocity [8].

$$< \sigma v > = \frac{\sqrt{m_i}}{\sqrt{\pi (kT)^{3/2}}} \int_0^{\infty} \frac{m_i}{2} v^2 \sigma(v) \exp\left(\frac{m_i v^2}{kT}\right) dv^2 \quad (31)$$

In terms of ICF.

$$< \rho R > \equiv \int \rho d_r = \frac{R_0 \rho_0(0) f(B)}{\left(1 - \tau^2\right)} \quad (32)$$

Numerical Results of the Energies (Input And Overall Gain) of Fusion Reaction: This section explores, by computer simulation, the energy of the three reactions, D^3He, $H^{11}B$ and DT. The implications of equation (8) are employed. The changes in volume and density, as well as energy over time are examined.

In the case of D^3He especially the algorithm allows for four temperature changing effects:

T_{ad}: Adiabatic cooling, a thermodynamic expansion process

T_α: *α particle reheat*
T_p: *proton reheat*
} Due to coulomb collisions with electrons of the plasma.

T_{br}: Bremsstrahlung

The full dynamic temperature becomes:

$$\Delta T = -T_d + T\nabla A + T_p - T_{br} \quad (33)$$

The inertial temperature for each time step:

$$T_{n+1} = T_n + \Delta T, \quad T_0 = T_0(E_0) = \frac{E_0}{2n_0 v_0 k_H} \quad (34)$$

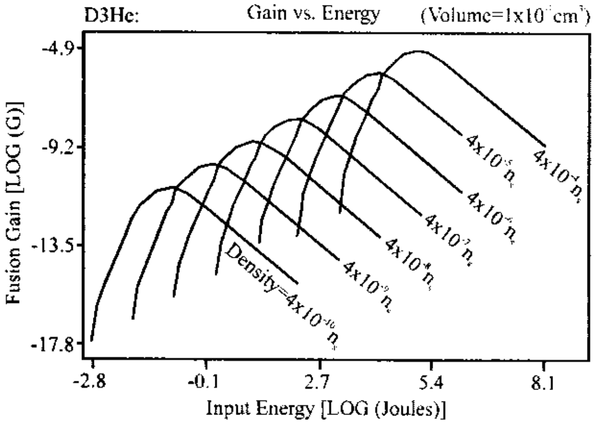

Fig. 1: Energy Dependence of the Fusion Gain of the D3He Reactions

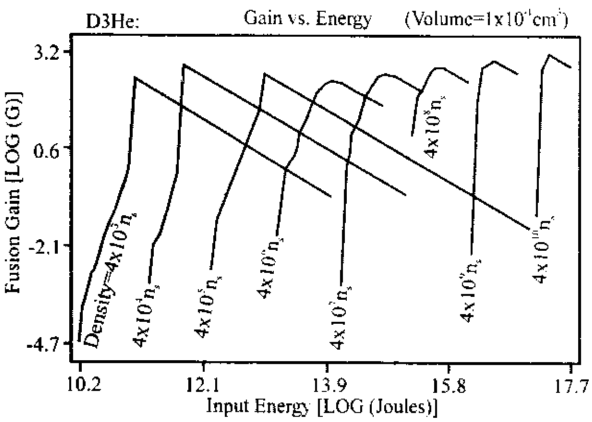

Fig. 2: Energy Dependence of the Fusion Gain of the D3He Reactions

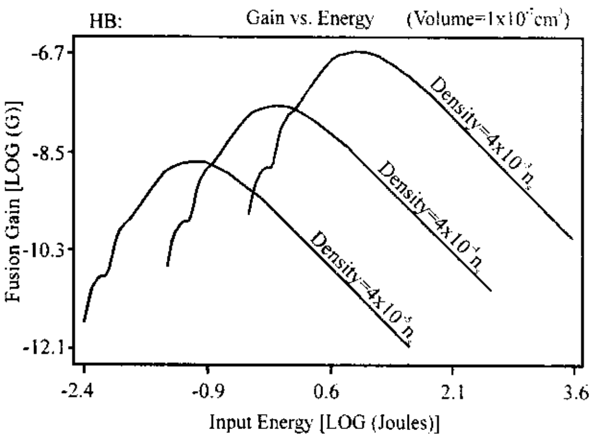

Fig. 3: Energy Dependence of the Fusion Gain of the HB Reactions

again, a non-linear mathematical description.

The overall process involves high compression involving:

* Shaping in time by the input energy of the driver
* "Clever" pellet design [12]

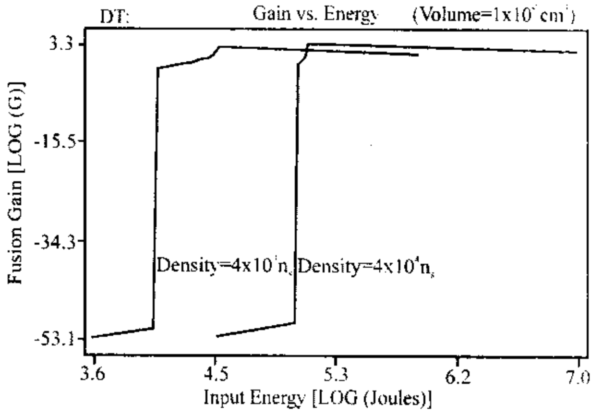

Fig. 4: Energy Dependence of the Fusion Gain of the DT Reactions

The sequence is:

Energy absorption (of driver) → Energy transport → Compression → Nuclear fusion.

Following is a series of simulations of fusion gains verses input energy. The first fuel examined is D^3He. It is examined over a range of densities, which are expressed as so many times solid state; and a range of volumes. It will be seen that sometimes the density is fixed and the volume allowed to vary; while at others the volume will be fixed and the density varied. The energy is taken to be that of a 10% efficient laser. The energy offered is therefore the energy actually captured by the plasma and is examined over a range of values. The reactions are viewed omitting energy loss via bremsstrahlung (when later it was included it showed to have little effect at the parameters chosen). The number of points plotted to define the graph ranges from 1,000 to 10,000. The choice of values is based upon common values used for ICF by authors such as [8]. The concept here being to examine values further a field purely to identify any trends. It is acknowledged that the plasma is usually expanding, so there is a time constraint on the time that the plasma was at the stated volume. Clearly, it is taken that fusion has occurred and the program gives what gain one could expect. Later temperature changes over time will be considered.

The first graphs to consider are Fig. 1 and 2. The volume is fixed at $1\times10^{-1}cm^3$ for while the density is explored over 4×10^{-3} to 4×10^{-10} and 4×10^{3} to $4\times10^{10}n_s$, thus offering less solid state to ten times a giga solid state. The idea behind "$4\times$" is to place the sample in the middle of the range; ie use intermediate values. From Fig. 1 it can be seen that small energy values maintain the reaction, but the gains are very small. Certainly not worth pursuing. Overall though an upward trend in the tangent to curves at maximum value is evident. Higher initial values are required but the gain

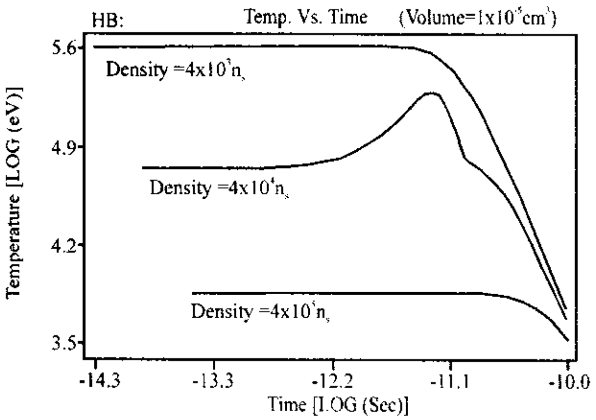

Fig. 5: Temperature-time Dependence of the HB Reactions

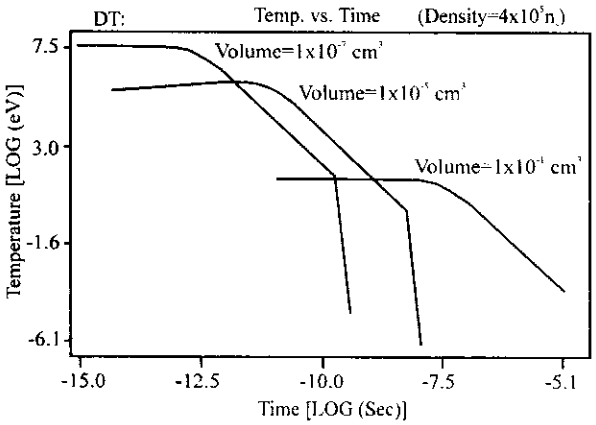

Fig. 6: Temperature-time Dependence of the DT Reactions

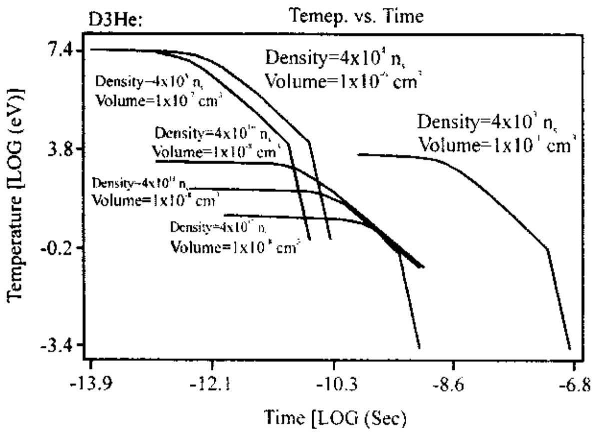

Fig. 7: Temperature-time Dependence of the D3He Reactions

trend is moving in the desired direction, in a beautiful uniform manner. The leap to tens, millions times solid state density, Fig. 2 shows positive returns. These are still noted as very modest and not economically viable. The degree of gain, compared to input energy drops off. $10^{10.1} J$ at $10^3 n_s$ gives 'nearly' the gain of $10^{2.2}$;$10^{17.5} J$ (approx) at $10^{10} n_s$ gives $10^{3.2}$. Thus indicating it may not be worth trying to increase the density further.

Figure 3 shows very small densities may only require small input energies, but there is virtually no gain, for example $10^{-6.7}$ ie 1.995×10^{-7}. At this stage D^3He appears to be a better fuel, purely on a gains basis. HB at $4\times10^5 n_s$, volume $1\times10^{-7} cm^3$ give a gain of $10^{1.2}$ for an input energy of $10^{8.1} J$, as opposed to for the same parameters D^3He gives $10^{2.3}$, the input energy being $10^{7.1} J$. The better D^3He may actually be $4\times10^3 n_s$, volume of $10^{-1} cm^3$ and a gain of $10^{2.4}$. The input energy is higher at $10^{8.1} J$, though. as opposed to $10^{7.1} J$ for $4\times10^5 n_s$. It is the more realistic density value that highlights its choice. No matter which one is used, D^3He is proving to be the better fuel, on a return for energy basis, against parameters required to set it up. The role bremsstrahlung so far does not appear to be major. The scenarios were run including it and little change in the print out appeared. This may not be the case when considering temperature effects. Further, these simulations do not extend to hybrid reactions, such as DD with D^3He. The work of [8] would show a slight fusion gain increase for such reactions.

Turning now to the third fuel, *DT*, Deuterium-Tritium and using densities and volume relevant to the "successful" parameters for the other fuels. Figure 4 shows that at the smallest volumes and reasonable solid state densities, fusion gain is good. Taking values. volumes of $10^{-7} cm^3$,$10^{-5} cm^3$ and densities of $4\times10^4 n_s$,$4\times10^5 n_s$; fusion gains are 3.4 for input energy of $10^{5.1} J$; 3.5 for $10^{8.2} J$, respectively. Reviewing the best energy gains for the three fuels, a simple table can be constructed. Clearly the most efficient fuel is *DT* at density $4\times10^4 n_s$, volume $10^{-7} cm^3$ for an energy input of $10^{5.1}$ *J*; the gain is $10^{3.4}$.

Numerical Results of Temperature Time Relationship of the Plasma in Fusion Reactions: It is now time to look at the role of temperature. Starting with Fig. 5 where the program was to reduce the density to $1\times10^5 n_s$ while maintaining the volume of $1\times10^{-5} cm^{-3}$. The real test was to 'spread' the input energy base. This approach gave two 'peaks'. This is virtually [8] approach to illustrate the temperature spikes associated with volume ignition. *DT* seems to follow the same pattern as *HB*, raise the volume and the

temperature is lowered quite considerably. On the basis of lowest optimum temperature *HB* at $4 \times 10^5 n_s$, volume $10^{-3} cm^3$ is the most manageable fuel, with a temperature of $10^{1.8} eV$. Against this *DT* has $4 \times 10^5 n_s$, volume $10^{-1} cm^3$, having a temperature of $10^{1.5} eV$.
Considering next the third fuel D^3He, Fig 7 shows that as the density is raised from $10^{10} n_s$ to $10^{12} n_s$ but volume is maintained at $10^{-8} cm^3$, the optimum temperature drops dramatically, $10^{3.4}$ to $10^{1.4} eV$. Figure 7 helps make the point that as volume increases, from 10^{-7} to $10^{-1} cm^3$, the temperature from $10^{7.4}$ to $10^{1.4} eV$ respectively. Clearly $4 \times 10^5 n_s$ has emerged as the best density and when coupled with a volume of $10^{-1} cm^3$ gives a low temperature of $10^{1.4} eV$.

CONCLUSION

The process of identifying the appropriate fuel and the correct parameters for its operational success is a careful balancing act. The density, volume and input energy required to give a worthwhile return are mediated by the temperature produced. Given the limitations of the model used and the limited scope of factors that can be manipulated; the question as to which fuel, in what form is a likely candidate could be answered.

Clearly with all three fuels increasing density, decreases temperature. Further, the three also would indicate increasing volume decrease temperature. This set of trends is going to work against some of the candidates from section 3. *DT* emerges as the 'best' fuel. The most desirable parameters for it being: density $4 \times 10^5 n_s$, volume $10^{-1} cm^3$ using input energy from $3.2 \times 10^{10} J$ to $10^{12.2} J$ (depending on graph/model used.) The last vital statistic is the optimum temperature and it comes in a 'cool' $10^{1.5} eV$. These parameters, given good fuel pellet quality, best engineering, should give a return of $10^{3.3}$.

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