**The Ignition Parameter $Tn\tau$
and the Energy Multiplication Factor k
for Fusing Plasmas**

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MASTER

OAK RIDGE NATIONAL LABORATORY

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MULTIPLICATION FACTOR k FOR FUSIONING PLASMAS

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ABSTRACT

This paper presents some novel interpretations of fusion plasmas which may be of interest to both fission and fusion scientists and engineers. A new fusion ignition parameter $(Tn_e \tau_E)_I$ is proposed which is proportional to $\beta^2 B^4$ and inversely proportional to the fusion power density (P_{Fusion}) of a reacting plasma. Curves are given for many potential nuclear fusion fuels. The energy utilization factor in existing devices is defined as $f = P_{\text{Fusion}}/P_{\text{Loss}} = (Tn_e \tau_L)/(Tn_e \tau_E)_I$; in experimental plasmas, f has increased by about two orders of magnitude in the past decade and now exceeds 10^{-4} (a "nearest" f^* exceeds 10^{-3}). The f factor is also analogous to its fission counterpart in the four-factor neutron multiplication factor $k = f \eta \epsilon p$, where f is the neutron thermal utilization factor. Past, present, and future fusion experiments are discussed briefly in this context.

I. INTRODUCTION

The goal of scientific feasibility for controlled fusion research is to achieve in hydrogen plasma a plasma temperature T , electron density n_e , and energy confinement time τ_E which together satisfy conditions for igniting a DT plasma. The simple product $Tn_e\tau_L$ for experimentally achieved plasmas is a very useful and meaningful criterion for evaluating the degree of closeness to achieving an ignition $(Tn_e\tau_E)_I$ in at least an elementary way. Here, τ_L = net energy confinement time and τ_E is the energy confinement time for an ignited plasma.

The partial product $n_e\tau_E$ used here differs from Lawson's nr [1] in that the evaluation of a plasma ignition $n_e\tau_E$ uses only the charged particle energy deposition in the plasma, although in dense pellet fusion some neutron energy deposition and neutron reactions may also be incorporated [2]. Lawson used both the charged particle energy contribution and that of the neutron (four times the energy of the alpha particle in the DT case) as well as bremsstrahlung radiation losses and a thermal energy recovery efficiency to give an energy break-even condition.

It is quite likely that magnetically confined fusing plasmas must be ignited to ensure a reasonable economic return. Since $(Tn_e\tau_E)_I$ is defined here as the "bare" or elemental value required to ignite the plasma over all energy losses, one has for the energy confinement time $\tau_E = 1/\Sigma(1/\tau_L) = \Sigma(\frac{1}{2}n_k T_k / P_{\text{Fusion}})$, where k stands for both ions and electrons. For pure DT fuel, $T_e = T_i$, and $P_{\text{Fusion}} = n_D n_T \langle\sigma v\rangle_{\text{DT}} Q_+$, the ignition parameter $(Tn_e\tau_E)_I$ becomes simply $12T^2/(\langle\sigma v\rangle_{\text{DT}} Q_+)$ for $n_D = n_T$ and where the charged particle energy release is $Q_+ = 3520$ keV and T is in keV.

The $Tn_e\tau_E$ product was apparently first proposed in 1973 [3]. It has two very important physical meanings: 1) the ignition parameter $(Tn_e\tau_E)_I$ for a given fuel is inversely proportional to the fusion power density of the ignited plasma and hence its minimum value, for a given fuel, corresponds to the maximum fusion power density for that fuel mix; and 2) the ratio of the experimentally achieved $Tn_e\tau_L$ product to that required for "bare" ignition $(Tn_e\tau_E)_I$ is defined as the "energy utilization factor f ," quite analogous to the "neutron thermal utiliza-

tion factor f used in the neutron multiplication factor, $k = f \eta \epsilon p$ for nuclear fission reactors [4]. Thus, the simple ignition parameter $(Tn_e \tau_E)_I$ is only a first-cut at evaluating the plasma energy criticality or ignition. The physical interpretations of both $(Tn_e \tau_E)_I$ and k_{Fusion} are the subjects of the next two sections. It should be noted that while considerable progress has been made in recent years, presently achieved values of f for the fusion case are less than 10^{-3} and hence the f factor dominates the fusion k factor at the present time.

II. THE IGNITION FEASIBILITY CRITERION, $(Tn_e \tau_E)_I$

The general expression for the fusion ignition parameter is

$$(Tn_e \tau_E)_I = \frac{Tn_e \sum_k \left(\frac{3}{2}\right) n_k T_k}{\alpha_{ij} n_i n_j \langle \sigma v \rangle_{ij} Q_{ij}} \quad \text{in keV cm}^{-3} \text{ sec}$$

where $\alpha_{ij} = 1$ for $i \neq j$ and $1/2$ for $i = j$, n_i and n_j are fuel ion densities, Q_{ij} is the charged particle energy release in keV and T is the plasma temperature in keV. One obtains

$$(Tn_e \tau_E)_I = \begin{cases} \frac{\left(\frac{3}{2}\right) T^2 n_e [n_e + \alpha_{ij} (n_i + n_j) + n_x]}{\alpha_{ij} n_i n_j \langle \sigma v \rangle_{ij} Q_{ij}} & \text{for } T_e = T_i = T \\ \frac{\left(\frac{3}{2}\right) T^2 n_e [n_i + n_j + n_x / \alpha_{ij}]}{n_i n_j \langle \sigma v \rangle_{ij} Q_{ij}} & \text{for } T_e \ll T_i = T \end{cases}$$

Here, x designates alphas and/or other impurities and $n_e = \alpha_{ij} (Z_i n_i + Z_j n_j) + \sum_x Z_x n_x$. Thus, $(Tn_e \tau_E)_I$ is proportional to $T^2 / \langle \sigma v \rangle_{ij}$ and is inversely proportional to the fusion power density as shown below.

The fusion power density is defined as

$$P_{\text{Fusion}} = \alpha_{ij} n_i n_j \langle \sigma v \rangle_{ij} Q_{ij}$$

and the plasma beta is for B in Tesla, T in keV and n in cm^{-3}

$$\beta = \frac{8\pi \sum_k n_k T_k (1.6 \times 10^{-17})}{B^2}$$

Thus, one obtains for P_{Fusion} now in watts/cm³

$$(Tn_e \tau_E)_I = 1.5 \times 10^{15} \left(\frac{n_e}{\Sigma n_k} \right) \frac{\beta^2 B^4}{P_{\text{Fusion}}} \quad \text{for } T_i = T_e$$

and for a given plasma β and magnetic field B the ignition criterion is inversely proportional to the fusion power density. In the case of pellet fusion $(Tn_e \tau_E)_I \propto p^2/P_{\text{Fusion}}$, where p is the plasma pressure (or the stored energy density).

The energy confinement time τ_E represents all energy losses such as those due to radiation (line, bremsstrahlung, and synchrotron), particle diffusion, charge exchange, conduction, convection, instabilities, etc. and $1/\tau_E = \Sigma 1/\tau_L$ for ignition.

The principal fusion reactions with their $Q_{ij} = Q_+$ values and the associated ignition parameter, assuming $n_x = 0$ and $T_i = T_e$, are:

$$\begin{aligned} D + T &\rightarrow n + \alpha + 3520 \text{ keV} \\ (Tn_e \tau_E)_{DT} &= 12T^2 / (3520 \langle \sigma v \rangle_{DT}) \end{aligned} \quad \text{for } D/T = 1 \quad \left. \vphantom{\begin{aligned} D + T &\rightarrow n + \alpha + 3520 \text{ keV} \\ (Tn_e \tau_E)_{DT} &= 12T^2 / (3520 \langle \sigma v \rangle_{DT}) \end{aligned}} \right\} (1)$$

$$\begin{aligned} D + D &\rightarrow \begin{cases} n + {}^3\text{He} + 800 \text{ keV} \\ p + t + 4000 \text{ keV} \end{cases} \\ (Tn_e \tau_E)_{DD} &= 6T^2 / (2400 \langle \sigma v \rangle_{DD}) \end{aligned} \quad \bar{Q}_{DD} \sim 2400 \text{ keV} \quad \left. \vphantom{\begin{aligned} D + D &\rightarrow \begin{cases} n + {}^3\text{He} + 800 \text{ keV} \\ p + t + 4000 \text{ keV} \end{cases} \\ (Tn_e \tau_E)_{DD} &= 6T^2 / (2400 \langle \sigma v \rangle_{DD}) \end{aligned}} \right\} (2)$$

For catalyzed DD in which the t and ${}^3\text{He}$ are burned 100% with D fuel

$$\begin{aligned} 2D + 4D &\rightarrow 2n + 2p + 2\alpha + 13,400 \text{ keV} \\ (Tn_e \tau_E)_{\text{CATDD}} &= 6T^2 / (13,400 \langle \sigma v \rangle_{DD}) \end{aligned} \quad \left. \vphantom{\begin{aligned} 2D + 4D &\rightarrow 2n + 2p + 2\alpha + 13,400 \text{ keV} \\ (Tn_e \tau_E)_{\text{CATDD}} &= 6T^2 / (13,400 \langle \sigma v \rangle_{DD}) \end{aligned}} \right\} (3)$$

$$\begin{aligned} D + {}^3\text{He} &\rightarrow p + \alpha + 18,400 \text{ keV} \\ (Tn_e \tau_E)_{D{}^3\text{He}} &= 22.5 T^2 / (18,400 \langle \sigma v \rangle_{D{}^3\text{He}}) \end{aligned} \quad \text{for } D/{}^3\text{He} = 1 \quad \left. \vphantom{\begin{aligned} D + {}^3\text{He} &\rightarrow p + \alpha + 18,400 \text{ keV} \\ (Tn_e \tau_E)_{D{}^3\text{He}} &= 22.5 T^2 / (18,400 \langle \sigma v \rangle_{D{}^3\text{He}}) \end{aligned}} \right\} (4)$$

$$\begin{aligned} {}^3\text{He} + {}^3\text{He} &\rightarrow 2p + \alpha + 12,900 \text{ keV} \\ (Tn_e \tau_E)_{{}^3\text{He}{}^3\text{He}} &= 18 T^2 / (12,900 \langle \sigma v \rangle_{{}^3\text{He}{}^3\text{He}}) \end{aligned} \quad \left. \vphantom{\begin{aligned} {}^3\text{He} + {}^3\text{He} &\rightarrow 2p + \alpha + 12,900 \text{ keV} \\ (Tn_e \tau_E)_{{}^3\text{He}{}^3\text{He}} &= 18 T^2 / (12,900 \langle \sigma v \rangle_{{}^3\text{He}{}^3\text{He}}) \end{aligned}} \right\} (5)$$

$$\begin{aligned}
 & p + {}^6\text{Li} \rightarrow {}^3\text{He} + \alpha + 4000 \text{ keV} \\
 & {}^3\text{He} + {}^6\text{Li} \rightarrow p + 2\alpha + 16,800 \text{ keV} \\
 & (Tn_e \tau_E)_{\text{CAT } p {}^6\text{Li}} = 30 T^2 / (20,800 \langle \sigma v \rangle_{p {}^6\text{Li}}) \quad \text{for } p/{}^6\text{Li} = 3
 \end{aligned}
 \quad \left. \vphantom{\begin{aligned} & p + {}^6\text{Li} \rightarrow {}^3\text{He} + \alpha + 4000 \text{ keV} \\ & {}^3\text{He} + {}^6\text{Li} \rightarrow p + 2\alpha + 16,800 \text{ keV} \end{aligned}} \right\} (6)$$

$$\begin{aligned}
 D + {}^6\text{Li} \rightarrow & \left\{ \begin{array}{l} n + {}^7\text{Be} + 425 \text{ keV} \\ n + {}^3\text{He} + \alpha + 660 \text{ keV} \\ p + {}^7\text{Li} + 5000 \text{ keV} \\ p + t + \alpha + 2600 \text{ keV} \\ 2\alpha + 22,400 \text{ keV} \end{array} \right. \\
 (Tn_e \tau_E)_{D {}^6\text{Li}} = 30 T^2 / \Sigma (\langle \sigma v \rangle_{ij} Q_{ij}) \quad \text{for } D/{}^6\text{Li} = 3
 \end{aligned}
 \quad \left. \vphantom{\begin{array}{l} n + {}^7\text{Be} + 425 \text{ keV} \\ n + {}^3\text{He} + \alpha + 660 \text{ keV} \\ p + {}^7\text{Li} + 5000 \text{ keV} \\ p + t + \alpha + 2600 \text{ keV} \\ 2\alpha + 22,400 \text{ keV} \end{array}} \right\} (7)$$

$$\begin{aligned}
 & p + {}^{11}\text{B} \rightarrow 3\alpha + 8700 \text{ keV} \\
 & (Tn_e \tau_E)_{p {}^{11}\text{B}} = 58.5 T^2 / (8700 \langle \sigma v \rangle_{p {}^{11}\text{B}}) \quad \text{for } p/{}^{11}\text{B} = 10
 \end{aligned}
 \quad \left. \vphantom{\begin{array}{l} p + {}^{11}\text{B} \rightarrow 3\alpha + 8700 \text{ keV} \\ (Tn_e \tau_E)_{p {}^{11}\text{B}} = 58.5 T^2 / (8700 \langle \sigma v \rangle_{p {}^{11}\text{B}}) \end{array}} \right\} (8)$$

Figure 1 illustrates the temperature dependence of the ignition parameter for the various fusion fuels. The appropriate $\langle \sigma v \rangle$ values are taken from the advanced fuels reactivity code of McNally and Sharp [5]. The ignition curves for DT, D³He and D⁶Li do not include the D + D reaction contributions which would increase the reactivity and lower the respective $(Tn_e \tau_E)_I$ values for these fuels. This is especially true in case (7) for D⁶Li where deuterium is taken to be three times the ⁶Li abundance. Also, catalyzed burning of in situ generated T and ³He would lower these three curves still further. Ash or impurity buildup, as well as early reaction product losses (occurring at $E > \frac{3}{2} T$ or $\tau < \tau_E$), would raise all curves somewhat.

The "classical" fusion fuel DT has the lowest $(Tn_e \tau_E)_I$ curve and hence would have the highest power density for given $\beta^2 B^4$. It may be too reactive in large systems in the range $T < 80$ keV; thus, it may be important to evaluate the advanced fuels with this aspect in mind as well as considerations of tritium inventory, first wall damage and 14 MeV neutron radiation damage. To attain the same power density with the advanced fuel reactors as with DT fuel at $T < 80$ keV, the advanced fuel reactors would need larger values of $\beta^2 B^4$.

Catalyzed DD fueled fusion reactors have an ignition parameter only about 10 times higher than pure DT at 10 keV, not 100 times as is commonly implied.

Should DT plasmas burn best at $T = 100 - 300$ keV the catalyzed DD and "cleaner" D^3He fueled reactors [6] would have a real competitive economic advantage as well as have comparable power densities. The more advanced fuels p^6Li , $p^{11}B$ or $^3He^3He$ would require a significantly larger β^2B^4 value in this temperature range. Recent studies suggest that catalyzed DD, DD, D^6Li , and D^3He can operate in principle as steady state reactors provided $\beta \gtrsim 20\%$, $n_e \tau_E \gtrsim 2 \times 10^{15} \text{ cm}^{-3} \text{ sec}$, and $T > 50$ keV [6 - 8].

If the various experimental loss dependences are known as a function of T , the appropriate curve for each loss can be superposed on Figure 1. For example, the bremsstrahlung limited loss curve $(Tn_e \tau_L)_B$ is for $T_e = T_i$:

$$(Tn_e \tau_L)_B = 10^{15} \frac{3}{2} [n_e + \alpha_{ij}(n_i + n_j) + n_x] / [2(\sum_l Z_l^2 n_l + 0.006 n_e T)],$$

and for $n_x = 0$ and DT or DD fuel the bremsstrahlung loss curve passes through the points $(1, 10^1)$ and $(100, \sim 10^4)$ except for minor variations due to Z_l (l represents ions only) and high temperature relativistic effects. For the other fuel mixes the bremsstrahlung limited curve is lower by up to a factor of three. The allowable operating range for an ignited plasma lies below the loss curve(s) but above the gain curve $(Tn_e \tau_E)_I$. Should T_e be much less than T_i the ignition curve is slightly lower by $\sum_l Z_l / \sum_k Z_k$ and the bremsstrahlung loss curve is higher by approximately $\sqrt{T_i/T_e}$.

The simple magnetic mirror is expected to have a quite low $Tn_e \tau_L$ value as a result of severe end losses and $(Tn_e \tau_L)_M$ is about $T(3 \times 10^{10} T^{3/2} \log R) \sim 10^{10} T^{5/2}$ for a 2/1 magnetic mirror containing deuterium fuel ions. This straight line curve intersects the points $(100, 10^1)$ and $(1000, 3 \times 10^3)$ on Fig. 1 and hence falls well below the ignition curve for any fuel. Thus, for an ignition plasma the magnetic mirror losses must be grossly reduced as in the Ion-layer or proton E-layer [9] or other reversed field mirror [10], or the mirror connected bumpy torus [11]. At this time the fuel feed mechanisms and transport loss mechanisms are essentially unknown for these potential reactor configurations.

III. THE FUSION ENERGY MULTIPLICATION FACTOR, k

The operation of nuclear fission reactors involves an important factor defining criticality called the neutron multiplication factor, k [4]. There is a somewhat analogous factor which may be applied to nuclear fusion reactors and this section makes a first attempt at defining k for nuclear fusion reactors. By replacing "neutrons" by "energy" one can transfer some of the fission concepts to fusion analogies and an effective energy multiplication factor can be defined which is basically a measurement of ignition for $k = 1$ and prompt criticality or thermal runaway for $k > 1$ (buildup of reactive T and ^3He may be analogous to delayed neutrons). It may prove very beneficial to delineate more exactly the presently used definition of k for the fusion case as future plasmas approach ignition conditions. Present plasmas have k values which, while increasing substantially as experiments are improved, are at present less than 10^{-3} .

In the event of a thermal runaway the nuclear burn undergoes an instability (when $k = 1$), through a thermal runaway (when $k > 1$), to a stable equilibrium at the burning or operating temperature (when k reverts back to 1). Figure 2 illustrates schematically the thermal runaway of a radiation dominated, closed, pulsed DT burn. Other energy and particle losses will shift the burning or operating temperature down to lower temperatures. For a fixed fuel mix the burning temperature is stable, i.e., it has a negative temperature coefficient. The operating temperature is unstable to fuel mix perturbations, i.e., it has an important positive density coefficient, which must be feedback controlled.

The k for fission reactors is defined as $k = f \eta \epsilon p$, where f is the neutron thermal utilization factor or the fraction of thermal neutrons which induce fissions. η is the average number of fast neutrons produced by fission per thermal neutron. ϵ is the fast fission factor due to suprathreshold neutrons inducing fission reactions and ϵ is then slightly larger than unity. p is the resonance escape probability due to the loss of fast neutrons by nonfission (and usually resonance) capture processes, and p is always less than unity.

The fusion "energy multiplication factor k " is defined by the relation

$$\frac{d}{dt} \left(\Sigma \left(\frac{3}{2} \right) n_k T_k \right) = (k - 1) \frac{\Sigma \left(\frac{3}{2} \right) n_k T_k}{\tau_E}$$

which has the exponential solution for k and τ_E taken as constants

$$\Sigma \left(\frac{3}{2} \right) n_k T_k = \left(\Sigma \left(\frac{3}{2} \right) n_k T_k \right)_0 e^{(k - 1)t/\tau_E}$$

For $k > 1$ the plasma energy content grows exponentially in time, for $k = 1$ the stored energy is at an equilibrium which may be stable or unstable, and for $k < 1$ the energy content of the plasma decays exponentially or quenches. k and τ_E may actually be complex functions of n and T so the analogy to the fission case is not exact.

A generalized form of this power density equation is

$$\begin{aligned} \frac{d}{dt} \left(\Sigma \left(\frac{3}{2} \right) n_k T_k \right) &= P_{DT} + P_{SIDE} + P_{EXT} + P_{BP} + P_{NE} + P_C - P_{ESC} - \frac{\Sigma \left(\frac{3}{2} \right) n_k T_k}{\tau_L} \\ &= (k - 1) \frac{\Sigma \left(\frac{3}{2} \right) n_k T_k}{\tau_L} \end{aligned}$$

giving

$$k = \left(\frac{\tau_L P_{DT}}{\Sigma \left(\frac{3}{2} \right) n_k T_k} \right) \left(1 + \frac{P_{SIDE} + P_{EXT}}{P_{DT}} \right) \left(1 + \frac{P_{BP} + P_{NE} + P_C}{P_{DT} + P_{SIDE} + P_{EXT}} \right) \left(1 - \frac{P_{ESC}}{\Sigma P_+} \right)$$

and, analogous to the fission reactor case, we define the four terms as $k = f \eta \epsilon p$. Note that $k = f(\tau_E, n, T_i, T_e)$ except in a narrow sense.

The various power expressions are defined as P_{DT} = fusion power density due to DT thermal reactions; P_{SIDE} = fusion power density due to side thermal reactions (e.g., DD, TT, D^3He); P_{EXT} = P due to external feed of energy (e.g., injected beams, ohmic heating, ECH, etc.); P_{BP} , P_{NE} , and P_C are fast or suprathermal power terms due to beam-plasma or suprathermal second generation reactions and nuclear elastic (and in some cases nuclear inelastic), and hard Coulomb collisions which promote fuel ions to suprathermal energies; and P_{ESC} represents direct or early alpha particle (or other charged fusion reaction products) escape, i.e., losses due to large particle orbits intersecting walls or being otherwise lost at $E > \left(\frac{3}{2} \right) T$ and/or $\tau < \tau_E$. ΣP_+ is the sum of

all positive power terms. In the case of advanced fusion fuels f , η , ϵ and p would be defined relative to the leading fusion reaction, e.g., for DD $f \rightarrow \tau_L P_{DD} / (\Sigma (\frac{3}{2}) n_k T_k)$ and the DT and $D^3\text{He}$ are the important side reactions.

The "energy thermal utilization factor f " defines the efficiency of the alpha particles from DT thermonuclear reactions in supporting the plasma energy content. It has a simple form as follows:

$$\begin{aligned} f &= \tau_L P_{DT} / (\Sigma (\frac{3}{2}) n_k T_k) \\ &= P_{DT} / P_{\text{LOSS}} \\ &= T n_e \tau_L \langle \sigma v \rangle_{DT} Q_{DT} / 12 T^2 \text{ for pure DT and } T_i = T_e \\ &= (T n_e \tau_L) / (T n_e \tau_E)_I \end{aligned}$$

which is to be evaluated at the experimental temperature T .

Table I compares the energy thermal utilization factor f for several experimental plasmas (see DIRECT column). The very low f values for present devices ($\lesssim 2 \times 10^{-4}$) indicate that this is the dominating influence in the attainment of a fusion energy multiplication factor $k \geq 1$ for ignition.

The "fast fusion factor ϵ " measures the contribution of suprathermal reactions to the energy balance. These suprathermal ions may be energetic injected fuel ions, second-generation fuel ions, or knock-on fuel ions (produced by short-range Coulomb collisions or nuclear elastic collisions of fuel ions with highly energetic fusion reaction products). Eventually the unreacted suprathermal ions merge into the thermal distribution. The second generation fuel ions originate primarily in DD side reactions such as $D + D \rightarrow p + t(1000 \text{ keV})$ or $n + {}^3\text{He}(800 \text{ keV})$. $P_{BP} / (P_{DT} + P_{\text{SIDE}})$ may approach or exceed unity in high temperature plasmas [12]. At electron temperatures approaching 100 keV, $(P_{NE} + P_C) / (P_{DT} + P_{\text{SIDE}})$ may represent a significant fast fusion contribution. The macroscopic effect of nuclear elastic collisions has been considered in Ref. [8], but the proper way to treat these is as microscopic or individual suprathermal fuel ion events.

It should be noted that for externally driven systems (ohmic heating, beams, RF, ECH, etc.) at low temperatures (or low $T n_e \tau_L$ values)

P_{EXT}/P_{DT} may be very large and $k \rightarrow 1$ for a steady state, non-ignited plasma; however, in a truly ignited system k would remain at or above unity when $P_{EXT} \rightarrow 0$. A truly economic burn would have P_{EXT} very small or zero, otherwise one is dealing with a driven fusion burner with a large P_{EXT} and hence large circulating power. We consider here only ignited cases for which eventually $P_{EXT} \rightarrow 0$. Thus, the "energy increment factor η " due to side thermal reactions at low temperatures is nearly unity, i.e., $P_{SIDE} \ll P_{DT}$ unless there is a significant thermal runaway.

The "resonance escape probability p " measures the direct or high energy losses of the energy of charged fusion reaction products and p is less than unity. Such losses at $E > 3/2T$ and/or $\tau < \tau_E$ may occur as a result of direct collisions with the first wall, charge exchange, escape through the divertor region, etc. For pellet fusion p would include neutron energy losses (and $Q = Q_n + Q_\alpha$). A set of coupled particle conservation equations must also be included.

IV. EXPERIMENTAL STATUS AND PROSPECTS

Table I gives experimental results from the MIT Alcator [13], the ORNL ORMAK [14], the Kurchatov T-10 [15], the Princeton PLT [16], the Fontenay-Aux-Roses TFR [17], the LLL 2XII-B [18], the ORNL DCX-1 [19], and the FEC MIGMA [20]. The present status of plasma experiments are clearly far short of ignition feasibility, whether measured by direct comparison of the f value, i.e., the ratio of experimental $Tn_e \tau_L$ to the ignition $(Tn_e \tau_E)_I$ values at constant T (the energy utilization factor f), or indirectly in terms of f^* , the shortest distance to the nearest ignition $(Tn_e \tau_E)_{I^*}$ (as discussed in the Appendix).

Table II lists the "quantum jumps" which have occurred in the past 18 years as new devices and new physics and technology have emerged. Note that both toroidal devices and magnetic mirrors have exhibited dramatic improvements as measured by either f or f_{10}^* . Thus, tori have advanced by a factor of 10^4 (or 10^4) whereas magnetic mirrors have been improved by 200 (or 70) in f (and f_{10}^*). Both devices still require major improvements in the experimentally achieved $Tn_e \tau_L$ values to attain an f value near unity.

The five tokamaks and the 2XII-B mirror device listed in Table I emphasize large power pulsed heating technologies (large ohmic heating currents and/or intense neutral beam injection). Such approaches pose potential deleterious gas loading and first wall power loading problems which must be overcome to permit the ~ 1000 extrapolations to the ignition requirement.

The steady-state DCX-1 magnetic mirror experiment utilized modest beam power (~ 10 mA of 600 keV H_2^+). Attempts were made to achieve an exponential or vacuum buildup of the fast ion density (exponentiation occurs when the plasma trapping rate exceeds the charge exchange loss rate) which, if successful, would have given about a three-thousandfold increase of density provided ECH (electron cyclotron heating) were used to reduce the stopping power of the cold electrons. The energetic protons were confined for τ_p up to 150 sec; however, the highly organized proton orbits in DCX-1 drove a severe negative mass instability which prevented attainment of the exponential condition and eventually the experiment was terminated. The 2XII-B mirror experiment did achieve exponential density buildup but, because of the extremely large charge exchange loss cross section at the low beam energies, required about 300 A (eq.) of injected neutral deuterium atoms into the 5-liter volume.

The multi-MeV MIGMA mirror experiment presently uses 3 MeV D_2^+ injection and will attempt exponential buildup, as well as Lorentz trapping, and may ascertain the severity of instabilities in a well spread ion velocity distribution. Exponentiation appears much more favorable at these very high ion energies (especially for protons) because of the millionfold reduction of charge exchange losses compared to the 2XII-B case. If instabilities are surmountable, it appears very likely that intense ECH will be required to permit long ranging exponentiation or Lorentz trapping buildup in devices using only modest injection currents (~ 1 mA). The simple magnetic mirror devices may not allow economic fusion power unless the ends are stoppered in some way or one goes to the beam-driven fusion-fission option or the beam-driven, large circulating power pure fusion devices.

The history of controlled fusion research reveals that major experimental progress has been made (see Table II). Much of this progress is due to the development of very intense energetic neutral beams of hydrogen and deuterium atoms. Expectations are high for near-term existing device experiments on PLT, TFR, T-10, and a new ORNL ISX (Impurity Study Experiment), as well as on the next generation device experiments on Princeton's TFTR, the Kurchatov's T-20, and the LLL TMX devices. The author also feels that the prospects for exponential and Lorentz trapping buildup are worthy of further study [9].

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APPENDIX

In order to evaluate the shortest distance from the experimental $T_x n_x \tau_{Lx}$ to the DT ignition curve $T_I n_I \tau_{EI}$, multiply the T abscissa of an $n\tau$ vs T curve by $n_I \tau_{EI}$ and the $n\tau$ ordinate by T_I and evaluate the shortest distance as

$$d = \sqrt{(T_I n_I \tau_{EI} - T_x n_x \tau_{Lx})^2 + (n_I \tau_{EI})^2 (T_I - T_x)^2}$$

$$= (T n_e \tau_E)_I \sqrt{\left(1 - \frac{n_{ex} \tau_{Lx}}{n_e \tau_{EI}}\right)^2 + \left(1 - \frac{T_x}{T_I}\right)^2}$$

In the general case one has for DT when $T_i = T_e$ and there are no impurities

$$(T n_e \tau_E)_I = \frac{12 T_I^2}{\langle \sigma v \rangle_{DT} Q_+}$$

where $Q_+ = 3520$ keV. This equation then gives an exact expression for d which should be used as one approaches ignition since ignition may occur at any temperature within certain limits (e.g., bremsstrahlung losses in a DT plasma give a minimum T_I of about 4.5 keV and a maximum T_I of about 700 keV in the case of $T_i = T_e$ and optically thin plasmas).

For a simple evaluation in terms of the nearest $(T n_e \tau_E)_I^*$ value take $T_I \sim 10$ keV and $n_e \tau_{EI} \sim 3 \times 10^{14}$ cm⁻³ sec. Defining f_{10}^* as $T n_e \tau_L / (d + T n_e \tau_L)$ gives

$$f_{10}^* = T n_e \tau_L / \left(3 \times 10^{15} \sqrt{\left(1 - \frac{n_e \tau_L}{3 \times 10^{14}}\right)^2 + \left(1 - \frac{T}{10}\right)^2} + T n_e \tau_L \right)$$

Tables I and II tabulate this "nearest" energy utilization factor for a number of experimental plasma cases. $f_{10}^* \rightarrow 1$ as a maximum.

TABLE I. EXPERIMENTAL ACHIEVEMENTS IN PLASMA DEVICES AND COMPARISON
WITH SCIENTIFIC FEASIBILITY IGNITION REQUIREMENTS

Device	T(keV)	n_e (cm ⁻³)	τ_L (sec)	$Tn_e \tau_L$	Direct ^a f	Indirect ^b f_{10}^*
Alcator	0.7	$(1.4 \times 10^{13} \text{ cm}^{-3})$	10^{-3} sec	10^{13}	$<10^{-5}$	2.5×10^{-3}
ORMAK ^c	1.8	$(2.3 \times 10^{11} \text{ cm}^{-3})$	10^{-3} sec	4×10^{11}	5×10^{-6}	10^{-4}
ORMAK ^d	1.3	$(1.3 \times 10^{12} \text{ cm}^{-3})$	10^{-3} sec	1.7×10^{12}	7×10^{-6}	4×10^{-4}
T-10	0.8	8×10^{13}	0.04	2.6×10^{12}	$<5 \times 10^{-6}$	7×10^{-4}
PLT	1.0	1.1×10^{14}	0.04	4.4×10^{12}	10^{-5}	10^{-3}
TFR	0.95	7.1×10^{13}	0.017	1.2×10^{12}	2.5×10^{-6}	5×10^{-4}
2XII-B	9.	$(7 \times 10^{10} \text{ cm}^{-3})$	10^{-3} sec	6×10^{11}	2×10^{-4}	2×10^{-4}
DCX-1	300 ^e	10^8	150	(4.5×10^{12})	(1.4×10^{-5})	(5×10^{-5})
MIGMA	1500 ^e	$(2 \times 10^9 \text{ cm}^{-3})$	10^{-3} sec	(3×10^{12})	(1.4×10^{-6})	(7×10^{-6})

^aEnergy utilization factor $f = Tn_e \tau_L / (Tn_e \tau_E)_I$ at same temperature.

^b"Nearest" energy utilization factor, f_{10}^* (see Appendix).

^cORMAK with neutral beams.

^dORMAK with neutral beams and gas puff.

^eInjection energy, not a temperature.

TABLE II. CHRONOLOGICAL JUMPS IN RELATIVE $Tn_e \tau_L$ VALUES

Type	Device	Year	Experiment	T(keV)	n_e (cm ⁻³)	τ_L (s)	$Tn_e \tau_L$	f	f_{10}^*
Tori		1958	Stellarator	<0.1	$\sim 10^{14}$	10^{-4}	$<10^9$	$<10^{-9}$	$<3 \times 10^{-7}$
		1968	Tokamak T-3	0.5	5×10^{13}	7×10^{-3}	2×10^{11}	$<2 \times 10^{-7}$	5×10^{-5}
		1976	Alcator	0.7	(1.4×10^{13})		1×10^{13}	$<10^{-5}$	2.5×10^{-3}
Mirrors		1958	DCX-1 ^a	(300) ^b	10^{11}	0.01	(3×10^{11})	(1×10^{-6})	(3×10^{-6})
		1966	DCX-1 ^c	(300) ^b	10^8	150.	(4.5×10^{12})	(1.4×10^{-5})	(5×10^{-5})
		1976	2XII-B	9.	(7×10^{10})		6×10^{11}	2×10^{-4}	2×10^{-4}

^aWith carbon arc as localized dissociator of injected H_2^+ ions.

^bInjection energy, not a temperature.

^cWith very low background gas density.

Fig. 1. The ignition parameter $(Tn_e \tau_E)_I$ vs kinetic temperature T with $T = T_i = T_e$.

Fig. 2. Schema illustrating radiation dominated, closed, pulsed, pure DT burn. The ignition temperature is unstable and the plasma will quench below T_{IGN} if the external power is turned off, or undergo a thermal runaway above T_{IGN} independent of P_{EXT} . The burning or operating temperature will be lower in the presence of additional energy and/or particle losses or ash buildup.

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