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A Simple Measure of Merit for Fusion Feasibility

J. Rand McNally, Jr.

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CONTENTS

ABSTRACT	v
1. INTRODUCTION	1
2. THE SIMPLE MERIT FACTOR	2
3. EFFECT OF BEAM-PLASMA REACTIONS ON THE IGNITION CONDITIONS IN TFTR	4
4. SUMMARY AND COMMENTS	6
REFERENCES	7

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ABSTRACT

A simple merit factor for fusion related experiments is discussed in terms of several fusion goals and compared with past and present experimental achievements. The merit factor is taken to be $M = \log_{10} k$, where k is the four-factor fusion formula ($f_n \epsilon p$) and represents the fusion energy multiplication factor defining ignition for $k \geq 1$ or $M \geq 10$. The value of k can in most present cases be approximated by f , the thermal energy utilization factor, which equals the ratio of the alpha particle fusion power to the thermal power losses from the plasma. For upcoming large tokamak experiments, such as TFTR, the fast fusion factor ϵ due to beam-plasma reactions may appreciably exceed unity and thus reduce the $Tn\tau_E$ requirements for ignition through f . In the past 20 years, M has increased by six units and k or f by 10^6 !

1. INTRODUCTION

It would be very useful to have a simple merit factor on a scale of ten defining the nearness of existing fusion related experiments to various goals of scientific feasibility for fusion. Analogous to criticality in fission reactors there is a thermal energy multiplication constant, k , which represents the goal of plasma ignition when $k \geq 1$ in a pure DT plasma. Thus, if we define the merit factor as simply $M = \log 10^{10} k$ we obtain a useful measure of merit on a scale of ten for ignition.

The four-factor fusion energy multiplication constant is $k_{\infty} = f\eta\epsilon p$, where f is the thermal energy utilization factor due to DT thermonuclear reactions, η is the energy increment factor due to side reactions (e.g., DD, TT, $D^3\text{He}$, $T^3\text{He}$, and $^3\text{He}^3\text{He}$), ϵ is the fast fusion factor due to nonthermal (i.e., suprathermal or beam-plasma reactions), and p is the fusion alpha particle energy nonescape probability.¹ The f term can be expressed as $P_{\alpha}/P_{\text{loss}} = (Tn\tau_E)_{\text{exp}}/(Tn\tau_E)_{\text{ign}}$, where P_{α} is the alpha particle power produced in DT reactions, P_{loss} is the thermal power loss which equals $3nT/\tau_E$ for a pure DT plasma in temperature equilibrium, $(Tn\tau_E)_{\text{exp}}$ represents the experimentally achieved value of $Tn\tau_E$, and $(Tn\tau_E)_{\text{ign}}$ represents the theoretical ignition value for $Tn\tau_E$ in a pure DT thermalized plasma. T is the kinetic temperature in keV, $n (= 2n_D = 2n_T$ in a pure DT plasma) is the electron density in cm^{-3} and τ_E is the thermal energy confinement time in seconds. In the fusion case, $k_{\infty} = k$ if there are no profile or finite size effects analogous to buckling or leakage probabilities in fission reactors, otherwise $k_{\infty} < k$. The ignition definition in this note is $k_{\infty} = k = 1$.

Assuming that the energy increment factor η , due to side reactions, is unity (at $T = 10$ keV it is about 1.05 in a pure DT plasma) and that the nonescape probability p for fusion alpha particles is also unity (for TFTR it should be about 0.9 for alphas born at the axis²), one obtains $k \sim f\epsilon$. In the next section, we take $\epsilon \equiv 1$ and discuss the goals and achievements in terms of f and M values. In a later section, we evaluate ϵ for TFTR on the assumption that 170 A of 120 keV deuterons are injected into a pure DT, thermalized plasma at 10 keV — as we shall see for this optimized case, ϵ may be of order three and f , in this case, perhaps only needs to be one-third for ignition.

2. THE SIMPLE MERIT FACTOR

The simple merit factor is defined as $M = \log 10^{10} f$ on the assumption that $n\tau_E \equiv 1$. Figure 1 illustrates $Tn\tau_E$ ignition values vs kinetic temperature for three selected fusion fuels (DT, catalyzed DD, and D^3He). Here, $f = 1$ for DT ignition. DT curves falling below the $f = 1$ curve ($f = 10^{-1}$, 10^{-2} , etc.) are also given as well as the Lawson breakeven curve for DT and the DT energy breakeven curve for zero blanket energy release ($E_B = 0$). Numerous experimental points are also indicated in Fig. 1. All experimental points for magnetic confinement shown in Fig. 1 fall below $f = 10^{-3}$ (or $M = 7.0$). Thus, present magnetic confinement devices are a factor of 1000 away from ignition. The f value for any particular experiment is the ratio of $(Tn\tau_E)_{\text{exp}}$ to $(Tn\tau_E)_{\text{DT ign}}$ taken at the same temperature, or $M = 10 + \log(Tn\tau_E)_{\text{exp}} - \log(Tn\tau_E)_{\text{DT ign}}$. Here, f is also equal to P_α/P_{loss} .

Values of f and M are tabulated for several potential goals and actual achievements in Table 1 (see Fig. 2). M ranges from 1.0 ($f = 10^{-9}$) for the 1958 stellarator achievement to 7.3 ($f = 0.002$) for the laser-pellet case (DT gas in glass "pellet") attained at Lawrence Livermore Laboratory.³

There are several proximate goals which should be achieved earlier than simple ignition of pure DT fuel ($f = 1.0$ or $M = 10.0$). The Lawson criterion utilizes the 3.52 MeV alpha particle energy and the 14.07 MeV neutron energy, plus a thermodynamic conversion efficiency of one-third to attain an overall energy breakeven condition but neglecting magnet power and other power inputs. This Lawson criterion is approximately one-half as difficult to achieve as the simple ignition condition (see Fig. 1). Ordinary energy breakeven, not counting the efficiency of the thermal convertor (and that of the associated reheat injection system), occurs at about 0.2 (i.e., $3.52/17.59$) of the simple DT ignition value. Utilizing the energy released by a neutron on capture in a blanket of ^6Li (4.8 MeV/n), Na (12.6 MeV/n), ^{232}Th or ^{238}U breeding blankets (≤ 200 MeV/n), or subcritical fission blankets (up to ~ 1000 MeV/n) will in principle ease the goal requirements somewhat further (see Table 1 for case $E_B = 200$ MeV/n). Achievement of any one of these goals will represent a significant milestone even though energy breakeven according

FUSION EXPERIMENTS PROGRESSING TOWARD GOALS OF BREAKEVEN AND IGNITION AS MEASURED BY $T_i \tau_E$

Fig. 1. Inverse power density plot ($T_e \tau_E$) vs kinetic temperature (+ indicates mean ion energy due primarily to beam ions and does not represent a thermalized Maxwellian plasma). Experimental points and ignition curves ($f = 1.0$) for DT, DD (catalyzed), and $D^3\text{He}$ are illustrated as well as the Lawson curve and energy breakeven curve with blanket energy $E_B = 0$.

Table 1. Merit factors for selected experiments and goals*

G or A	f	M	Reference
Ignition	1.0	10.0	1
Lawson criterion	0.5	9.7	1
Energy breakeven ($E_B = 0$)	0.2	9.3	-
Energy breakeven ($E_B = 200$ MeV)	0.016	8.2	-
LLL-DT pellet	2×10^{-3}	7.3	3
PLT (1.1 MW I) [†]	(10^{-3})	(7.0)	5
2XII-B [†]	(2×10^{-4})	(6.3)	1
Alcator (GP)	$<3 \times 10^{-5}$	<5.5	1
TFR (I + GP)	2.6×10^{-5}	5.4	1
PLT (1.1 MW I)	2×10^{-5}	5.3	5
DCX-1 [†]	(1.4×10^{-5})	(5.1)	1
ORMAK (I + GP)	10^{-5}	5.0	1
MIGMA [†]	(1.4×10^{-6})	(4.1)	1
T-3 (1968)	$<2 \times 10^{-7}$	<3.3	1
Stellarator (1958)	10^{-9}	1.0	1

*G = Goal, A = Achievement, I = Injection, GP = Gas Puff.

[†]Using $\bar{E}_i(0)$, not $T_i(0)$. This mean energy (due to beams primarily) does not provide a good indicator due to lack of Maxwellianization and thermalization of the particles.

ORNL/DWG/FED 78-246

Fig. 2. Time dependence of merit factor M suggesting that, with comparable improvements in the future, ignition might be achieved in toroidal devices after 1990.

to any definition used here does not represent even zero net electrical power output, since magnet and refrigerator power as well as other power inputs may be involved as are discussed below.

The various goals of energy breakeven can be achieved more easily than that of "ignition," which counts only the trapped fusion alpha energy, whereas energy breakeven includes the neutron energy plus energy release in a blanket on neutron capture. It should be noted, however, that certain inefficiencies (lasers, beam production, etc.) plus a thermal conversion efficiency of about 0.35 make ignition the desirable economic goal, i.e., M should be 10.0 or more, dependent on profile or finite size effects analogous to buckling or leakage probabilities in fission reactors ($k_{\infty} < k$). With ignition, one may then be able to reduce or hopefully turn off the heat sources required to reach the ignition point after which fusion alphas drive the plasma. The burning or operating temperature will be somewhat higher than the ignition temperature due to the thermal instability (sometimes called thermal runaway or escalation to the burning temperature) which occurs at ignition.

Nozawa and Steiner suggested that the required energy or power multiplication Q_c (= fusion produced power including Li blanket power release of 4.8 MeV per neutron/plasma heating power) should be at least 0.759 for mirror fusion reactors, 2.34 for tokamak fusion reactors, 4.62 for theta pinch reactors, and 65.8 for laser fusion reactors in order to give overall energy or "economic" breakeven, including magnet and injection power and various efficiencies.⁴ To give significant electrical power output free from extraneous losses such as circulating power, downtime, etc., one would probably need to achieve at least $Q_c = 3$. Thus, net electrical power systems would need to operate at $f \geq 2$ to 200 or $M \geq 10.3$ to 12.3 for these four cases assuming no thermal instability at ignition.

The table may be readily used to compare one experiment with another or with the various possible goals by evaluating $10^{M_i - M_j}$. Thus, the Livermore DT pellet (gas in glass microsphere)³ is a factor of 100 away from energy breakeven ($E_B = 0$) or 500 away from ignition — the closest of all experimental systems to these simple breakeven definitions [although the PLT-(1.1 MW I)[†] case⁵ is within a factor of two of the LLL-DT pellet case but correspondingly much closer to "economic" breakeven — see above].

As is true of all cases, the efficiency of the laser (or beam ohmic heating and/or magnet and refrigerator power supplies in the other cases) must be factored in to evaluate an overall system efficiency.

There may be a plasma gain factor of several to possibly 100 should ignition occur as a result of the associated thermal instability at ignition. This would compensate some of the inefficiency of plasma production. In order for a steady-state device to be economic, one would satisfy at least $k = 1$ even with some ashes present, with hot ash exhaust, and with radiation losses — and potentially with cold fuel feed. Advanced fusion fuels require $M > 10.0$ although DT ignited fuel may have a thermal instability sufficient to increase $Tn_e\tau_E$ to their ignition range [compare DT with DD (catalyzed) and D^3He in Fig. 1 — see Ref. 1 for other fuels].

3. EFFECT OF BEAM-PLASMA REACTIONS ON THE IGNITION CONDITIONS IN TFTR

The ignition condition for a fusion reactor is defined by the four-factor fusion multiplication constant¹

$$k = f n_e \epsilon \geq 1.0 ,$$

where the fast fusion factor (or beam-plasma factor) is approximately

$$\epsilon \approx 1 + \frac{P_{BP}}{P_{DT}} ,$$

where P_{BP} is the power released by suprathermal DT reactions as the deuterons slow down and P_{DT} is the alpha power released in thermal DT reactions. Thus, if ϵ is significantly greater than unity due to the contribution of beam-plasma reactions, the simple ignition condition for a pure DT plasma becomes

$$f = \frac{(Tn_e\tau_E)_{exp}}{(Tn_e\tau_E)_{ign}}$$

$$= \frac{1}{\epsilon}$$

at $T = T_e = T_i = 10$ keV (for which $n_p \sim 1.0$ in TFTR — see earlier discussion).

The value of ϵ can be obtained using the f_{DFT} factor of Dawson, Furth, and Tenney⁶ which we redefine in terms of f' here, i.e., f' is the fusion energy release probability factor for an energetic deuteron reacting during its slowing down in a pure deuterium-tritium plasma. We further choose $f' = f_{\text{DFT}}/2$ for a 50:50 DT plasma since for easiest ignition one requires a DT plasma and 50:50 is near optimum at 10 keV. We also have

$$f' = \frac{f_{\text{DFT}}}{2} = \frac{FW_0}{E(2)} \sim \frac{1.75(120)}{22,400(2)}$$

for the TFTR 120-keV deuteron, $E = 22,400$ keV, and $F \approx 1.75$ at $T = 10$ keV from Fig. 3 and Ref. 6. The F factor of Dawson, Furth, and Tenney is equivalent to the Q_c definition of Nozawa and Steiner (see page 3).

Since 170 A(equivalent) of D^0 will be injected into TFTR, we optimistically take D^+ feed to the plasma as 170 A. Neglecting profile effects this leads to

$$\epsilon = 1 + \frac{If'Q_+}{2\pi^2 R a^2 \left(\frac{1}{4} n_e^2 \langle \sigma v \rangle Q_+\right)},$$

and taking for TFTR

$$R = 250 \text{ cm}$$

$$a = 85 \text{ cm}$$

$$I = 170 \text{ A} = 170(6 \times 10^{18}) D^+/\text{sec}$$

$$n_e = 10^{14} \text{ e/cm}^3$$

$$\langle \sigma v \rangle = 1.1 \times 10^{-16} \text{ cm}^3/\text{sec at } 10 \text{ keV}$$

we obtain

$$\epsilon = 1 + 0.48 \text{ for } n_e = 10^{14} \text{ e/cm}^3$$

or in general

$$\epsilon = 1 + 0.48 \times 10^{28}/n_e^2.$$

Thus, the fast fusion or beam-plasma contribution will be small unless the TFTR density is low; for example, if $n_e = 5 \times 10^{13} \text{ e/cm}^3$, ϵ becomes ~ 3 and the requirement for f is thereby reduced three-fold.

It should be noted that the volume filled by the injected beams, especially in a low-density peaked profile case, will be reduced and ϵ will increase further, provided the deuteron trapping fraction is not reduced. Dilution of the 50:50 DT mixture by added deuterons (or tritons or buildup of alphas or other impurities) will reduce the thermal energy utilization factor or f factor by increasing $(Tn\tau_E)_{\text{ign}}$, thus requiring ϵf to be somewhat larger than unity to achieve ignition.

Conn, Houlberg, and Kesner⁷ and Conn and Kesner⁸ indicate that DT thermonuclear reactions in a 50:50 DT mixture make a very significant contribution to the Q -factor compared to the two component or beam-plasma tokamak contributions (see Fig. 6 of Ref. 7 which is presented here as Fig. 4).

4. SUMMARY AND COMMENTS

Major advancements have been made in our progress toward controlled fusion (compare the Stellarator of 1958, the T-3 tokamak of 1968, and the more recent accomplishments in magnetic and inertial confinement as illustrated in Fig. 2 and Table 1). Thus, in the past 20 years, M has increased by six units and k or f by 10^6 !

There is still a long way to go to demonstrate energy breakeven and especially ignition. It is hoped that this perhaps sobering measure of merit for experimental fusion devices will serve as a catalyst for improving present and proposed experiments, and generate new ideas for major improvements in present or proposed devices, and perhaps rejuvenate discarded but potentially promising concepts to bring fusion power closer to actuality.

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Fig. 3. Energy multiplication factor F as a function of deuteron injection energy W_0 for various electron temperatures of cold triton-target plasma, assuming total energy release of 22.4 MeV (see Ref. 6).

Fig. 4. Optimum Q as a function of plasma current for $Z_{\text{eff}} = 1$ (Ref. 7). Note that the charged particle Q_+ is one-fifth of the Q ordinate.

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