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ON CTR BREAKDOWN INCLUDING ENERGY TRANSFER AND RECOVERY EFFICIENCIES

by

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ABSTRACT

Breakdown conditions for controlled thermonuclear reactions (CTR) are addressed. Simple but general equations are presented which include energy transfer (ϵ_i) and recovery (η_i) efficiencies for energies in various forms. A general equation for breakdown is developed, showing the sensitivity of the efficiency factors. Each experiment will have its own breakdown curve, depending on the η 's and ϵ 's.

I. INTRODUCTION

The simple Lawson criterion for CTR breakdown^{1,2} does not include separate transfer and recovery efficiencies for each of various energy forms. We attempt here to update the breakdown criterion by formulating breakdown in general but still somewhat simple terms amenable to easy use. We include transfer efficiencies, i.e., that fraction ϵ_i of input energy E_0 that ends up in some other form (e.g., thermal, radiation, fields). We also include recovery efficiencies η_i , i.e., the fraction of energy in the system in the i^{th} form that can be recovered in one manner or another for recycling or conversion.

The efficiencies can be invoked into general equations together with only a few assumptions, to give solutions for $n\tau = f(T, \eta_i, \epsilon_i)$ where n is the ion number density, τ is the plasma confinement time, and T is the plasma temperature. A point that emerges is that each experiment has its own breakdown curve, depending on the ϵ_i 's and η_i 's.

II. GENERAL EQUATIONS

Consider an equal mixture of deuterium (D) and tritium (T) in a pulsed CTR experiment that is powered with some input energy E_0 needed for the first cycle. This energy will appear in various forms in the system.

We assume a Maxwellian distribution in the plasma, nonrelativistic species, and $T = T_e = T_i$. Then for input energy balance, the terms of prime

but still general interest are:

$$E_0 = E_p + E_b + E_k + E_c + E_m = E_0 \sum \epsilon_i \quad (1)$$

where,

$$E_p = \epsilon_p E_0 = \text{plasma thermal} = \int \frac{3}{2} kT(t) \eta_i(t) dv^* \quad (1a)$$

$$E_b = \epsilon_b E_0 = \text{Bremsstrahlung} =$$

$$= \iint 5.35 \times 10^{-31} n_e(t) \sum [\eta_i Z_i^2] T^{1/2} dv dt; \quad (1b)$$

$$E_k = \epsilon_k E_0 = \text{plasma kinetic}$$

$$= \frac{1}{2} M V^2 = \frac{1}{2} \sum m_i n_i V^2; \quad (1c)$$

$$E_c = \epsilon_c E_0 = \text{cyclotron (with pressure balance)}$$

$$= \iint_{V_s} 5 \times 10^{-32} n_e^2 T^2 dv dt; \quad (1d)$$

$$E_m = \epsilon_m E_0 =$$

energy in electric and/or magnetic fields, (1e)

and dv = elemental volume, V_p , V_s , and V_{KE} are, respectively, the volumes associated with the thermal plasma, the skin depth, and the plasma in global motion, with dt = time increment, Z = stripping number, n_i = species number density, m_i = mass of i^{th} species particle, and $0 \leq \epsilon_i < 1$, $\sum \epsilon_i = 1$.

*Including electrons but neglecting binding energies.

Fig

In Eqs. (1) we have, in a sense, used a peculiar energy breakdown by distributing E_o between E_p , E_b and E_c independently when they are in fact coupled, both together and with E_m . For example, E_b and E_c might be drawing upon E_p during the confinement time. Nevertheless, at the end of that time, one certainly has energy balance, $E_o = E_p + E_b + E_c + \dots$, where the RHS of Eq. (1) contains the energy left in the plasma at that time, the Bremsstrahlung radiation up to that time, etc. Used above, E_p is the plasma thermal energy at the end of confinement time, and what follows implies the assumption that E_p (end) $\sim E_p$ (average, during τ). For detail, coupled rate equations should also be considered,³ which in general would include bootstrap heating from fusion products.⁴ Nonetheless, we proceed here with the format of Eqs. (1) because it is similar to Lawson's;¹ and gives results that are instructive in terms of functional dependencies and sensitivities.

We now assume that impurities are negligible, and $n = \sum_i n_i$ ($n_o = n_T = 1/2 n$, $n_d n_T = 1/4 n^2$), whence

$$P_b = 5.35 \times 10^{-31} n^2 T^{1/2}, \quad (2)$$

and

$$P_c = 5.0 \times 10^{-32} n^2 T^2. \quad (3)$$

We further assume that mean values can be assigned to T , the various V 's, t 's, and n . This then allows the introduction of normalization factors:

$$\xi_{c,b,k} = V_{c,b,k}/V_p, \quad (4)$$

$$\phi_{c,b,k} = \tau_{c,b,k}/\tau_p, \quad (5)$$

where $\tau_p = \tau$, and $V_p = V$ (volume).

Thus Eq. (1) may be rewritten as

$$E_o = E_o \sum_i \xi_i$$

$$3nkT + \phi_b \xi_b P_b V \tau + \phi_c \xi_c P_c V \tau + \phi_k \xi_k \lambda n V + E_m, \quad (6)$$

where λ involves the particle masses and mean velocity of the total mass. Using $E_o = 3nkTV/\xi_1$, and solving Eq. (6) for E_m yields:

$$E_m = 3nkTV \left(\frac{1}{\xi_1} - 1 \right) - \phi_b \xi_b P_b V \tau - \phi_c \xi_c P_c V \tau - \phi_k \xi_k \lambda n V. \quad (7)$$

We now consider breakeven. Note for DT:

$$D + T \rightarrow He^{(4)} (3.5 \text{ MeV}) + n (14.1 \text{ MeV}). \quad (8)$$

In discussing breakeven it was assumed by Lawson that the neutron energy was lost, and thus

$$P_f = \text{fusion power density} = 5.6 \times 10^{-13} \langle \sigma v \rangle n_d n_T, \quad (9)$$

where

$$\langle \sigma v \rangle|_{DT} = \frac{3.68 \times 10^{-12}}{T^{2/3}} \exp \left(-\frac{19.94}{T^{1/3}} \right), \quad (10)$$

for lower T 's (see page 18, Ref. 2). Here we generalize and include neutron energy, by introducing the quantity $f \equiv f_I + f_N$, where f_I relates to the ion energy and f_N relates to the neutron energy such that $0 \leq f \leq 5$, $0 \leq f_I \leq 1$, and $0 \leq f_N \leq 4$. The f 's are taken to be the fractions of recoverable fusion energy.

We now define various η 's to be recovery efficiencies. A similar approach is used by Nozawa and Steiner.⁵ Then for breakeven,

$$(\eta_I f_I + \eta_N f_N) P_f V \tau + E_o \sum_i \eta_i \xi_i = E_o. \quad (11)$$

Introducing $P_f = n^2 F$ where $F = \langle \sigma v \rangle$, $P_b = n^2 B$, and $P_c = n^2 C$, then Eq. (11) may be rewritten as:

$$\begin{aligned} & (\eta_I f_I + \eta_N f_N) n^2 F V \tau + \eta_p 3nkTV + \eta_b \phi_b \xi_b n^2 B V \tau \\ & + \eta_k \phi_k \xi_k \lambda n V + \eta_c \phi_c \xi_c n^2 C V \tau + \eta_m E_m = \\ & 3nkTV + \phi_b \xi_b n^2 B V \tau + \phi_k \xi_k \lambda n V \\ & + \phi_c \xi_c n^2 C V \tau + E_m, \end{aligned} \quad (12)$$

where F , B , and C are only functions of T .

Substituting Eq. (7) into Eq. (12) and rearranging,

$$\begin{aligned} & n \tau |_{REQ'D} = \\ & \frac{3kT[(1 - \eta_p) + (1 - \eta_m)(\frac{1}{\xi_1} - 1)] + (\eta_m - \eta_k)\phi_k \xi_k \lambda}{(\eta_I f_I + \eta_N f_N)F + (\eta_b - \eta_m)\phi_b \xi_b B + (\eta_c - \eta_m)\phi_c \xi_c C}. \end{aligned} \quad (13)$$

If global kinetic energy and cyclotron radiation are negligible ($\lambda = C = 0$), Eq. (13) becomes:

$$n\tau|_{REQ'D} =$$

$$\frac{3kT[(1 - \eta_p) + (1 - \eta_m)(\frac{1}{\epsilon_p} - 1)]}{(\eta_I f_I + \eta_N f_N)F + (\eta_b - \eta_m)\phi_b \xi_b B} \quad (14)$$

which shows, as in Eq. (13), that if $\eta_m = 1$ then $n\tau$ becomes independent of ϵ_p explicitly.

If $\epsilon_m = \eta_N = 0$, $f_I = \phi_b = \xi_b = \epsilon_p = 1$, $\eta_p = \eta_b = \eta_I = 1/3$, then Eq. (14) reduces to

$$n\tau = \frac{6kT}{F - B} \quad (14a)$$

which is the classical Lawson criterion. Note that $\epsilon_m = 0$ and $\epsilon_p \sim 1$ are not realistic.

In a real world CTR reactor, kinetic, thermal, cyclotron, bremsstrahlung, and fusion-ion energies will probably be recovered by the same process, with some efficiency η ($= \eta_p = \eta_b = \eta_k = \eta_c = \eta_I$), where $\eta \sim 0.40$ for a modern boiler-steam generator cycle. With magnetic energy transfer and storage, η_m may be as high as ~ 0.62 . (Ref. 6)

Remarks on Eqs. (13-14):

- Because η_m will probably exceed η_k , it is desirable to have $\phi_k \xi_k \lambda = 0$.
- If $\eta_m > \eta_c$, η_b , the denominator gets smaller and thus $n\tau$ gets larger, unless $\phi_b \xi_b B$ and $\phi_c \xi_c C$ are small. Because $\phi_b \xi_b B$ cannot be eliminated, it is at least desirable to eliminate $\phi_c \xi_c C$. In another sense, this implies that a high- β plasma is desirable.
- It is desirable to make η_N as large as possible.
- It is desirable to make $\eta_{p,b,k,c,I}$ as large as possible.
- If η_N also is ~ 0.40 , $\eta_{p,b,k,c,I} \sim 0.40$, and $\eta_m \sim 0.62$, then Eq. (14) becomes

$$n\tau = \frac{3kT[0.60 + 0.38(\frac{1}{\epsilon_p} - 1)]}{[0.4fF - 0.22\phi_b \xi_b B]} \quad (14b)$$

- It is obviously desirable to make ϵ_p as large as possible.
- Assuming $\phi_b = \xi_b = 1$, then Eq. (14b) becomes

$$n\tau = \frac{3kT[0.60 + 0.38(\frac{1}{\epsilon_p} - 1)]}{[0.4fF - 0.22(5.35 \times 10^{-31})T^{1/2}]} \quad (14c)$$

where $F = \langle \sigma v \rangle$.

III. COMPUTATIONAL RESULTS

For a computational example we use Eq. (14c).

We assume that all fusion neutrons and ions can be captured, and their energy converted to heat. Thus, $f = 5$, ($f_I = 1$, $f_N = 4$).

For computational purposes, Eq. (14c) reads

$$n = \frac{3kT[0.60 + 0.38(\frac{1}{\epsilon_p} - 1)]10^{19}}{0.4(5)\langle \sigma v \rangle - 0.22(5.35 \times 10^{-31})T^{1/2}}, \quad (14d)$$

where $k = 1.38 \times 10^{-23}$ (J/°K), T is in keV, $\langle \sigma v \rangle$ is in $\text{cm}^3 \text{s}^{-1}$ from page 19 of Ref. 2, and the factor 10^{19} in the numerator converts the numerator to consistent units with the denominator using 1 keV $= 10^7$ °K and $10^6 \text{ cm}^3 = 1 \text{ m}^3$.

Equation (14d) is plotted in Fig. 1 for various ϵ_p and for $T = 3$ to 100 keV.

Here again it is unrealistic to expect $\epsilon_p \sim 1.0$, i.e., that all the power supply energy ends up in $3nkT$. If $\epsilon_p = 10\%$, Fig. 1 shows that breakeven would be achieved for $n\tau = 10^{15}$ and $T > 3$ keV.

For comparison and checks in calculation method consistency, we have computed breakeven on the basis of Lawson's formulation. For computational purposes, Eq. (14a) becomes

$$n\tau|_{\text{Lawson}} = \frac{6kT \cdot 10^{19}}{\langle \sigma v \rangle - 5.35 \times 10^{-31} T^{1/2}} \quad (14e)$$

with the same term units as above. Results are shown in Fig. 2, in agreement with Lawson and Linhart's calculations.⁷

When the $\epsilon_p = 1.0$ curve of Fig. 1 is compared to the Lawson curve shown in Fig. 2, it is seen that the former lies further to the left. This is due to

Fig. 1. Breakeven curves for various ϵ_p .

Fig. 2. Lawson's breakeven curve and performance of various plasma experiments

the fact that we have stipulated that all fusion neutrons are captured, and have used a thermal-to-electric conversion efficiency of 40%, versus Lawson's 33%. Because ~ 80% of the fusion energy is released in neutron kinetic energy, the $\epsilon_p = 0.20$ curve of Fig. 1 should be in rough agreement with the Lawson curve of Fig. 2; inspection shows that this is the case.

IV. DISCUSSION

In past years it was perhaps heuristically valid to compare the status of one's experiment to the Lawson curve (see Fig. 2) because all experiments were a considerable "distance" from breakeven in the $n\tau$ versus T plane. Yet such comparisons are, in general, not valid for at least two reasons:

- 1) The Lawson criterion assumes $\epsilon_m = 0$ and $\epsilon_p \sim 1.0$, which are not realistic.
- 2) All ϵ_i 's, η_i 's, ϕ_i 's, and ξ_i 's should at least be considered, via Eq. (13). The point is that each experiment will have its own breakeven curve, because each experiment has its own unique ϵ 's and η 's.

We have neglected the effects of impurities in the above discussion. High-Z gases containing many internal energy states are "soft", i.e., they can absorb energy with relatively less change in temperature as compared to an ideal gas. Unless fully ionized, the expression for internal energy of a

high-Z gas will be rather complex.^{8,9} Also, $P_b \propto Z_j^2$ [see Eq. (1b)]. Impurities in the plasma should move the breakeven curves (of Fig. 1) upward and to the right.

If η_m can be made greater than the value 0.62 used above, then $n\tau$ could be reduced. Also note that f_N may effectively exceed the value of 4.0 used. The energy released by moderated neutrons captured in ${}^6\text{Li}$ (tritium breeding) via

supplies additional energy for conversion. The ${}^6\text{Li}$ constitutes ~ 7.5 atomic percent of natural lithium.² This added energy will also somewhat reduce the required $n\tau$.

Note also that there are many possible paths or trajectories in the $n\tau$ -vs- T plane for moving towards breakeven.

For example, most magnetically controlled thermonuclear reaction (MCTR) experiments currently fall to the left or lower left of breakeven (see Fig. 2), and experimental efforts are to move performance upward and to the right, across the breakeven curve. But the "shortest distance" may not be the easiest or most efficient.

There are several other paths that could be pursued in the $n\tau$ -vs- T plane. One possibility which has been discussed is the concept of heating "magnetically prepared" plasmas with lasers.

Shatas, et al.,¹⁰ discuss this possibility for the dense plasma focus wherein a CO_2 laser would be used; others¹¹ have also been interested in pursuing this.

Hertzberg, Vlases and Hoffman¹² have been investigating laser heating of a linear θ -pinch. We understand that an experiment for laser heating of the Scylla 1-B θ -pinch is under development.¹³

The basic process involves exciting plasma electrons with laser light, whence the (hotter) electrons then heat ions. To heat the electrons, the laser frequency,

$$\omega_L = \frac{2\pi c}{\lambda_L} \quad (16)$$

should be close to but greater than the electron plasma frequency

$$\omega_{pe} = 5.63 \times 10^4 \sqrt{n_e}, \quad [n_e \text{ in cm}^{-3}]. \quad (17)$$

Thus if $\lambda_L \sim 10.6 \mu$ (CO_2) then the desired $n_e \sim 10^{19} \text{ cm}^{-3}$. In general $\lambda_L \sim n_e^{-1/2}$.

For current regimes of operation, Fig. 2, laser heating would miss the knee of the Lawson curve. We suggest a different path in the n - T plane for theoretical consideration. The conceptual path is indicated by the dashed line in Fig. 2:

1. Increase the MCTR nT by raising n . For a given power supply energy, T will be lowered. In short, try to move existing MCTR experiment performance under the knee of the breakeven curve to point (L).
2. Then heat with a gas laser, moving performance upward across the breakeven curve. During this phase the confining field may have to be increased.

The laser frequency needed will be determined by the n achieved at point (L) and by the laser-beam/plasma coupling efficiency desired.

Note that long ($> 100 \text{ ns}$) laser pulses would probably be acceptable. For such pulse widths, gas laser efficiency ($E_{\text{beam}}/E_{\text{power supply}}$) may be as high as 25%.¹²

If good laser-beam/plasma coupling efficiencies, say 80%, could be achieved, then the laser-system/plasma coupling efficiency might be as high as $\sim 20\%$. This is extremely important for breakeven where it is desirable to maximize the energy transfer from power supplies to plasma $3nkT$. Most magnetic fusion experiments are currently operating with power supply to plasma $3nkT$ efficiencies on the order of 1%.

For example, let ϵ_m and ϵ_L represent the fraction of energy transferred from E_m (MCTR Power Supply) and E_L (laser power supply) respectively. For a M/L CTR hybrid

$$\begin{aligned} 3nkT &= \epsilon_m E_m + \epsilon_L E_L \\ &= \epsilon_T (E_m + E_L) = \epsilon_T E_{\text{TOTAL}} \end{aligned} \quad (18)$$

Here, ϵ_T is our new ϵ_p that includes the effect of laser heating. Figure 3 shows ϵ_T versus E_L/E_m for $\epsilon_m = 0.01$ and $\epsilon_L = 0.20$. Higher ϵ_m and/or ϵ_L will raise the curve, and vice versa. From the figure, if $(E_L/E_m) = 1$, then $\epsilon_T \sim 10.5\%$, which would be more efficient than either MCTR or LCTR alone; laser/pellet fusion is predicted to be $\sim 7\%$ efficient, whence the curve of Fig. 3 would ultimately fall off to the right if solid targets are also considered.

Fig. 3. Total transfer efficiency for various ratios of laser and magnetic power supply energies.

Other factors such as system Q , circulating power, etc., must all be investigated in a system study to find what point on the ϵ_T versus E_L/E_m graph would be optimum for operation. Several scaling laws have already been investigated by Ellis and Sawyer,^{14,15} though for total laser heating of gaseous DT.

Note that increasing n (and thus sacrificing T) for the magnetic compression phase may help reduce certain instability growths. The growth time $\tau_{ig} \sim 2\pi r/U_e \sqrt{N}$ where N is the mode number (number of flutes) and $U_e = \sqrt{B^2/4\pi\rho}$, $B^2 - P \sim nkT$. Thus $\tau_{ig} \sim \sqrt{\rho/B^2} \sim \sqrt{\rho/T}$. Increased ρ and decreased T would both appear to suppress the instability growth; upon laser heating the increased T would tend to be offset by the increased density operation.

The fusion reaction rate R goes as $R \sim n^2 \langle \sigma v \rangle$, where, in probable regimes of interest (e.g., point (L) on the n - T graph), $\langle \sigma v \rangle \propto T^4$, i.e., $\langle \sigma v \rangle$ is very sensitive to T as shown in Fig. 4. With efficient laser-beam/plasma coupling, small changes in T can give rapid gains in $\langle \sigma v \rangle$, and thus R . The increased n will also aid R ($\propto n^2$). The hybrid concept would thus appear to make maximum use of the most sensitive functions. Further theoretical investigation and optimization is needed.

Heating with pulsed relativistic electron beams is another concept being explored,¹⁶⁻²⁰ though not particularly in the "dog-leg path" concept shown in Fig. 2. For electron beam heating, the effect of the excess electrons on bremsstrahlung radiation, and thus on the breakeven equations, needs to be explored.

Fig. 4. Maxwell velocity-averaged reaction cross-section parameter versus temperature.

The above discussion also assumes a Maxwellian plasma. Theory for hybrid experiments might consider the possibility of using an appropriate beam to excite a bump on the tail of the ion distribution function, as is currently under study for so-called two-component Tokamaks.

Obtaining the desired physics is only the first step in developing a CTR concept. The second step is to achieve sound engineering for a net power CTR reactor in terms of reliability, safety, and longevity²¹ (e.g., minimize material damage from radiation). Finally, the third step is to put together a package of the first two steps that will provide economically competitive electrical power.²² We suggest that the three steps are distinctly different, and that analysis of all three together via systems studies will suggest most promising directions for pursuit. A system that is relatively simpler and easier to maintain will be more acceptable to the private power industry (given comparative economics) when the time comes for technology transfer.

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We have just learned that the concepts presented in Sections I-III are apparently somewhat similar to those of S. Gralnick of PPPL,²³ whose work may have been proceeding along parallel lines.

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