ON THE IGNITION OF THE ITER MACHINE

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ABSTRACT

The present study on a simple model of the ITER machine (International Thermonuclear Experimental Reactor) shows that this machine, as presently designed, might not be able to reach either ignition or power breakeven. The large cost and the long time frame of the ITER program, on the other hand, do not allow for any doubt that the machine must reach its stated goal of ignition. Consequently, as long as these doubts persist, and cannot easily be dissipated, the ITER program should be put on hold, and fusion alternative concepts should be pursued.

1. INTRODUCTION

The generation of energy by fusing together the isotopes of hydrogen, namely deuterium and tritium, is an objective pursued for the past 50 years by virtually all nations. In principle, it is the same process occurring in the sun and the stars, which has naturally powered the universe for billions of years. The need for pursuing this objective on Earth is compelling. If we assume that the world population stabilizes at 10 billion, consuming energy at 2/3 of the U.S. 1985 rate, the energy available from fossil, hydro, and non-breeder fission will suffice approximately until the year 2030. After that, the shortfall will be increasing, and must be made up by other sources. The only alternative is fusion energy.

2. THE PRESENT APPROACH TO FUSION[1]

ITER (International Termonuclear Experimental Reactor) is a machine that has been proposed as a reactor of the magnetic confinement type to demonstrate the scientific and technological feasibility of fusion power. It is a machine of about 30 m diameter, and 36 m height. To accommodate it, a facility of ~ 30,000 m^2 for a total cost of ~ U.S. \$$10^{10}$ will be required. Its construction should begin around the year 2000, with completion by about 2010. An intense debate has been going on within the fusion community about the desirability of building such a machine. Specifically, the magazine *Physics Today* reported in its June 1996 issue an opinion piece titled "Build the International Thermonuclear Experimental Reactor?", in which Andrew M. Sessler and Thomas H. Stix on one side, and Marshall N. Rosenbluth on the other side, debated the issue. This opinion piece best represents the two sides of the issue. The arguments were as follows.

Arguments Against ITER (by Sessler and Stix)

- The ITER machine would be genuinely huge.
- The toroidal field coils would be 17 m high.
- The plasma volume would be 20-40 times larger than that of today's largest tokamaks.
- Construction time has been estimated at 10-12 years.
- Construction costs, in 1996 dollars, has been estimated at $10 billion.
- Although the magnetically confined plasmas most closely approaching fusion conditions have been produced in tokamaks, an eventual fusion reactor will look very different.
- Proceeding with ITER may not only preempt funding for alternative concepts, but also could freeze reactor design and engineering at a premature stage.
- Finally, the construction of ITER would be a poor choice for the following reasons:

  - The machine's untested attributes and unresolved technical issues.
  - Questions of science policy, including the narrowed focus on conventional tokamak.
  - Diversion and dedication of great human, scientific and fiscal resources to this single project.
  - The 10 or more years to "first plasma".
  - The time periods typical for fusion innovation and for political change of will.
  - The negative impact on future research that would rebound from a mechanical or physics failure in this single device.

In short, Sessler and Stix conclude, the step is too large and the overall concept, for all its attractiveness, is both premature and over ambitious with respect to current knowledge.

Arguments in Favour of ITER (by Rosenbluth)

- The nonlinear physics and novel engineering issues of fusion are so complex that only a real experiment at the approximate parameters required for ignition will ever resolve them quantitatively.
- Fusion research requires a test bed such as ITER that could be used to design a desirable reactor by interpolation rather than continual extrapolation from undersized experiments.
- If Japan assumes the major financial role in constructing ITER, with U.S. support at about its present level of 20% ($55 million) of the annual U.S. fusion budget, this is a wonderful bargain, because, for 5% of the cost, the U.S. could participate in designing and experimenting on fusion's flagship experiment.
- The U.S. fusion community should not turn its back on an internationally agreed upon experiment designed as the first exploration of the burning plasma experiment.

3. SCIENTIFIC CONSIDERATIONS ON THE POSSIBILITY FOR ITER TO REACH IGNITION.

The above debate is indicative of the uncertainties surrounding this major fusion program. The debate is at the level of opinions and speculations. It would be desirable if the analysis of the performance of ITER were done at a scientific level. The purpose of the following section is to provide such scientific analysis. We remind that instabilities[2], and turbulence[3] have already been mentioned as significantly serious to preclude ignition for ITER. I shall give an account, from a different perspective, of the reason why ITER might have some difficulties in reaching ignition for the present design parameters of this machine. The calculations presented here are based on a simple model of the machine. They are nonetheless sufficiently convincing to show that the present design of ITER is not reassuring.

The design parameters of ITER are:[4]

Temperature profile	20 kV at center decreasing linearly towards the periphery
Driver power	400 MW
Particle density	10^{14} cm^{-3}
Major radius	8 m
Minor radius	2.8 m to 4 m

The most elementary definition of ignition is that plasma condition for which bremsstrahlung and conduction losses cannot cool the plasma because the α particles heating is able to compensate for these losses and maintain the plasma at a constant temperature. We shall refine this definition later on.

One can verify if ignition is achieved by analyzing the temporal evolution of the plasma through the following relation:

$$a W(t) + P_\alpha(t) = H(t) + R(t) + C(t) \qquad (1)$$

where W(t) is the power available from a driver to heat the plasma core, a is the efficiency of coupling the driver power to the plasma core, $P_\alpha(t)$ is the α particle power, H(t) is the rate of heat energy change in the plasma core, and R(t) and C(t) are the rate of energy loss by radiation and heat conduction, respectively. Other losses, such as synchrotron or inverse compton radiation production, are not included here.

Let us consider the case when one has a driver of maximum power W_{max}. As soon as it is turned on, the driver power will rise within a certain time until W_{max} is reached, after which it remains constant. At that time equilibrium is established, the plasma will have reached a certain constant equilibrium temperature, and P_α, R,

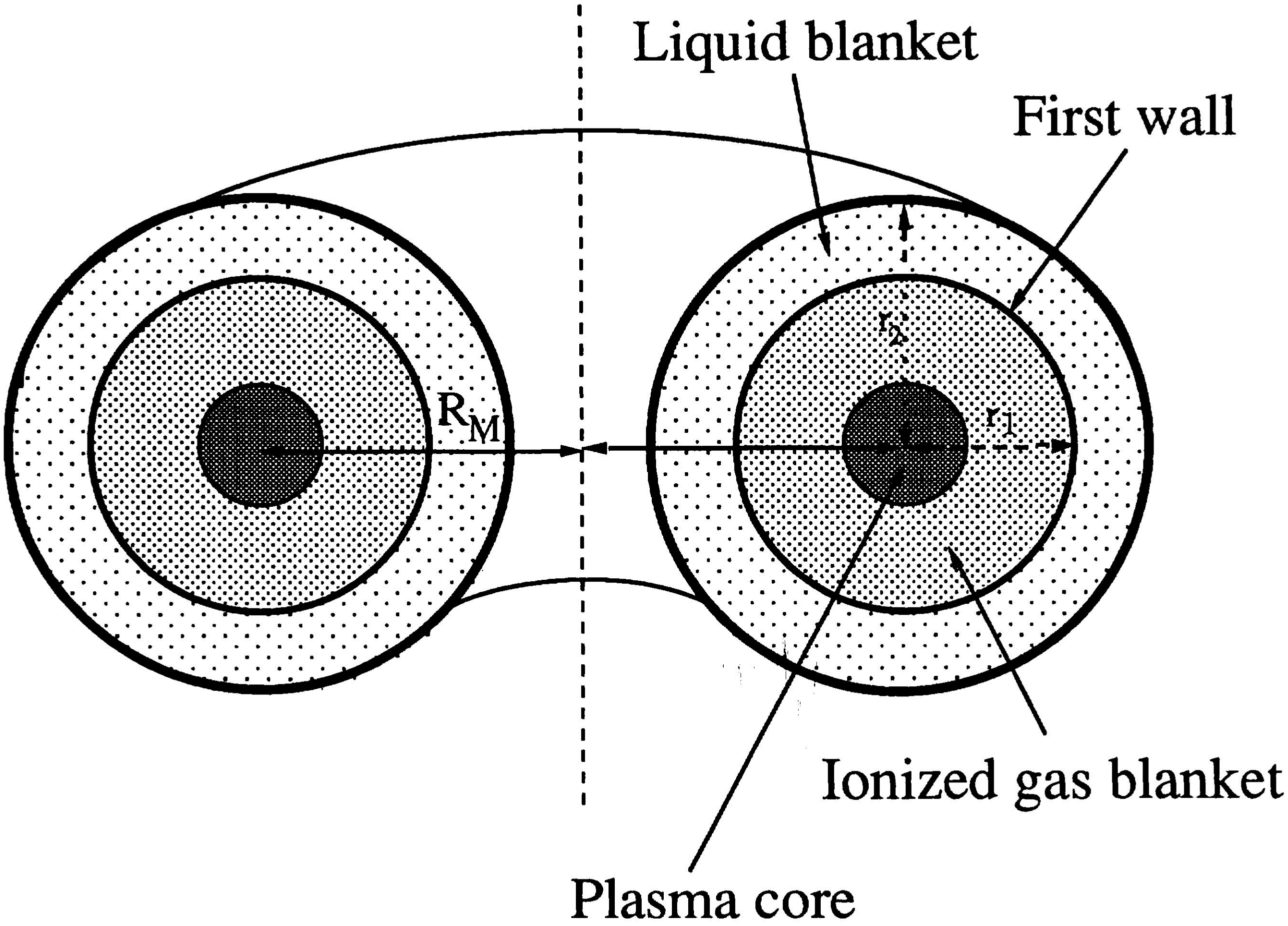

Figure 1. Simplified configuration of the ITER machine.

and C will also have constant values. However, H = 0, because the plasma has now constant temperature. During this steady-state condition we have:

$$aW_{max} + P_{\alpha} = R + C. \tag{2}$$

Eq. (2) is satisfied for any steady-state driver input W_{max}. However, ignition is not achieved with a driver input for which $P_{\alpha} < R + C$. Only when

$$P_{\alpha} = R + C \tag{3}$$

ignition is achieved, and one can turn the driver power off at that time. It is not advisable to keep the driver power W_{max} on after ignition, because the reactor might be damaged from the combined action of W_{max} and P_{α}.

The objective of this analysis is not to derive from (1) the conditions to be satisfied in order to reach ignition. Rather, it is to verify if, for the ITER design parameters provided above, ignition can be achieved. In other words, since it has been claimed that, for the design parameters listed above, ITER should reach ignition,[4] we first want to derive from (2) some additional operating parameters of ITER, and then we want to proceed to verify if ignition can be achieved for those parameters.

Determination of the Temperature of the First Wall

The following analysis aims at deriving the temperature of the first wall (Fig. 1). We assume that the first wall is surrounded by a liquid blanket which absorbs whatever heat leaks out from the plasma, as well as the neutron and bremsstrahlung powers (the bremsstrahlung absorption in the first wall converts into heating of the latter with heat transfer to the liquid blanket). For simplicity the liquid blanket is considered to be made up of water at 300° C, whose thermal conductivity is:[5]

$$K_{LB} = 6.27 \times 10^{4} \frac{W}{cm \cdot keV} \tag{4}$$

Eq. (2), which is valid at the time immediately before the driver power is turned off at ignition, can be converted into:

$$C = P_{\alpha} - R + aW_{max} \tag{5}$$

In the toroidal geometry of ITER, the total heat conduction loss rate C flowing into the liquid blanket is given by:[6]

$$C = 4\pi^{2} R_{M} \frac{K_{LB} T_{1}}{\ln\left(r_{2}/r_{1}\right)} \tag{6}$$

where R_M = 8 m is the major radius of the torus, T_1 is the temperature of the first wall located at r_1 = 2.8 m - 4 m, and r_2 is the radius of the external wall of the liquid blanket container. We assume r_2 = 6 m. Eq. (5) becomes:

$$4\pi^{2} R_{M} \frac{K_{LB} T_{1}}{\ln\left(r_{2}/r_{1}\right)} = \int_{0}^{V_{p}} \left(p_{\alpha} - r_{B}\right) dV_{p} + aW_{max} \tag{7}$$

where V_p is the plasma volume, and p_α and r_B are the α particle and bremsstrahlung power per unit volume, respectively.

Let us convert the integral in (7) over volume V_p into an integral over minor radius r_1 of the torus:

$$dV_p = 4\pi^2 R_M\, r\, dr$$

$$4\pi^2 R_M \frac{K_{LB} T_1}{\ln\left(r_2/r_1\right)} = 4\pi^2 R_M \int_0^{2.8\text{ m to }4\text{ m}} \left(p_\alpha - r_B\right) r\, dr + aW_{max}$$

$$\frac{K_{LB}\, T_1}{\ln\left(r_2/r_1\right)} = \int_0^{2.8\text{ m to }4\text{ m}} \left(p_\alpha - r_B\right) r\, dr + \frac{aW_{max}}{4\pi^2 R_M} \qquad (8)$$

Inserting in (8) the known numerical values of the various parameters, one can get the temperature T_1 (in keV) of the first wall:

$$T_1 = \frac{\int_0^{280\text{ cm}} \left(p_\alpha - r_B\right) r\, dr + 1.27 \times 10^4\, a}{8.23 \times 10^4} \qquad \text{for } r_1 = 2.80\text{ m} \qquad (9)$$

$$T_1 = \frac{\int_0^{400\text{ cm}} \left(p_\alpha - r_B\right) r\, dr + 1.27 \times 10^4\, a}{1.55 \times 10^5} \qquad \text{for } r_1 = 4.00\text{ m} \qquad (10)$$

The α particle power and bremsstrahlung power per unit volume for a 50% D-T mixture are given by the following expressions, respectively:[7]

$$p_\alpha = 2.06 \times 10^{-24}\, \frac{n^2}{4}\, T(r)^{-(2/3)}\, e^{-\frac{19.94}{T(r)^{1/3}}} \qquad (11)$$

$$r_B = 2.14 \times 10^{-30}\, \frac{n^2}{4}\, T(r)^{1/2} \qquad (12)$$

where p_α and r_B are expressed in watt/cm^3, T(r) is the plasma temperature in keV, and n is the particle density in cm^{-3}.

Inserting (11) and (12) in (9) and (10), with $n = 10^{14}$ cm^{-3}, one gets:

$$T_1 = 3.04 \times 10^{22} \int_0^{280\ cm} \left[2.06 \times 10^{-24}\, T(r)^{-(2/3)}\, e^{-\frac{19.94}{T(r)^{1/3}}} - 2.14 \times 10^{-30}\, T(r)^{1/2} \right] r\, dr$$

$$+\ 1.54 \times 10^{-1}\, a$$

$$\text{for } r_1 = 2.80 \text{ m} \qquad (9')$$

$$T_1 = 1.61 \times 10^{22} \int_0^{400\ cm} \left[2.06 \times 10^{-24}\, T(r)^{-(2/3)}\, e^{-\frac{19.94}{T(r)^{1/3}}} - 2.14 \times 10^{-30}\, T(r)^{1/2} \right] r\, dr$$

$$+\ 8.19 \times 10^{-2}\, a$$

$$\text{for } r_1 = 4.00 \text{ m} \qquad (10')$$

The plasma temperature T(r) is a function of the minor radius r of the torus, starting at 20 keV in the central core and decreasing linearly towards the periphery, where it reaches T_1 at the first wall.[6] Hence:

$$T(r) = 20 - \frac{20 - T_1}{280}\, r \qquad \text{for } r_1 = 2.80 \text{ m} \qquad (13)$$

$$T(r) = 20 - \frac{20 - T_1}{400}\, r \qquad \text{for } r_1 = 4.00 \text{ m} \qquad (14)$$

and (9'), (10') transform, respectively, into:

$$T_1 - 1.54 \times 10^{-1}\, a$$

$$= 3.04 \times 10^{22} \int_0^{280\ cm} \left[2.06 \times 10^{-24} \left(20 - \frac{20 - T_1}{280}\, r\right)^{-(2/3)} e^{-\frac{19.94}{\left(20 - \frac{20 - T_1}{280}\, r\right)^{1/3}}} - 2.14 \times 10^{-30} \left(20 - \frac{20 - T_1}{280}\, r\right)^{1/2} \right] r\, dr$$

$$\text{for } r_1 = 2.80 \text{ m} \qquad (9'')$$

$$T_1 - 8.19 \times 10^{-2}\, a$$

$$= 1.61 \times 10^{22} \int_0^{400\ \mathrm{cm}} \left[2.06 \times 10^{-24} \left(20 - \frac{20 - T_1}{400}\, r\right)^{-(2/3)} e^{-\frac{19.94}{\left(20 - \frac{20 - T_1}{400}\, r\right)^{1/3}}} - 2.14 \times 10^{-30} \left(20 - \frac{20 - T_1}{400}\, r\right)^{1/2} \right] r\, dr$$

for $r_1 = 4.00$ m (10″)

Eqs. (9″) and (10″) can be solved numerically for T_1 as a function of a. Table 1 reports the results.

Table 1. Temperature of the first wall as a function of the energy transfer efficiency a from driver to plasma, for two minor radia , i.e., $r_1 = 2.8$ m and $r_1 = 4.0$ m.

T_1 (keV)	a	
	$r_1 = 2.80$ m	$r_1 = 4.00$ m
0.181	**0.996**	-
0.15	0.796	-
0.111	0.543	**0.997**
0.10	0.472	0.860
0.09	0.407	0.739
0.08	0.343	0.617
0.07	0.278	0.496
0.06	0.213	0.374
0.05	0.148	0.252
0.04	0.084	0.131
0.03	0.019	0.008

In the above Table we have highlighted the first wall temperature when $a \approx 1$. It is 0.181 keV for $r_1 = 2.80$ m, and 0.111 keV for $r_1 = 4.00$ m.

Verification of Ignition

Although the most general definition of ignition is the one provided by Eq. (3), a more appropriate one for ITER stems from the consideration that this machine is designed to be a proof-of-principle reactor. Therefore, the reaction product, namely the neutron output power, should be taken into account in the energy balance equation. This is because this power will help in achieving the goal of the reactor, which is production of electricity.

Since the neutrons escape from the plasma and are absorbed by the liquid blanket, together with the heat and bremsstrahlung radiation losses, the power available from the liquid blanket W_{LB} for conversion into electricity is:

$$W_{LB} = P_n + R + C \tag{15}$$

where P_n is the neutron power.

A fraction b of this power is converted into electricity, where b is typically 30%. Hence:

$$W_{electr.} = b\,(P_n + R + C) \tag{16}$$

ITER is supposed to be able to reach ignition. If this is so, at ignition $W_{max} = 0$, and Eq. (2) becomes:

$$W_{max} = \frac{1}{a}\left(R + C - P_\alpha\right) = 0. \tag{2'}$$

The electricity production, if any, from ITER is obtained by subtracting (2′) from (16):

$$W_{electr} = b\,(P_n + R + C) - \frac{1}{a}\left(R + C - P_\alpha\right) \tag{17}$$

This general expression is justified because, if indeed ignition is achieved, the second term on the right-hand side of (17) is equal to zero, and (17) reduces to (16).

Equation (17) transforms into:

$$\frac{W_{electr}}{b} = P_n + \frac{1}{ab} P_\alpha + \left(1 - \frac{1}{ab}\right)(R + C) \geq 0 \tag{18}$$

where $P_n = p_n V_p$, and p_n (neutron power per unit volume) is given by:[7]

$$p_n = 8.31 \times 10^{-24} \frac{n^2}{4} T(r)^{-(2/3)} e^{-\frac{19.94}{T(r)^{1/3}}} \tag{19}$$

By inserting (6), (11), (12), and (19) in (18), one has:

$$4\pi^2 R_M \int_0^{2.8\text{ m to }4\text{ m}} \left[\left(8.31 \times 10^{-24} + \frac{2.06 \times 10^{-24}}{ab}\right)\left(\frac{n^2}{4}\, T(r)^{-(2/3)}\, e^{-\frac{19.94}{T(r)^{1/3}}}\right) + \left(1 - \frac{1}{ab}\right)\left(2.14 \times 10^{-30}\, \frac{n^2}{4}\, T(r)^{1/2}\right) \right] r\, dr$$

$$+\ 4\pi^2 R_M \left(1 - \frac{1}{ab}\right) \frac{K_{LB} T_1}{\ln\left(r_2/r_1\right)} \geq 0 \qquad (20)$$

Inserting in (20) the values of a and T_1 reported in Table 1, and of T(r) as provided by (13) or (14) for $n = 10^{14}$ cm^{-3}, and carrying out the operations on the left-hand side of the above inequality, one finds that the inequality is not satisfied, and one always gets negative numbers, rather than positive numbers, or at most zero. In (20) we have assumed b = 30%. Table 2 reports the results.

Table 2. Values of the left-hand side of inequality (20), as a function of a and b, for two minor radia, i.e., r_1 = 2.8 m and r_1= 4.0 m.

T_1 (keV)	a		b	Left-hand side of (20)	
	r_1 = 2.80 m	r_1 = 4.00 m		r_1 = 2.80 m	r_1 = 4.00 m
0.181	**0.996**	-	0.3	-4.91×10^8	-
0.15	0.796	-	0.3	-5.73×10^8	-
0.111	0.543	**0.997**	0.3	-6.77×10^8	-3.73×10^7
0.10	0.472	0.860	0.3	-7.13×10^8	-1.02×10^8
0.09	0.407	0.739	0.3	-7.34×10^8	-1.41×10^8
0.08	0.343	0.617	0.3	-7.56×10^8	-1.93×10^8
0.07	0.278	0.496	0.3	-7.87×10^8	-2.45×10^8
0.06	0.213	0.374	0.3	-8.20×10^8	-2.91×10^8
0.05	0.148	0.252	0.3	-8.46×10^8	-3.42×10^8
0.04	0.084	0.131	0.3	-8.59×10^8	-3.78×10^8
0.03	0.019	0.008	0.3	-8.87×10^8	-3.00×10^8

Since the above table shows that ignition is not achieved, this means that Eq. (2′) is not zero but greater than zero. Despite this, one can still verify if ITER can reach power breakeven, i.e., $W_{electr} = W_{max}$, provided, of course, that the driver power W_{max} is kept on. Subtracting (2′) from (16), one gets:

$$W_{electr} - W_{max} = b\,(P_n + R + C) - \frac{1}{a}\left(R + C - P_\alpha\right) \qquad (17')$$

which becomes, for power breakeven:

$$\frac{W_{electr} - W_{max}}{b} = P_n + \frac{1}{ab} P_\alpha + (1 - \frac{1}{ab})(R + C) = 0 \qquad (21)$$

Eq. (21) is the same as (18), and the negative numbers of Table 2 show that ITER might not even reach power breakeven for the design parameters provided before.

CONCLUSIONS

An analysis carried out on a simple model of ITER has shown that this machine might have difficulties in reaching ignition with its present design parameters.

It is recommended that Canada take a leading role in questioning the usefulness of the role of ITER and promoting alternative fusion concepts studies, as is being done elsewhere in the world now, and most notably in the U.S.A.

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