Tokamak Reactor Issues

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5/15/23
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Tokamak research has been ongoing since the 1950's based on increasingly large and costly devices. ITER is supposed to be the next and last major experimental step before the first tokamak demonstration fusion reactor can be built. However, ITER is one of the most difficult and expensive (~$50B) technological projects ever attempted.

Below is a list of issues which could prevent the successful operation of a practical tokamak fusion reactor. These have all been known within the field for at least 40 years, but only rarely discussed in public [1]. This list is by no means complete. Below that is a rough estimate of the probability of successfully resolving these issues.

A. Tokamak reactor issues

1) Energy confinement time:

The magnetic confinement of plasma energy has been the main physics issue in tokamak research since the 1950's. The global energy confinement time of the ITER plasma τ_E (stored plasma energy/plasma heating power) needs to be about $\tau_E \geq 4$ sec for ITER to achieve its goal of Q (fusion power out/plasma heating power input) = 5-10 [2]. This τ_E is about 4x higher than that of the largest existing tokamak JET. The ITER energy confinement as predicted from existing tokamak data using "empirical scaling" is about $\tau_E = 3.0 \pm 0.5$ sec [3]. The ITER τ_E cannot yet be predicted accurately from plasma theory due to the complexity of the small-scale turbulent transport which dominates the confinement physics. Thus the energy confinement time is marginal for the success of ITER.

2) Impurity contamination:

Any impurity ions in the plasma core originating from the vessel wall or from helium "ash" will reduce the D-T fusion power for a given energy confinement time. The impurity fractions are almost entirely unpredictable in ITER due to the uncertainties in the plasma-wall interaction and the impurity ion particle confinement. The allowable fraction of tungsten in the core of ITER is only $\sim 10^{-4}$ due to the high tungsten radiation rate at $T_e \sim 10$ keV [4]. The recent fusion performance of JET with tungsten walls was generally worse than with previous carbon walls due to such radiation. There is presently no demonstrated method to preferentially remove impurities or helium ash from a tokamak, so the level of impurities is very uncertain.

3) MHD instabilities:

Tokamak plasmas have many types of MHD (magnetohydrodynamic) instabilities driven by the large-scale gradients in the plasma pressure or current. Most of these are self-regulating, such as the internal sawtooth instability and the edge ELMs. However, these instabilities can affect the local transport and/or global confinement in steady-state plasmas. Much of this MHD physics is understood in theory, but self-consistent (nonlinear) predictions are still highly uncertain. New types of MHD instabilities may be driven by the relatively large population of high energy alpha particles produced by D-T reactions at high Q [5].

4) Disruptions:

The most dangerous tokamak instability is a plasma "disruption", which causes a very rapid (few msec) loss of the entire plasma energy and plasma current to the wall. Disruptions occur in all tokamaks, but in ITER they can cause extremely large electromagnetic forces and heat loads on the vessel and wall components [6]. Disruptions are caused by high impurity content or MHD instability, usually triggered by exceeding the plasma density, pressure, or current limits. ITER is built to withstand a certain number of disruptions, but its high-Q operation will probably be near the disruptive instability boundary. Prediction and/or mitigation of disruptions is planned, but it is still possible that a single large disruption could significantly damage or destroy the ITER tokamak or a tokamak reactor.

5) Wall erosion:

There will inevitably be a gradual erosion and redeposition of the tokamak divertor plates and first wall due to plasma heat and particle loss, even without the transient loads due to MHD instabilities such as ELMs or disruptions. The location and rate of this erosion are difficult to predict or control, since it depends on largely unknown turbulent transport loss in the edge plasma. Excessive wall erosion or cyclic stress could lead to a leak from the water cooling lines just below the divertor plates or walls. Even a tiny water leak could force a very costly machine shutdown for repair. A sudden leak or flake of wall material falling into the plasma could cause a major plasma disruption. A serious water leak inside the vessel during operation could also cause an explosive loss of coolant accident (LOCA) [7], which could destroy the tokamak.

6) Magnets:

ITER will have the largest and most complex set of superconducting magnets ever built (~10 m, ~10 T), many of which need to be pulsed every shot (e.g. the Ohmic transformer) [8]. All these magnets need to be cooled with liquid helium and tightly restrained from huge JxB huge forces, and some (non-superconducting) magnets are actually within the vacuum vessel. The magnets can fail due to coolant leaks, mechanical stress, or electrical arcing. Most tokamaks have had coil failures requiring magnet repair or replacement; for example, the newest large superconducting tokamak JT-60SA [9]. It would be very difficult or impossible to repair or replace any of the major ITER coil after D-T operation.

7) Current drive:

Tokamaks require externally driven plasma current to operate in steady state, since Ohmic transformers have limited magnetic flux. Significant plasma current can be made using fast electrons driven by radio waves or microwaves, but this is inefficient and expensive [10]. Current drive might be used to help control MHD stability, but not disruptions or ELMs. Failure of current drive systems can be caused by damage to in-vessel launchers, unexpected changes in plasma profiles, or defective external power systems.

8) Tritium inventory:

The tritium fuel for D-T tokamak reactors needs to be created in on-site breeding blankets located outside the plasma but inside the toroidal field coils [11]. The design of these blankets is extremely complicated due to neutronic, thermal, and mechanical interactions, and none has been tested so far in a D-T neutron environment. There will be an in-vessel tritium inventory limit of only a few kg due to radiological safety, so removal of tritium from the vessel walls, ports, and large amounts of dust inside the vessel will be necessary. This tritium recovery process is difficult and will probably require extensive machine shutdowns.

9) Radiation damage:

In a tokamak reactor the first wall will be subject to very high 14 MeV neutron radiation loads, typically a few MW/m^2 over many years [12]. This will eventually cause radiation-induced damage of the structural materials, typically measured as the average number of displacements per atom of the material lattice (perhaps 1-10 dpa). Radiation damage causes many changes to metals such as softening or helium embrittlement, and could eventually result in structural failure of the wall. Advanced materials such as SiC composites might be a solution [13], but these materials have not yet been tested in appropriate neutron environments.

10) Availability factor:

A practical tokamak reactor should be operated with a full power availability factor comparable to other power sources, which ranges from nuclear fission (>90%) to solar (25%) [14]. At present the longest D-D tokamaks pulses last for about 1000 sec several times per day [15], or <5% of the time. Full-power operation of ITER is planned with 400 sec pulses at perhaps 2 per day, or also <5% availability. A considerable increase in availability is needed for a practical tokamak reactor.

11) Safety:

The main safety issues for a tokamak reactor are due to the inventory of tritium and radioactive dust created by plasma-wall interactions inside the vessel [16]. Although there is little danger of widespread nuclear contamination such as from Chernobyl, a local public evacuation plan due to potential radioactive release will be needed for ITER and larger D-T tokamaks. A tokamak reactor will also create a very large amount of low-level radioactive waste due to neutron activation of the vacuum vessel, which needs a long-term decommissioning process. Finally, any fusion reactor poses a potential threat of nuclear proliferation, since plutonium 239 can be made by placing natural or depleted uranium oxide near neutrons of any energy [12,17].

12) Cost:

Assuming all the issues above are resolved and a tokamak reactor can be built to produce net electricity, it will be practical only if its cost of electricity is comparable or less than that from other sources. This seems extremely unlikely based on the $50B+ cost of ITER, which cannot produce any net electricity. A detailed preconceptual design for the European tokamak DEMO reactor was made in collaboration with experts from industry, utilities, grids, safety, and licensing [18]. This design is sobering in scope and complexity, with a 40-year timetable for net electricity production of a few hundred MW, but with no attempt to assess the cost or cost of electricity. A novel conceptual design for a compact high-field tokamak Pilot Plant was costed at $5.5B [19], which might be capable of making some net electricity. Given the simplicity and falling costs and of solar and wind power, it would be very surprising if a tokamak reactor could ever be cost competitive.

B. Probability of a tokamak reactor ?

Each of the issues above has been studied within the tokamak community for the past 40 years. The near-term issues #1-8 have been resolved satisfactorily at the level of existing tokamaks, but those solutions are not likely to be adequate for ITER or for a reactor. The more reactor-relevant issues #9-12 have been addressed only in engineering design studies.

Table 1 assigns a *tentative* probability for successful resolution of each issue as 50%, but 10% for the cost issue which seems more difficult. Assuming the solution to one of these does not affect the others, the total probability for a successful tokamak reactor is the product of these, or 1/20,000. These estimates are obviously very rough, with some probabilities overestimated and others underestimated. Of course, these probabilities also depend on the degree of effort made on each, and on other unpredictable difficulties or constraints.

Table 1: rough probabilities for resolution of tokamak reactor issues

Issue for reactor	**Probability of success**
1. confinement	50%
2. impurities	50%
3. stability	50%
4. disruptions	50%
5. wall erosion	50%
6. magnets	50%
7. current drive	50%
8. tritium	50%
9. radiation	50%
10. availability	50%
11. safety	50%
12. cost	10%
total product	**1/20,000**

What we can confidently deduce from this simple analysis is that a practical tokamak reactor is highly unlikely, given what we know now. This can be contrasted with the US space shuttle program, an effort of similar complexity and cost but with a much lower expectation for failure of ~10^{-2}, as analyzed by Feynman after the Challenger accident [20]. It seems worthwhile to do a realistic risk analysis for the tokamak reactor program, even during ITER construction.

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