A Skeptical View of Fusion Research

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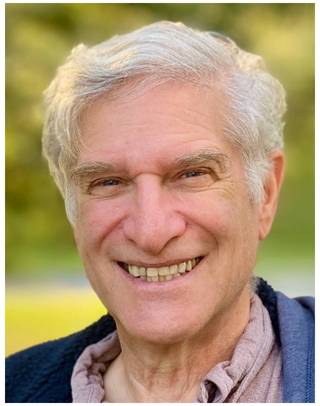
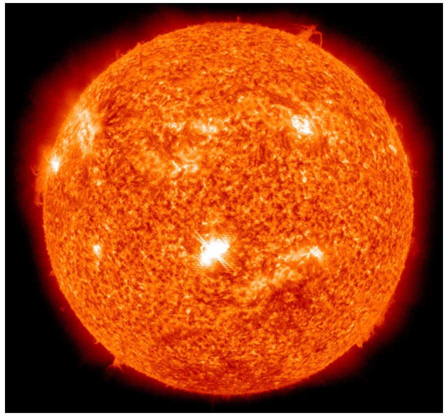


- **Introduction to nuclear fusion**
- **The tokamak and its problems**
- **Other types of fusion devices**
- **Conclusion – will fusion work ?**

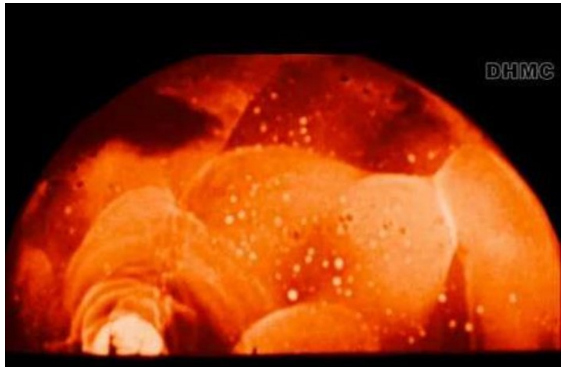
Origins of Fusion Research

1920 - Astronomer Arthur Eddington hypothesized that stars are powered by nuclear fusion



1938 - Nuclear physicist Hans Bethe develops a model of how fusion reactions occur in the sun

1952 - First hydrogen fusion bomb tested, yielding the equivalent of about 10 MT of TNT



Controlled Nuclear Fusion

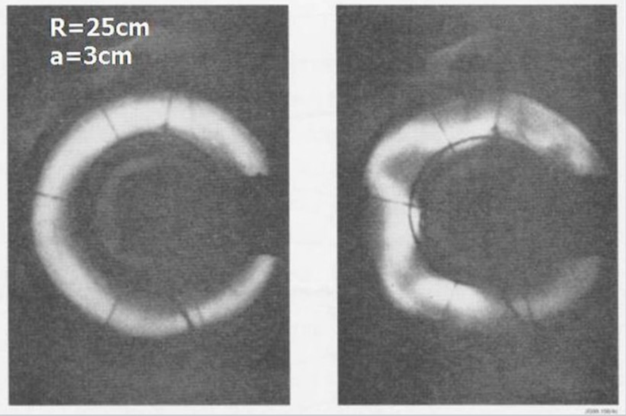
In theory, there is enough fusion fuel (deuterium) in the oceans to power mankind for millions of years

But the fusion fuel of deuterium needs to be heated to ~100,000,000 ºC to start significant fusion burning

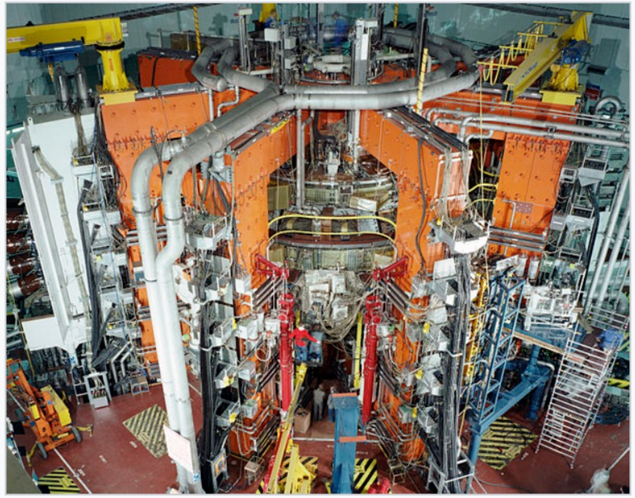
Tabletop experiments in 1950's reached 1,000,000 ºC

House-size devices in the 1990's reached 100,000,000 ºC!

So, what's the problem ?



Early photo of plasma inside a pinch machine (Imperial College 1950–1951)



The Joint European Torus (JET) magnetic fusion experiment in 1991

General Problems of Fusion

- **Physics – complexity and rapid motion of the hot “plasma” fuel**
- **Engineering – pushing material and thermo-mechanical limits**
- **Safety – radioactive fuel and first wall; possible proliferation**
- **Cost – potentially high cost of fusion reactor vs. solar, wind**

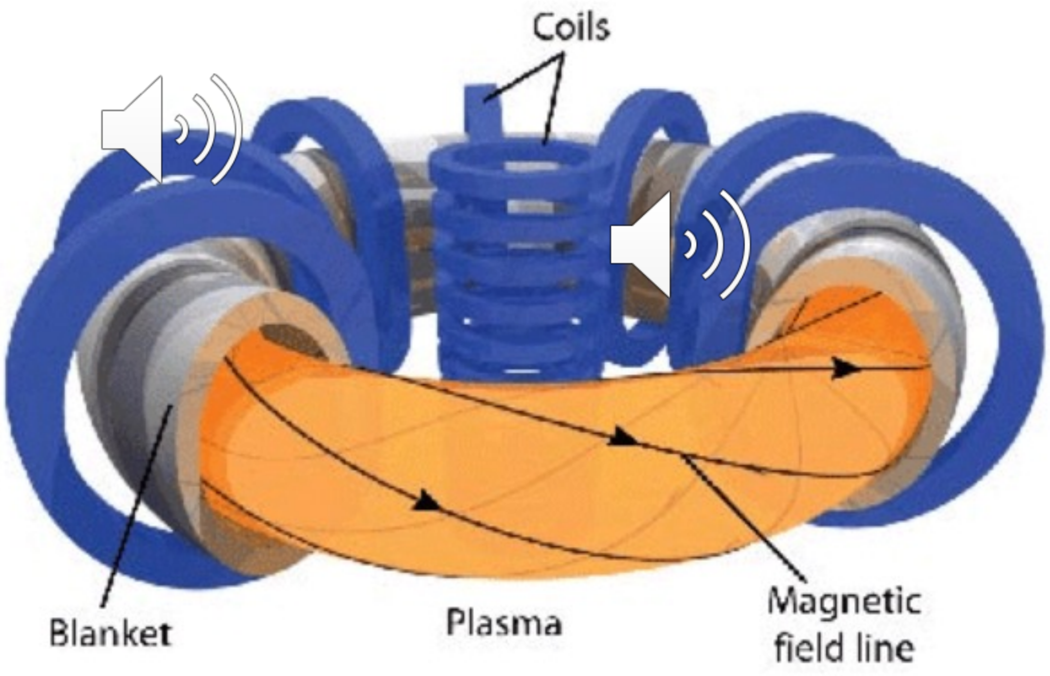
No single problem completely prohibits a fusion reactor

But solving all these problems together in one device will be very difficult!

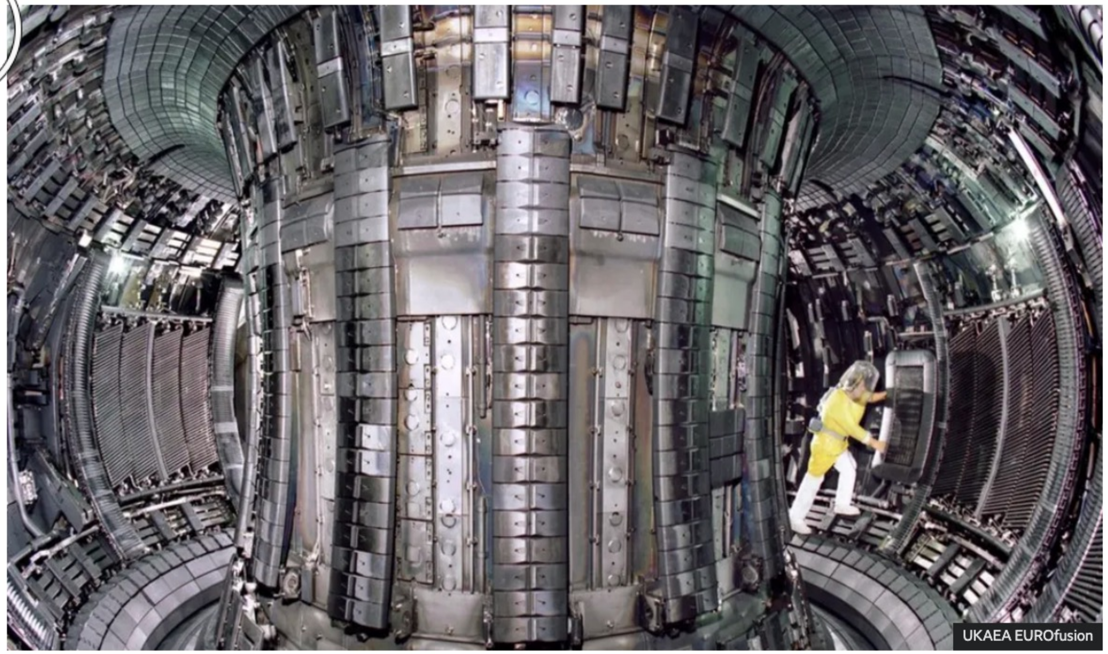
Specific Example: the Tokamak

The tokamak (Russian for ”toroidal magnetic chamber”) has been the most successful fusion device since the 1950’s (over 100 built)

Magnet coils (blue) outside plasma



Inside the JET tokamak vacuum chamber



Major Problems for a Tokamak Reactor

1) Plasma confinement
2) Plasma impurities
3) Disruptions
4) Wall erosion
5) Magnet failure
6) Tritium breeding
7) Radiation damage
8) Power availability
9) Safety
10) Cost

The first 5 are problems for existing tokamaks

The second 5 are problems for future tokamak reactors

Each has been known for 40 years!

1. Plasma Confinement

Hot fusion plasma moves at up to ~1,000 km/sec, so it must be very well confined or it will hit a wall and cool before significant fusion can occur.

The plasma energy can be guided inside a tokamak chamber using a strong magnetic field in a donut-shaped configuration (“magnetic bottle”).

The energy confinement time of largest ($2B) existing tokamak is only ~1 sec, much less than the confinement time needed for a tokamak reactor (~5 sec).

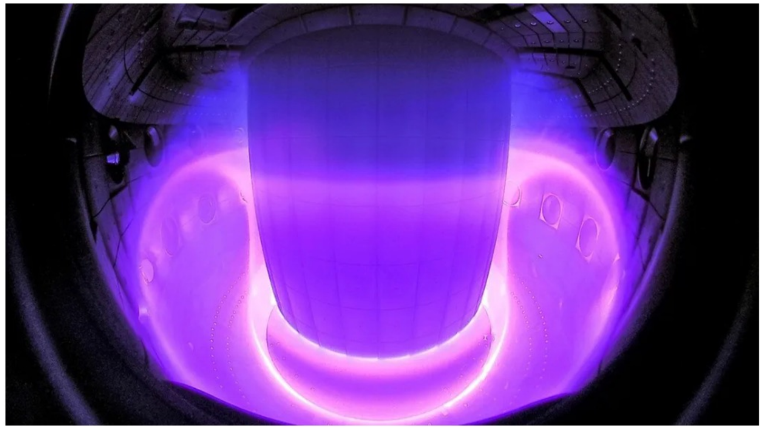
Solar flare in magnetic field at sun’s surface

Tokamak plasma confined by a magnetic field ~1 m in size

2. Plasma Impurities

The best fusion fuel is a near 50:50 mixture of deuterium (D) and tritium (T), which has an optimum reaction rate at about ~100,000,000 ºC.

Tokamak reactors can only tolerate ~0.01% of tungsten (wall) impurity atoms before fatal cooling occurs due to atomic radiation.



Visible light radiation from a tokamak

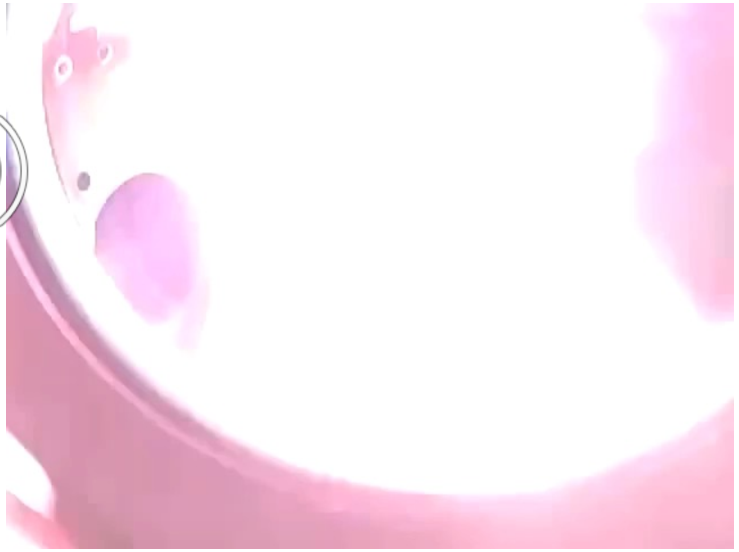
In addition, helium atom “ash” from D-T burn itself will dilute fuel and reduce fusion power.

The impurity and He ash content can not yet be predicted for a reactor.

3. Disruptions

All tokamaks have violent plasma “disruptions” when the plasma explodes within a fraction of a second and hits the wall, ending the tokamak pulse.

The physics of this instability has been studied for 40 years, but there is still no foolproof way to prevent it.



Alcator C-Mod disruption video

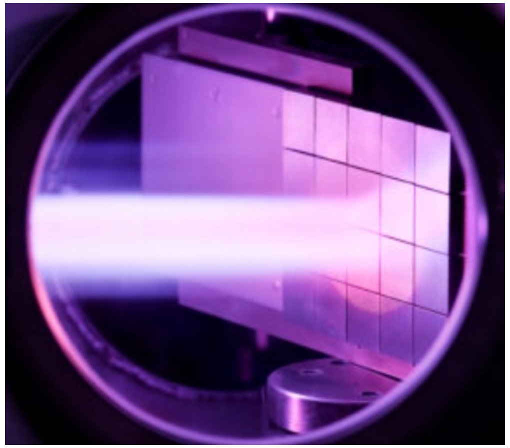
A single disruption in a tokamak reactor could blow a large hole in the inner wall and decommission the reactor for years, or perhaps permanently.

4. Wall Erosion

Gradual erosion and/or melting on the inner vacuum vessel wall surface is inevitable due to continuous plasma particle and heat loss.

The expected wall heat flux will be close to the thermal limits of the strongest first wall material, tungsten.

At least some of the reactor wall surface will need to be replaced every few years due to this erosion.

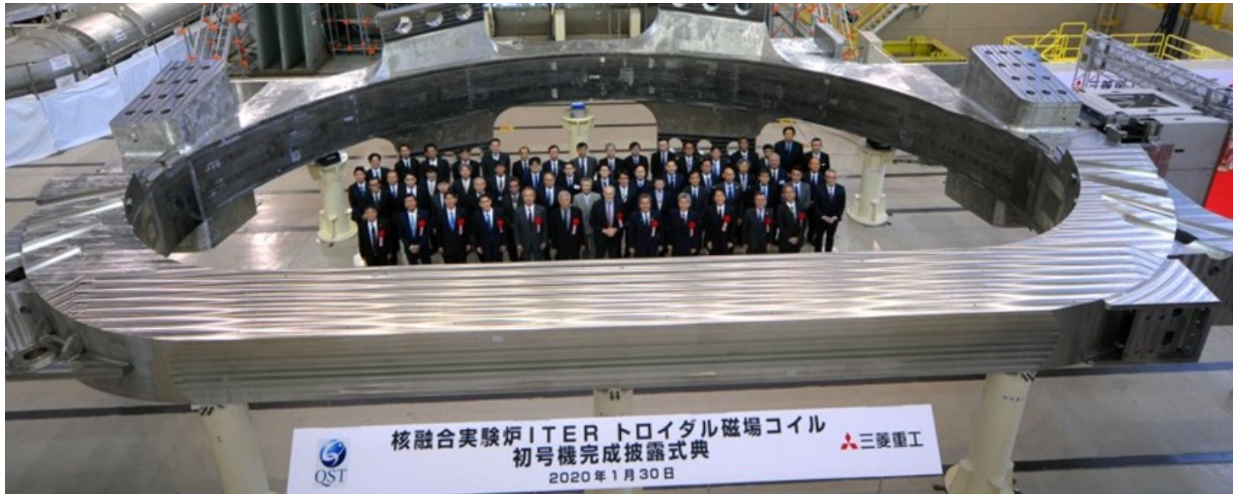


Test of tungsten tiles under plasma heat

5. Magnet Failure

Almost every tokamak experiment has had a major magnet failure, including the recent $B superconducting tokamak in Japan in 2021.

But failed superconducting magnets in a tokamak reactor can not be replaced after D-T starts due to high radiation levels and huge cost.

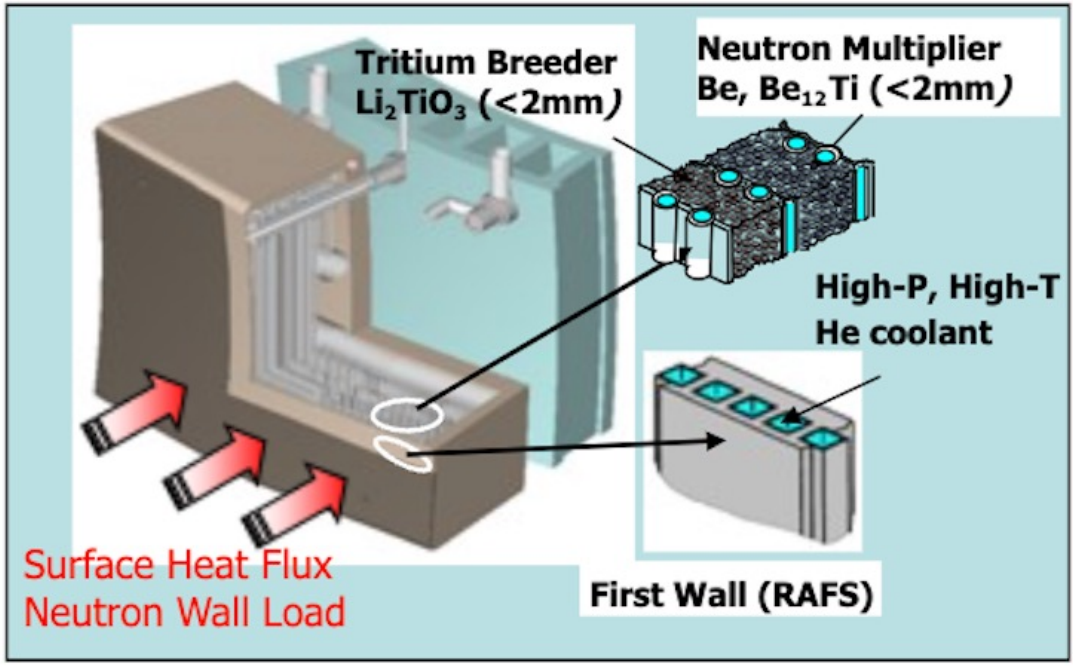


A tokamak superconducting magnet

6. *Tritium Breeding*

All the tritium fuel in a tokamak reactor must be created within the reactor, since tritium radioactively decays in 12 years and so is not found on Earth.

In principle, just over one tritium atom can be "bred" in the wall for each fusion neutron. This requires nearly the whole inner wall to be covered by a breeding blanket.

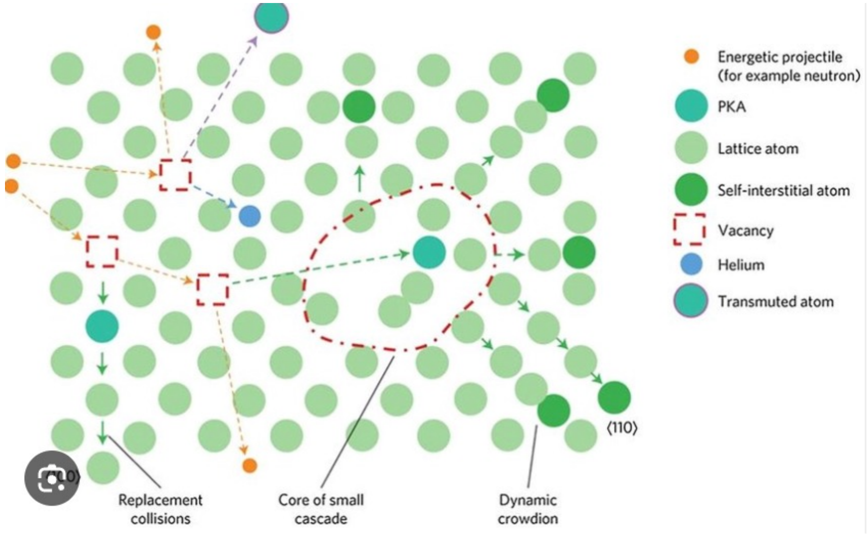


Simplified tokamak blanket design

7. Radiation Damage

D-T fusion reactions create high energy neutrons which penetrate up to 1 meter into the blanket structure. These neutrons microscopically displace atoms and eventually damage the metal (steel) structure.

This will require wall/blanket replacement every few years in a tokamak reactor. This must be done robotically while the tokamak is shut down.



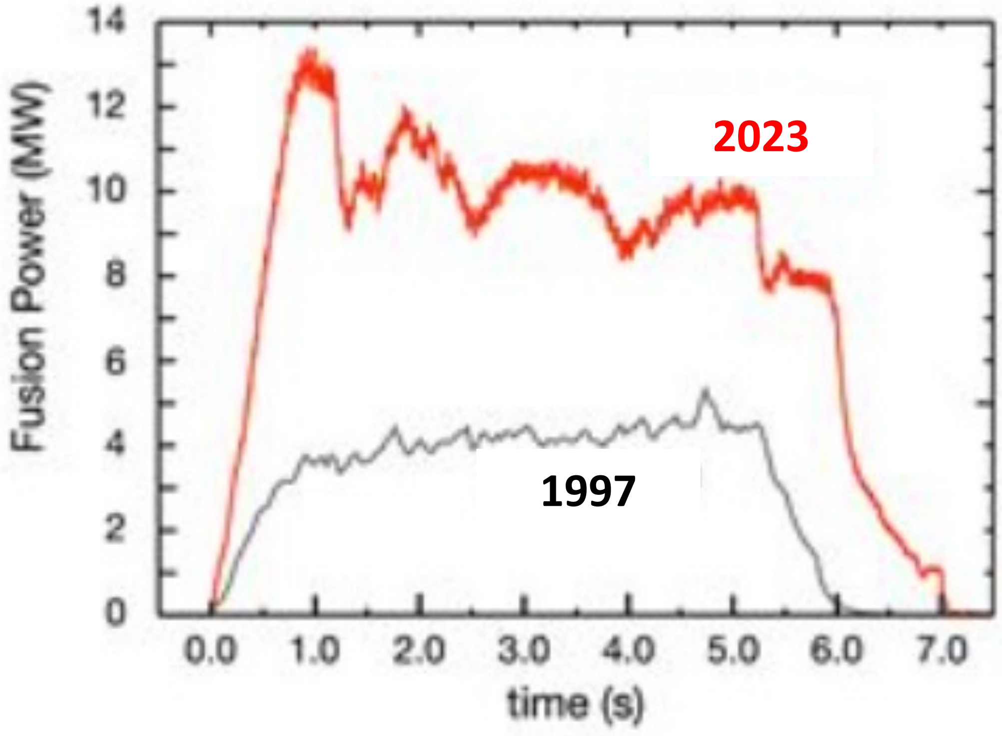
Every atom of the fusion reactor wall will be displaced ~100 times by high energy neutron collisions

8. Power Availability

The best tokamak D-T pulses have so far made about 10 MW of fusion power for ~7 seconds, at best a few times per year.

The next major tokamak "ITER" is planning to make 500 MW of fusion for ~7 minutes, at most once a day.

A practical fusion power plant should make ~3000 MW for at least 10 hours a day every day, for many years.



Record JET D-T pulses

9. Safety

A tokamak reactor will contain many kg of radioactive tritium, which must be carefully handled to avoid public exposure (not as dangerous as radium or plutonium).

Thousands of tons of radioactive waste due to neutron activation of the tokamak wall will require decommisioning and long-term storage after reactor lifetime.

Tritium dial

Fissile (explosive) nuclear fuel can be made by exposing natural uranium to D-T fusion neutrons, creating a risk of nuclear weapons proliferation.

10. Cost

Large fusion power plants would very likely require expensive nuclear licensing and governmental regulation, similar to fission power plants.

The untested technology of fusion reactors implies highly uncertain electricity costs until their operation is demonstrated extensively.

It is nearly certain that fusion power will never be cost-competitive with solar or wind energy, which are infinitely simpler.

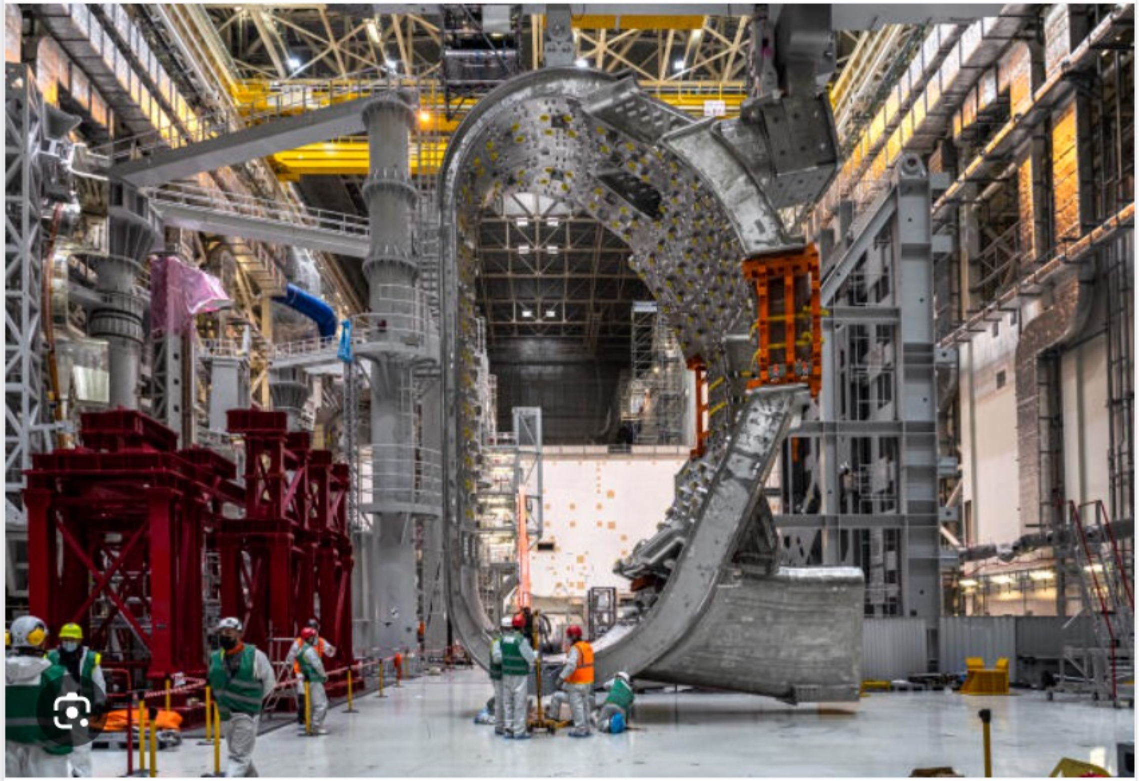
Solar and wind are simple

The ITER Tokamak

ITER construction started in France in 2013 as an international collaboration, with D-T operation planned for 2035.

One of its 9 nine large vacuum vessel segments is shown at the right. ITER will be about 30 meters tall.

ITER might make 500 MW of fusion power, but it will not and could not make any net electricity.

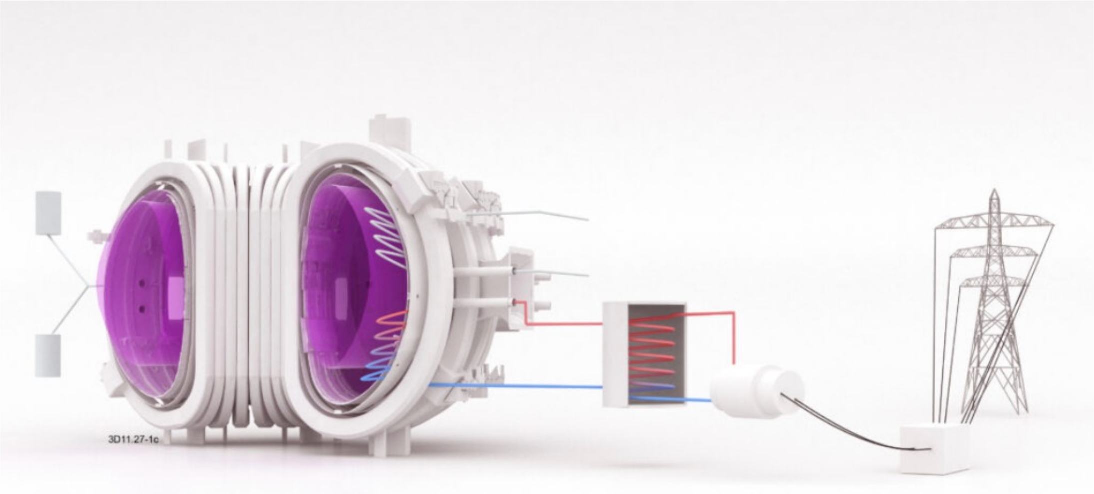


ITER under construction in 2023

DEMO Tokamak

A DEMO tokamak would aim to put electricity onto the grid, maintain tritium self-sufficiency, and try to demonstrate safe and cost-effective operation of a prototype fusion power plant.

But a DEMO would be much more difficult to build and operate than ITER. It would be one of the hardest technological challenges ever.



Artistic impression of a DEMO tokamak connected to the electric grid (EUROfusion)

Likelihood of Tokamak Reactor Success ?

1) Plasma confinement - 1/2
2) Plasma impurities - 1/2
3) Disruptions - 1/4
4) Wall erosion - 1/4
5) Magnet failure - 1/2
6) Tritium breeding - 1/8
7) Radiation damage - 1/8
8) Power availability - 1/8
9) Safety - 1/2
10) Cost - 1/8

These are just guesses based on experience of the past 40 years.

If so, the overall chance that all of these problems will be solved together in a tokamak reactor is:

~1 / 1,000,000 !

Other Types of Fusion Devices

Even though the tokamak is very unlikely to succeed, it is still the leading fusion candidate based on its high fusion output and worldwide database.

Other magnetic fusion concepts aim to solve some of these problems, but their fusion output has so far been much below that of present tokamaks.

Inertial confinement fusion may be scientifically interesting but not credible as a practical reactor, due to intractable problems of driver efficiency, target cost, target alignment, chamber clearing, and tritium breeding.

Conclusion

Fusion reactors are unfortunately not going to be a practical source of electricity in the future.

This is due to the complexity and difficulty of fusion, compared to the simplicity of other options.

Some Related References

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