Nuclear fusion: when will it come together?

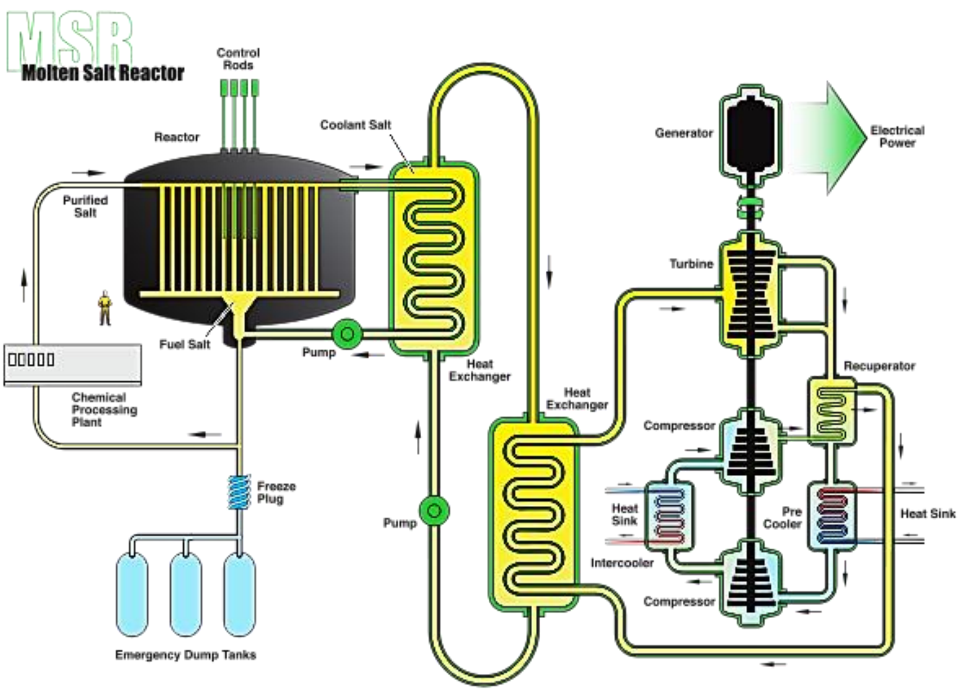
Nuclear fission is a well-established technique for power production. However after the recent Fukushima accident, Germany and Japan planned to completely shut down their existing nuclear fission programmes. Fusion does not suffer from the possibility of a radiation leak or a meltdown nor produce long term waste. Will the advantages of fusion at last allow it to supplant fission?

In the first half of the 20th century nuclear fusion and fission were both seen as processes that could potentially be harnessed as a powerful energy source. Research into fusion began in the 1920's, but it was too technically challenging to make a working fusion reactor. Fission developed much more successfully during the Second World War, when North America's Manhattan Project attempted to use the energy concentrated in the atom as a weapon.[1] This prompted much more research into the field of nuclear energy. In 1942 Enrico Fermi and his colleagues created the world's first controlled self-sustaining nuclear reaction under the University of Chicago's stadium.[1] Atoms were split, releasing neutrons that caused other atoms to fission on absorption. Reactor designs were made and improved and by 1948 the U.S.A announced plans to commercialise nuclear power production for consumer use.

At this time, nuclear power was expected to have a very low running cost once developed. Lewis Lichtenstein Strauss, in his speech to the National Association of Science Writers, in New York City, September 16th, 1954 famously said "*Our children will enjoy in their homes electrical energy too cheap to meter*" [2]. It was likely he was referring to hydrogen fusion. However, electricity from nuclear sources is still not cheaper than the burning of fossil fuels, but today it is favoured by some because it does not release CO_2. In current commercial plants, uranium is used as the primary fuel. In an active reactor, a U^{235} nucleus absorbs a neutron, becoming U^{236}. Usually, the nucleus then splits into several fragments, releasing 2 or 3 neutrons, an average of 2.42. They irradiate the fertile U^{238}, converting it into a fissile material, Pu^{239}, through two beta decays. Up to a third of the reactor power comes for the fission of Pu^{239}. Commercial reactors unfortunately do not produce as much fissile material by irradiation of fertile materials as they consume, so they require fissile fuel. Mined uranium is over 99% U^{238} and less than 1% U^{235}, which means the uranium has to be enriched before it can be used. The enrichment process concentrates the U^{235} to about 3% for reactor use. But the same process, if continued, creates weapons grade uranium at 20% U^{235}. This has created some concerns throughout the public at nuclear weapon material being made secretly.

As U^{235} is the necessary input fuel of current reactors, if current techniques are used more widely then a possible shortage of U^{235} is expected. If fission is going to remain the future's primary means of generating nuclear power, existing techniques need to improve significantly. Fortunately, as techniques for harnessing nuclear energy improve, reactors will become more efficient. The generation IV reactor designs are planned to be deployable around 2030. They aim to gain 100-300 times more energy yield from the nuclear fuel than current reactors, not produce long-lived waste and consume old nuclear waste in their operations while improving the safety of plant design. Many of the reactors are breeder reactors, which aim to produce energy by only refuelling with fertile fuel which is much easier to attain than fissile fuel.[4]

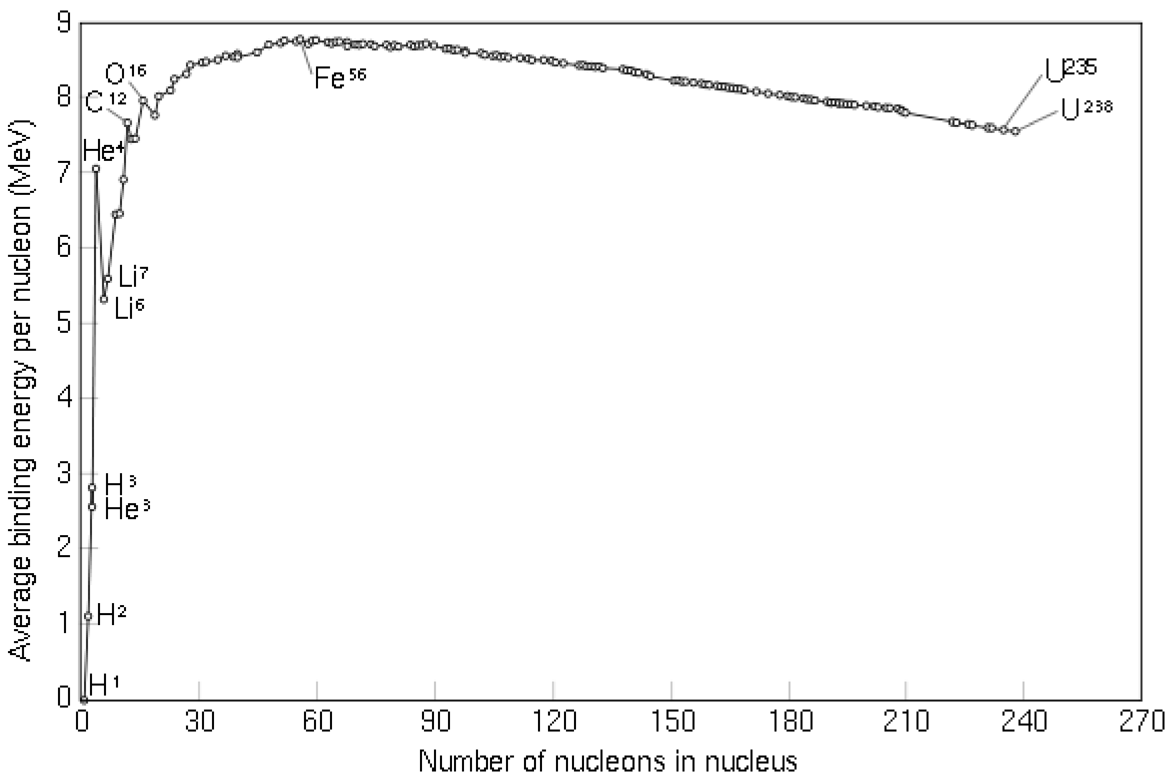
To achieve their goals, another potential nuclear fuel is being investigated for some of the generation IV reactors. Thorium, a slightly lighter element than uranium, was discovered in 1828 by Morten Thrane Esmark, a Norwegian mineralogist. One isotope, Th^{232}, makes up just about all naturally occurring thorium. This has a half-life of just over 14 billion years. The thorium decay cycle is much more efficient than the uranium decay cycle, and does not leave much long-lived waste. Unlike U^{235}, it is fertile rather than fissile. This means it has no critical mass and cannot initiate a nuclear reaction. But, in a reactor it can easily be converted to a fissile material, U^{233}, by neutron absorption. The Th^{233} undergoes beta decay with a half-life of 22 minutes, becoming protactinium-233. Pa^{233} also undergoes beta decay with a half-life of 27 days, into U^{233}. This has a half-life of 159,200 years, but usually fissions upon neutron absorption (a chance of about 92%). Most neutron absorptions in the decay chain will produce fissile isotopes after absorbing 1 neutron, meaning a good neutron economy and thus higher efficiency than using the uranium decay chain.[3]



A design for a Molten Salt Reactor, an type of Generation IV fission reactor

Most designs for reactors that use thorium as a fuel are molten salt reactors (shown above), which often have the fuel and coolant together as one liquid. Specifically the LFTR, Liquid Fluoride Thorium Reactor, uses thorium dissolved in a molten salt as thorium tetrafluoride as the fuel and coolant. This liquid is pumped into a critical graphite core, and then into a noncritical external heat exchanger. A nonradioactive coolant salt transfers the heat to another heat exchanger where water is boiled. This pressurised steam then drives turbines which produce electricity. LFTR's are breeder reactors, because fertile Th^{232} is added to the salt and all the fissile fuel is produced in the reactions, but are also thermal reactors because the neutrons released are moderated to generate heat. In the event of an emergency, the molten salt fuel and coolant can be easily drained into dump tanks beneath the reactor where the fuel becomes subcritical. A freeze plug between the reactor and the dump tanks is designed to melt unless constantly cooled, so a simple passive safety system is in place. Passive systems like these mean that the Fukushima accident could not have happened, as a loss of cooling would not mean a meltdown but an emergency cut-out. This provides a much more effective safety system than current plants. [5]

Fusion, in theory, is a much more advantageous process than fission, but it is much harder to make work. Recently, many developments have been made into the design of a working reactor. In stars, protons are fused together to form isotopes of helium. The graph below shows how the binding energy per nucleon increases rapidly with atomic number, peaks at iron, and then slowly falls. Up to iron, elements are fused together to release nuclear energy, and after iron elements are fissioned to release this energy. The increase from the reactor fuels to the waste is the amount of energy released.

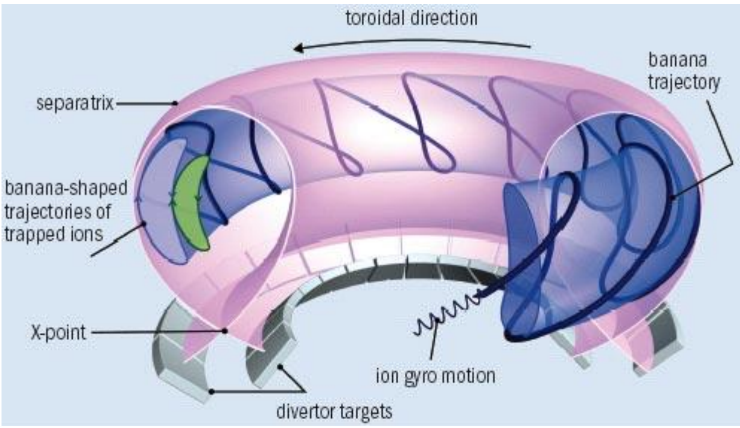


Graph illustrating how much more energy is released in a fusion reaction than in a fission reaction

This gives an instant appeal to nuclear fusion over fission, as much more energy is released per reaction. Many experimental reactors around the world exist attempting to harness the leap from hydrogen to helium. At JET, the Joint European Torus, deuterium and tritium (DT) are being fused together to produce helium and a neutron. Deuterium is found quite abundantly in water, about one in every 6 700 hydrogen atoms are deuterium, but tritium must be produced artificially.

The safety of a fusion reactor is also a great attraction. Nuclear fission releases harmful radiation which must be carefully controlled, but fusion does not, so all the damage a fault could do is on site. The fuels and wastes involved in fusion are not radioactive, whereas fission uses radioactive fuels and produces highly radioactive wastes.

There is of course a major difficulty. The conditions required for this reaction are very extreme, and so reactors are very technically complex. Although JET got very close[6], no reactor has yet been built that produces more energy than it uses creating these conditions, but it is hoped that the International Thermonuclear Experimental Reactor (ITER), under construction in Cadarache, southern France, will be the first to produce a net power output. The DT plasma, although one of the cooler fusion reactions, still needs to be heated to 150 000 000 degrees Celsius. No materials can withstand the temperature by a long way: the plasma needs to be confined by a magnetic field. The toroidal field system at ITER uses superconducting magnets to produce an 11.8 tesla field. The magnets used to generate this field are superconducting to maximise efficiency and minimise heat production. To keep the magnets at superconducting temperatures, liquid helium will be pumped around them from what will be the world's largest cryogenics facility. In tokamaks such as JET and ITER, the plasma is confined in a doughnut-shape. At the base of this doughnut there is an X point where rather than meeting the "edges" of the doughnut cross, and point onto the divertor targets. This is the only place where the plasma comes into contact with a material. The plasma here is "extinguished"- it is no longer reacting and the electrons are allowed to recombine with the ions to form atoms. But the energy of particles here is still high enough to release material from the surface of the divertor, which can pollute the plasma, reducing power and efficiency. To combat this, divertor targets are make out of specialist materials- often graphite or carbon fibre composites. These carbon-based materials are strong and can withstand high temperatures. However, carbon reacts chemically with the hydrogen



Magnetic field configuration and ion movement at ITER

isotopes and also traps it. This can mean that more than 350g of tritium, the nuclear licensing limit, is retained in the divertor. Metal divertors on the other hand do not react with the fuel, but are not as strong. Plans for ITER's divertor material use a combination of carbon-based materials in the most intense areas while beryllium and tungsten elsewhere. But in a reactor as large as ITER a small amount of carbon entering the divertor could quickly exceed the tritium retention limit. At JET, the only tokamak with technical specifications similar to ITER's, the divertor materials are being tested. The issue over divertor material is an example of one of the technical problems that ITER is yet to fully solve. [6]

If, when ITER is built, it can demonstrate that a large scale reactor can produce more power than it consumes, we will be one step closer towards a commercial fusion plant. The challenges have not been to fuse the particles together, but to do so in a viable way.

There is a need for nuclear power, as demand for low carbon electricity continues to rise and uncertainties remain over oil and gas supplies. The new Japanese government elected at the end of 2012 has announced that it will review the planned shutdown of their remaining nuclear plants. This is because of the sudden rise of their energy costs when they had to import more oil and gas.

Nuclear power is caught between the demands of safety, environmental impact and cost. Fusion has advantages in terms of safety and environmental impact, but despite decades of development, fusion has not yet become commercially viable. Furthermore, the difference between fission and fusion is not widely understood by the public. Therefore the advantages of fusion technology are not as well recognised as the science might suggest. At the same time, as we have seen, the safety and efficiency of fissional techniques is improving.

Although the possibility remains that fusion will supersede fission in the middle of this century, nuclear fission is likely to continue to dominate production of nuclear electricity for the next few decades.

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