A BRIEFING ON FUTURES WITH FISSION & FUSION

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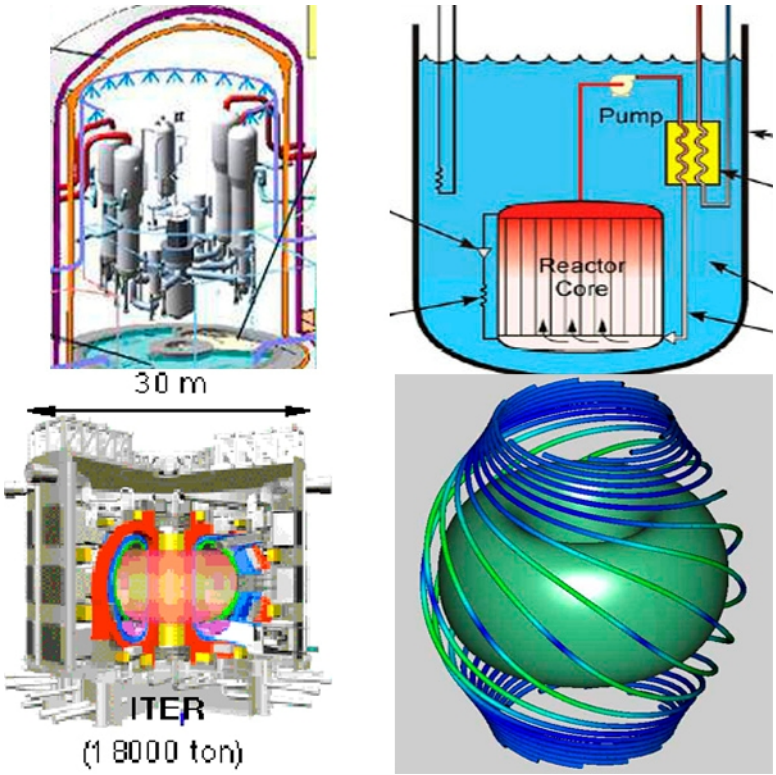
The cuts in the use of fossil fuels required to contain global warming expose enormous energy gaps for the world. The peak and decline of cheap oil are in the right direction and nature is forcing those cuts. Up to 90% of our future energy must be supplied in the form of electricity and Nuclear sources are the only ones able to deliver steady electrical energy on the required scale across the globe and are also the least expensive. The thirty years of research and development lost by minimal funding of all energy research means that everything must be achieved on highly compressed timescales. Here we examine what must be done and discover that a tight collaboration between Fission and Fusion is now necessary and made possible by the prospect of building small Fusion reactors within a decade.



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INTRODUCTION

Nuclear energy is widely recognised as the carbon free electricity source most likely to meet global needs and also to be the least expensive form of power [McNamara]. It is also hated by vociferous environmentalists who make the same claims for Wind and Solar energy. It would be better to acknowledge that all the forms of carbon free energy must work together as appropriate to different locations, budgets, and resources.

Replacing all the fossil energy systems we have grown up with is an enormous task which, when mapped out in detail, reveals difficulties with every option. With a simple model of the growth of carbon free sources we find that nuclear fission energy will probably run into insurmountable fuel supply and growth problems by 2050 if its deployment is based solely on the new Generation III reactors. It will be shown that this can be overcome with fissile materials from Fusion Fuel Factories. The Fusion systems also need their initial Tritium fuel to be manufactured by advanced fission reactors. The futures of fission and fusion will be tightly bound in a synergism of their separate technologies. Simple estimates are given for the R&D funds needed for an integrated system.

I. ENERGY GAPS

I.1 Climate Change

Every government policy on energy must now be directed at reducing CO_2 and other greenhouse gas emissions, with no evasions, postponements, or concessions to business interests**.** This statement now has all the force of a **political theorem**, like Pythagoras theorem in geometry.

Thanks to people like Al Gore world populations accepts this Emissions Theorem. The Kyoto agreement acknowledged this theorem but failed to identify the primary technological solutions, opting instead for the fashionable notion of looking to artificial markets as the mechanism [Prins & Rayner]. The caveats surrounding Carbon Trading are nicely given by Victor & Cullenward.

The threats from global warming have not really been grasped by those of us outside the IPCC community and many have sought to pick apart their work to show that man made emissions are not responsible and that we can therefore do nothing to change it. The physical evidence of global warming is actually appearing much faster than the IPCC has predicted, and new mechanisms in nature are recognised as they happen. The scientific evidence and understanding is very strong that we are indeed responsible and that makes it very probable that we can evade this scenario. We need not fear the ultimate disaster of runaway global warming but should focus on the terrible effects for us of the huge climatic and demographic changes arising at much lower temperature increases, man made or not [Lynas]. We must do our utmost to restore control of our global emissions. To be effective, action is required at a tremendous pace and very soon .

In this paper we assume that the battle against global warming and its consequences will dominate human activity over the next 50 years. Simple models of the existing and emerging technologies reveal significant problems which will arise from the required pace and the late start.

I.4 The Peak & Decline of conventional Oil

The task of financing the reinvention and rebuilding of our society faces another challenge - the imminent Peak and decline of conventional Oil supplies and the impact on the global economy. As the recent Bali conference has shown, world governments are unwilling to take any significant action on global warming. The decline of oil has the great benefit that it will force the issue.

The recent InterAcademy Council report, on sustainable energy [IAC] accepts the decline but goes on to violate the Emissions Theorem by noting the huge alternate fossil carbon sources like tar sands, methyl hydrates, and oil shales. However, the production from tar sands will be slowed by the need for large natural gas consumption in the processing and the technologies for the methyl hydrates and oil shales do not yet exist.

Thanks to Colin Campbell [Campbell] and the members of his Association for the Study of Peak Oil (ASPO), most citizens are aware that the high price of oil is indeed driven by oil demand as supply plateaus. Sympathisers with the US Geological Survey position, including most governments and all international energy agencies, accept their guesswork that there is great deal more to be discovered and that new technologies will extract a further bonanza from existing oil fields which produce no more than 40% of the estimated endowment in each field. This could be true, but the global results are otherwise: Discovery continues to decline far below production rates. There are now no new technologies, only old ones reworked to extract oil faster but with little improvement in total recovery. Small pockets of oil around existing oil fields are useful but deplete quickly. Several OPEC States have now realised that these methods only managed to sell off their reserves at a far lower price than today's. OPEC is now reluctant to increase supply and ASPO is informed by retired OPEC managers that their real reserves may, in any case, be much lower than their published figures.

The International Energy Agency [IEA] in Paris recently announced that supplies will decline after 2008 by 2 million barrels per day by 2012, and the head of the agency, Fatah Birol, says world supplies will be short by 13.5Mb/day by 2015 and that Russia may fail to meet its gas export agreements by 2015 due to rising national needs. One likely impact is that the IEA projection of 50% growth in global energy demand by 2030 will be much reduced or reversed by conservation, recession and privation.

The ASPO position is supported by many independent studies from the oil industry, as reported at ASPO conferences. Extraordinary and expensive efforts in the next few years could lift the peak from 85 Mb/day in 2010 to 100Mb/day in 2017 . Others predict a plateau at 90Mb/day till 2015 followed by a steeper decline at about 6% per annum. In all of the models based on current data and the realpolitck of production, supply is set to decline by over **40% by 2030,** which will also treble the price and value of natural gas again. Total oil supply will then drop to 15-29Mb/day by 2050. A compelling new report by the German Energy Watch Group is based on production figures which are accurately known rather than guesstimates of reserves. They predict an even faster drop by 2030 than used here

By 2050 the world will need at least 7000 GigaWatt- thermal-years (GWthermal-y, a million kWh per hour, every hour for a year) of electrical energy production, and strong improvements in energy efficiency and conservation, merely to maintain the 2007 energy levels and fill the gaps left by the fall and avoidance of fossil fuel energy (Fig. I.1). The usable electric energy delivered, measured in GWe-y, depends upon the conversion efficiency of each plant, which varies from 33% to 65% according to technologies used. A further fraction of the remaining thermal energy might be used for district heating, industrial processing, or Hydrogen production.

Adjustment of the global economy is likely to slow or even reverse the projected energy increases, but even this low target will strain our manufacturing and material resources. A 60% increase in delivered energy would be sufficient to bring living standards up to the EU standard for Russia and the top 1/3rd of the Chinese and Indian populations, assuming also a 20% efficiency gain in the EU but 40% in the profligate USA. The poor and the destitute are ignored in these estimates, including a possible addition of another 2 billion to their roles, as they consume so little and the cold reality is that there is no evidence that their plight will be addressed effectively this century.

I.5 The Four Primary Clean Energy Sources

There are only four clean energy technologies with the strength to meet our current needs, let alone rising demands - Biofuels, Nuclear, Solar, and Wind. Each of these has difficulties, all of which can be minimized or overcome [Forsberg], [Desertec].

Coal is the deadliest emitter and new stations should not be built without full CO_2 Capture & Storage (CCS). This technology works but is not applicable to old power plants or in all locations. The marketing term 'Clean Coal' does not include CCS and 'More Efficient' only means coal is burned more slowly and profitably. These claims are the case for breeching the Emissions Theorem by building more coal stations with a promise that CCS may be applied later.

Let us now work out how fission and fusion can play their major role in our minimal forecast for the energy transformation.

II. Fission

II.1 The Current Status.

Fission and Fusion are complex technologies and their slow development since 1980 has been due to politics not physics or engineering failures. Had Jimmy Carter not triggered the collapse of the US nuclear industry after Three Mile Island, and banned research on the essential technologies of fuel recycling, we could now be deploying advanced Generation IV reactors. As it is the Generation III offerings must be deployed urgently.

Having spent 25 years on Fusion research at the UKAEA Culham Laboratory and at the University of California's Lawrence Livermore National Laboratory, it was time for me to leave in 1984 when our $500M reactor prototype was closed without ever operating. Had Reagan not decimated Fusion in favour of Star Wars we could now be building the first pure Fusion commercial reactor, not the lone, final experiment, the 500MW ITER Tokamak reactor in France which is not due to lead to a commercial power station till about 2045. Fission and Fusion lost 30 years to these political decisions and are still miserably funded on a global scale.

France, Japan, Russia, India and China now lead the Fission and Fusion developments. The six new Generation IV fission reactor concepts that are ready for final design and demonstration will not burn or melt down and will consume their own higher actinide wastes. The small amount (5%) of remaining fission fragment wastes will decay below the radioactivity of natural Uranium in 100-300 years, allowing for much cheaper disposal than is currently proposed.

The first of these, the General Atomics Gas Turbine Modular Helium Reactor (GT-MHR, **Fig. II.1**) and its cousin, the Pebble Bed reactor, could be available by 2020 [La Barr]. The GT-MHR is an incredibly flexible design able to burn any fissile fuels including nuclear waste from Gen. II & III light water reactors. The reactor fuel is packaged as tiny pellets encased in a triple layer of graphites and Silicon Carbide (TRISO), strong enough to contain all fission products for a million years and thus burnable for 10 times longer than conventional Gen. III fuel. The reactors have been designed in 300MWe and 600MWe units.

The R&D efforts must be restored to their previous levels to make all these Gen IV designs a commercial reality. A mere $5Bn each will see these systems through to a prototype level, with two or more parallel projects.

II.2 Radioactive Waste

The Fourth Generation nuclear industry would use an Enclosed Radioactive Materials System (ERMS) run entirely by robots, especially in the fuel recycling and fabrication factories. This will keep all facilities clean, account for every gram of material, and reactor parks would become permanent with a design life of 10000 years. Reactors can be designed to reduce the volumes of intermediate level radioactive waste to be stored and the valuable metals content re-used on a 300 year cycle. The huge volumes of low level waste generated by current practices can be almost eliminated by better design and operation. A further $10Bn is needed to develop these integrated robotic systems. The fusion programme is already designing families of robots to service the ITER project which are far smarter than robots in mass production factories.

Many countries are already contemplating quite large nuclear fleets by 2050 - China(300 or 700 with Fusion Hybrids [Wu et al.]), USA(850), Japan(100), Russia (200) and India(300) but without any drive to replace coal or meet the decline of oil. The World Nuclear Association shows 220 new reactor proposals are now under consideration world wide. The EU has two under construction and four proposed. Only the small amounts of fission products or fragments from all these reactors would be put in deep disposal.

II.3 Nuclear Weapons & Proliferation

The proliferation of nuclear weapons is an international game in which Pakistan, for example, has been allowed to develop its own weapons, using aid funds and F-16 delivery systems from the USA has been given some assistance from China, and operates a global business in the procurement, manufacture and sale of weapons-

making equipment. Complete weapons have also been offered [Levy]. This makes all the discussion of proliferation and proliferation-resistant fuel cycles quite vacuous. Carter's prohibition of fuel recycling, on the grounds that it could lead to proliferation, merely paralysed the US development of advanced reactors and has now been repealed.

The goal must be to clearly separate the civilian nuclear power industry from any weapons programmes and no nuclear materials should be sold or traded without open agreements, permissions, and accounting. Every government must be fully engaged, open, and in control of its nuclear energy programmes which could still be managed by regulated corporations. The IAEA safeguards must be rewritten so that a continuous 24hr. lock-down and monitoring of all nuclear materials and facilities is an accepted part of any nuclear energy programme. These total safeguards would be operated by regions, since a single global authority seems politically implausible. The system would rely on Mutual Active Distrust (M.A.D.) between all partners in a region and fully shared information. [McNamara Weapons]

II.4 Uranium supply and Breeder Reactors

The Gen III reactors burn about one tonne of fissile material per annum per gigawatt-year of electricity. These reactors carry a full fuel load of 200 tonnes of Uranium enriched to about 4.9% and some 20 tonnes of spent fuel per annum is replaced. The total consumption of mined Uranium over the 60 year lifetime of a reactor, without recycling to recover unburned fuel, is about 15.5 thousand tonnes, with about 60 tonnes actually burned. A fleet of 1000 reactors needs 15.5 Million tonnes (Mt) of Uranium in this scheme.

The high operating temperature of the GT-MHR allows for a more efficient conversion to electricity and these reactors will consume only 0.65 tonnes per GWe-y. A 10MW experimental MHR is operating successfully at 950°C in Japan and a complete weapons Plutonium Burner project is under way in Russia, though both activities are under-funded and slow. China has had a 190MWthermal Pebble Bed reactor operational since 2004.

All Uranium reactors produce Plutonium, from transmutation of natural U-238 by absorption of a neutron to make Pu-239, breeding a replacement of about 60% of the fuel burned. Thorium is not fissile but is also transmuted by a neutron from Th-232 to fissile U-233 in a breeder reactor, in a cycle which does not generate any Plutonium. Thus, every tonne of Uranium and Thorium on the planet, and the reactor products of Plutonium, Neptunium, Curium and other transuranics (TRUs) can provide at least 1GWe-y in the appropriate fuel cycle. This means that the world could run 10,000 reactors for thousands of years from 2100. The UK already owns enough depleted Uranium, Plutonium, and other nuclear materials to run its 70-100 GWe-y share of the global reactor fleets for 500 years. The global stock of 1.3 Mt of depleted Uranium is, in principle, good for 1.3M GWe-years.

Because of the time lost in developing advanced reactors and fuel cycles there is now a problem. The IAEA keeps a record of all the known, expected, and speculated sources of mineable Uranium in each country with a concentration greater than 0.01%. The total listed in this 'IAEA Red Book' is about 20Mt, only 3.2Mt of which is in known mines, enough for only 206 Gen III reactors for 60 years. The dwindling Gen II fleets draw 30% of their fuel from existing stockpiles, which depressed the price for mined Uranium. Global exploration for Uranium has now increased dramatically and the price has leapt from $20/kg to over $200/kg in the last two years.

The IAEA data is not highly reliable, but the US case is very interesting: In the 1950s the government offered a reward for Uranium finds and distributed free radiation detectors which could sniff out Radon leakages from Uranium deposits, even from low flying aircraft. The USA therefore lists more expected Uranium, at 2.6Mt, than speculative at 2Mt whereas the speculation for the rest of the world is 4 times the expected discoveries. If the ratios were the same as the US figures then the total would still only be 24Mt.

British Petroleum used to own the world's largest mine, the million tonne Olympic Dam mine in Australia, an energy resource equivalent to 10 trillion barrels of oil. Without understanding the true value of the resource, the largest BP ever owned, they sold the last 53% holdings in 1994 for £2.5Bn. If a vigorous global search over the next decade uncovers all of the IAEA Red Book Uranium and far more, equivalent to another twenty Olympic Dam size deposits, the picture may change.

There has been some success in filtering the 3 parts per billion of Uranium from seawater. However, the engineering required to fuel the global fleets is on the scale of a barrier across the entire Gulf Stream.

Until more is known it would not be wise to base a business plan on much larger guesstimates such as the unsubstantiated MIT claim of 80Mt [Bunn et al.]. The underlying argument is that the amount available in the market grows exponentially with price, one of the arguments used by the oil industry to build confidence in future reserves. The Energy Watch Group report on Uranium Supply is pessimistic about even the IAEA figures but there is still enough for a 1000 year recycling programme in their estimate.

The Gen-III breeding ratio of 0.6 means that mined Uranium would always be the source of the extra 400kg of fissile Uranium per reactor year, after recovering the fissile content of the spent fuel. About 2000 reactors would consume all the Red Book fissile Uranium on the planet in 60 years in such a scheme. The global needs by 2050 are much higher than this and a suitable mix can be built as fast as new models become available (**Fig II.2).**

Breeder reactors have a much higher power density core which can also fission U-238 with the fast, 1 Mev neutrons produced by fission. With blankets of natural or depleted Uranium in and around the core the Sodium cooled Fast Reactors (SFRs) produce 1.2 times as much Plutonium as fissile atoms consumed [Dubberly et al.]. The SFR supports itself and the extra 200kg of Plutonium can be used to support half a Gen III type reactor or be used to help start a new breeder reactor. This is what would eventually allow the IAEA just the Red Book Uranium to support 10,000 reactors for several millennia, but it is already too late (**Fig II.3)**.

We are compelled now to deploy Gen III reactors as a fast as possible and our simple model shows about 1000 GWe-y is needed by 2030, about three times the current world supply of nuclear electricity. This will use 4.4Mt of mined Uranium and enrichment leaves a stock of 4.2Mt of depleted Uranium. The more efficient GT-MHR

needs final engineering demos to be built so commercialisation can begin from about 2020. A Fleet of 250 GWe-y of GT-MHR reactors may be built by 2030 and continue to grow through 2050 .

The fast breeders need even more development and are not expected to be ready before 2030. Fuel recycling must begin before 2030 to make startup fuel for the breeder fleet. By 2050 we could have a base load power mix of 1100 Gen IIIs, 1350 GT-MHRs, and 800 breeders in a fleet of 3250 reactors for which all spent fuel is reprocessed. Only 4.5Mt of the speculative Red Book Uranium is left. Then, the breeder fleet can either grow itself or sustain the thermal Gen III and GT-MHR fleets for more than another 20 years, but not both (**Fig II.4).** The Thorium cycle has the same problem as fissile Uranium is required to start the cycle and the breeding ratio is around 1.2.

Renewable sources are assessed at 15% of total supply by 2030, growing to 20% by 2050.

The mission to reduce greenhouse gas emissions by better than 60% by 2050 would be met but fission power would stall unless another large source of fissile fuel has been found.

III. Fusion

III.1 The Fusion Fuel Factory

Fusion produces 5 times as much energy per tonne of heavy Hydrogen fuel (Deuterium and Tritium) as fission and 20 times as many neutrons. Neutrons transmute the elements but the Fusion programme has been focussed on the pure goal of producing all our energy for hundreds of thousands of years. Distasteful as it is to the purists, fusion is now needed to use its neutrons to make fissile fuel and the two technologies will become tightly intertwined.

Fusion neutrons are emitted at 14 Mev and, in the right breeder blanket (**Fig III.1**), can make enough Tritium to refuel themselves and also breed 6400 kg of Plutonium per GWe-y in the Uranium part of the blanket. This is enough to support 16 Gen-III reactors or 20 GT-MHRs. [Moir].

A hybrid blanket has three layers of material: A neutron multiplier section of pebbles of a Beryllium-Titanium alloy [Mishima et al.], a TRISO Tritium breeding section, and a TRISO depleted Uranium section for making Plutonium . Packaged in larger spheres, like the Pebble Bed reactor, this would also allow for continuous extraction of the created fuels without shutting down the fusion reactor. This TRISO version is proposed here more for its reliance on a common technology at high gas coolant temperatures than any assurance that the neutronics will be efficient.

These studies are quite old but still relevant. They also aspired to make fissile fuel at a cost which would match that of mined and enriched Uranium. The Uranium cost is about 60% of today's total fuel cost and is set to soar to 3-4 times current prices by 2020. So, in the circumstances outlined above the fuel from fusion hybrids will be of immense value and so a price of 5 to 10 times the current $2500/kg of 4.9% enriched reactor fuel could make early fusion hybrids economically viable. The significant corollary of this is that the fusion hybrid reactor need not be a highly efficient power producer but should at least support itself.

It is important to note that the hybrid breeder is not also a fission reactor. A full merger of the two technologies as a power reactor has been promoted as a way to revive fusion but seems to compound all the technical problems without giving a clear advantage. Only depleted Uranium, recycled reactor Uranium, or Thorium would be used in breeder blankets. Larger hybrids than the ones discussed here could also burn packages of the tiny amounts of high Actinides from spent fuel.

The fusion programme has been forced onto a single track of building international ITER reactor in France (well, two tracks if we include Laser fusion which may reach ignition conditions in three years). All other possibilities languish as minor experiments in universities. One difficulty for breeding anything more than Tritium in a two layer blanket is that more than 50% of the surface of the burning Tokamak plasma is covered by magnetic coils or neutral beam inputs. Many of the alternative fusion devices have much better access for a breeding blanket.

Some of these devices, the compact torus family [Voss], have better access and already perform much better than the first Russian T-3 Tokamak which fired the JET-to-ITER programme (Fig. IV.2). Proposals are being advanced for a small fusion reactor to produce electricity within 10 years [Gryaznevich] and there is keen interest in this class of machines in China. This is a refinement of main steam Tokamak design, squashing the plasma ring into a compact sphere, not a completely new and untested device. Similar energy confinement scaling laws to those for ITER show that a 100-200MW-th reactor can be built with a smaller plasma only 6 m in diameter, at higher pressure, and lower heat loading to the walls allowing the machine to be built entirely with existing materials and technologies. The high magnetic fields needed can be generated with the latest commercial high temperature superconductors. The performance would be sufficient to generate enough electricity to at least run the reactor. This would be more than a demonstration of fusion in action: Such a reactor could also breed enough makeup Plutonium fuel to support a 1GWe GT-MHR. A successful demonstration of such a reactor would lead directly to mass production by a new Fusion Industry. Every reactor fuel reprocessing facility would include a battery of these small fissile fuel generators. They should be started as soon as practicable to start the conversion of clean, depleted Uranium into a fuel stockpile.

Others, such as the kinetically stabilised axisymmetric mirror machines [Post], the Gas Dynamic Trap [Anikeev], or the Spheromak [Romero-Talamas] are also worth bringing up to a real 'proof of concept' level with a mere $1Bn each. None of these poses any technical threat to ITER as all the engineering and materials results which will flow from ITER are needed for whatever final large reactor choice may be made.

The Gas Dynamic Trap needs only existing neutral beam and magnetic coil technologies and could prove to be a much better and earlier source of fusion neutrons for engineering and materials studies than the proposed IFMIF accelerator driven facility which may be funded on a 25 year time scale. The GDT has very poor energy containment and would need power to run it. It may be possible to add super-efficient energy recycling to make a plant more economic.

The ITER programme has a well funded development team devoted to the design of its Tritium

breeding blanket. It has the data and design codes to readily produce fissile fuel breeding blanket designs in the immediate time frame.

III.2 Tritium

There is yet another major obstacle. Tritium is radioactive with a half life of 12 years, decaying to the stable but higher temperature fusion fuel, Helium-3, and is not naturally occurring. It is currently manufactured very slowly from Canadian CANDU heavy water reactors. There is not enough Tritium in the world to start up the fusion hybrid breeders.

General Atomics have already shown that the GT-MHR reactor fuel can also carry Lithium pellets which breed Tritium when irradiated by neutrons at a rate of about 1.7kg/GWthermal-y. Startup Tritium fuel for a small Fusion Fuel Factory is no more than 20kg. so the fleet of 1350 GT-MHRs will have no difficulty in supplying their needs with production starting by 2020. The TRISO fuel packaging is strong enough to fully contain the Tritium till it is harvested, unlike the ceramic pellets being proposed for ITER. The GT-MHR fleet is ideal for generating the Tritium needed for the fusion hybrids.

The synergies between fission and fusion come full circle. The fusion hybrid programme should receive the same funding as the fission breeder programme and may well be quick enough to replace it as the method of choice for making fissile fuel.

The problem of Uranium supply is overcome and a combined future for millennia of fission and fusion power is realised.

This is not the end of the story. Many countries will just be clients for Gen III. nuclear reactors using low enriched fuels. They will not operate any of the other complex technologies in the fission fuel cycles. The only way to support this global fission system is with Fusion Fuel Factories.

IV. A UK Nuclear Energy Programme

The energy needs of just one country, the United Kingdom, serve to sharpen the view of the real scale and scope of the coming energy gaps and provides us with a simple model.

IV.1 Modelling UK Electricity Needs.

First consider the way energy is used in the UK as given in the UK Energy Statistics for 2006 (Fig. IV.1). The largest use is for home heating and electricity, most of this coming from natural gas which in the 2003 UK Energy White Paper was viewed as the cheapest source of energy for homes and industry in the UK. This is now far from true, the price having trebled, North Sea gas declining at 12% per annum, and new LNG facilities operating at 1/5th of capacity as cargoes are diverted at sea to places willing to pay more. The gas supply projections have been a huge forecasting and economic blunder and so, with real cost rises and supply problems we make the opposite prediction of a steady decline in the use of gas in the UK till 2050. The Gas price scenarios continue to be below actual market prices.

The second largest usage is of oil for transport. The Peak and Decline of cheap oil means that our usage will be down by 40% by 2030 and 80% by 2050. Even if several Saudi Arabia size oil finds were made they should not be used to maintain current supply levels as this would breach the Emissions Theorem.

The pace of change is soon to be faster than our engineering capacities can meet and big lifestyle changes are inevitable. Some 30% of all road journeys are unnecessary, most of them as commuter travel which must use carpooling and public transport on electric buses, trams, and trains. Almost all long distance freight and passenger travel must be by electric rail, so we estimate a 300% growth in UK rail capacity by 2050.

It is apparent from the chart that electricity is a small part of the total energy usage, about 25%. Trivial "Green" measures like turning off appliances on standby or getting an occasional kilowatt from rooftop wind or solar generators, are minute contributions on this scale and do not compare with the real problems of inadequate planning for major energy sources.

Electricity is now vital to our civilisation but coal use must be drastically and swiftly reduced except where Carbon Capture and Storage systems are used. Elimination of coal is a further huge energy gap in the UK.

The sum of these energy resource losses, less the conservation measures described, must be replaced by Nuclear energy and some Wind power, other sources being valuable but minor contributors.

A minimum of 2-3 GWe-y of nuclear power must be built every year and large offshore Wind farms integrated into the national grid to replace all the coal, oil, and gas energy usage. By 2050 a mix of 25 GWe-y of EPRs, 30GWe-y of GT-MHRs and 5 large Fusion Fuel Factories or 20 small ones would make the UK independent of all external energy sources, except biofuels, for 1000 years. Complementary steps in electrification, conservation, and transport optimisation are necessary for the transition.

IV.2 Load Variations

One final problem looms: The daily and seasonal energy variations mean that, in our UK example, the average electricity consumption is about 40 GWe-y but the peak capacity used is about 65GW with a reserve for maintenance and breakdowns of a further 10GW. However, natural gas for heating and oil for transport currently triple these energy variations at about the same times. In an all electric world these loads have to be spread out to make our final energy system at all sensible. Transport will use millions of batteries which can be charged overnight even from fluctuating sources like Wind. Electric home and office heating can also be done with night storage heaters. Many manufacturing processes will have to run at off peak times to bring hourly usage much closer to the average. Fission and Fusion reactors of various sizes from 300-1500 MWe can manage significant load following. Grid interconnectors will allow power to be shared across 3 or more time zones as the highest peaks are at the start and end of each working day. The very low losses on long distance D.C. power lines and the use of superconducting transmission lines will balance these systems. Connections between north and south will help smooth seasonal variations.

Clearly, as we move to an all electric world almost everything will have to be changed, by design or by force of circumstance.

IV.3 Energy Imperatives for the UK

The standard mathematical way to minimise any measure, such as total emissions, is the method of steepest descents. In this case it means that every tax, grant, regulation, law, treaty, initiative, or project must reduce actual associated emissions. The descending steps, mainly by the energy, transport, and construction industries, must be large enough to reach the minimum by 2050.

The lowest coal consumption in the world (BP Statistics 2006) is by France and Japan. The third largest consumer is Australia, also with the largest Uranium resources. Poland and Germany together burn ten times the amount of coal still being consumed in the UK. They should be leading the EU effort to deploy CCS systems but the UK may agree to allow German energy companies to trial CCS in the UK, essentially at our expense, after new coal stations have been built. Ten new opencast coal mines have recently been approved in the UK. These are not descending steps in emissions. It would be better, if desperate, to extend the life of old coal stations for 5 years than to build new ones to run 60 years.

The public nuclear power debate is dominated by Green propaganda based on the mixed history of UK designed and built nuclear power. Other reactor technologies worked much better and the Gen IV technologies resolve all the outstanding problems. The restraints placed on the profitability of the nuclear industry, and the consequent reduction in internal R&D, were a great triumph for the Green movement. The idea that no public support should be given to new R&D is a further triumph.

The media decline to publish articles on new nuclear technologies and there is no TV documentary on the world's best nuclear system - in France. A Royal Society group has linked our valuable 100 tonne stock of Plutonium fuel at Sellafield with terrorist fantasies [Boulton]. The government has just withdrawn from formal cooperation with the global Generation IV study programme.

The hugely expensive waste disposal methods proposed by the Nuclear Decommissioning Authority are not suited to the new technologies which produce far less and burn all the long lived waste as fuel. There is enough nuclear fuel now in storage at Sellafield to run a UK nuclear economy of 70-100 reactors for 500 years, but the NDA planning is focussed on the eradication of all traces of nuclear energy in the UK [NDA].

The UK nuclear industry and nuclear science and engineering capabilities have been all but dismantled and the rump industry was silenced as it waited for the government to pronounce judgement. They are now looking at the capricious nature of British nuclear regulation, a minimal and outdated Nuclear Inspectorate and the threat of random market manipulations and taxes. Meanwhile, huge subsidies are going to Wind and other renewable systems. The capital cost of the announced 33GW of offshore wind, which will generate less than a net 10GWe of fluctuating output, would cover 20GWe of steady nuclear power.

British North Sea Gas will be fully depleted in 5-6 years and the UK is set to be the world's third largest gas importer by 2012. The possibility of an energy famine in the UK hangs by a pipeline [Sharman].

Total UK emissions have risen steadily since 2000, along with everyone else's.

Like Fission, Fusion has made great strides despite the miserable funding. In the UK, Fusion has been relegated to an academic project, not a national project. It is clear that a new Department of Energy is required to support Fission, Fusion, Wind, energy storage, electricity grids, liquid fuels, and all other major energy programmes.

V. Concluding Remarks

Here, we have outlined the potential role of nuclear energy in beating climate change and supplying reliable energy for millennia. The remaining research costs are estimated at a modest $100Bn but the building of a fully electric civilisation will cost far more. Deployment of the first Gen IV fission reactor, the GT-MHR, and demonstration of the first small fusion reactor are both possible by 2020. We have shown that a full solution to the looming energy problems can be achieved with current and rapidly advancing nuclear technologies.

The argument for the need for Fusion Fuel Factories depends partly on the pace of Uranium discovery. Even so, fusion breeders are far more effective than fission breeders and will always be the preferred option.

It is up to every government to take charge of the process. The pace should match that set by the Apollo mission. All regulations, treaties, and financial instruments should be directed at meeting this Energy mission. Thanks to the peak and decline of oil these steps will be forced upon our governments.

The effort is for generations alive today since my children will be in their 80s by 2050 and their generation will manage the change. My youngest grandchildren will be in their 90s by 2100 and will know if we succeeded or failed.

Acknowledgements

R. Moir, formerly of Lawrence Livermore National Laboratories, and H. Sharman of Incoteco have contributed their expertise to several key results in this paper. The highly creative role of General Atomics in both Fusion and Fission technologies has been communicated to me by E. M. Campbell and K. Schultz. M. Gryaznevich has given freely of his knowledge of small Fusion systems. S. Locke Bogart made many suggestions and introduced me to key people in the nuclear industry.

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About the Author

Brendan McNamara worked on Fusion Theory and Computations with AEA Technology, Culham (1961-71)and at the Lawrence Livermore National Labs in California (1971-85). He also ran a series of Plasma Colleges and workshops at the International Centre for Theoretical Physics, Trieste, 1974-84. He was Exec. V.P. of a Supercomputer Center in Princeton (1985-88) and now operates Leabrook Computing as a Consultancy.

CHARTS & DIAGRAMS

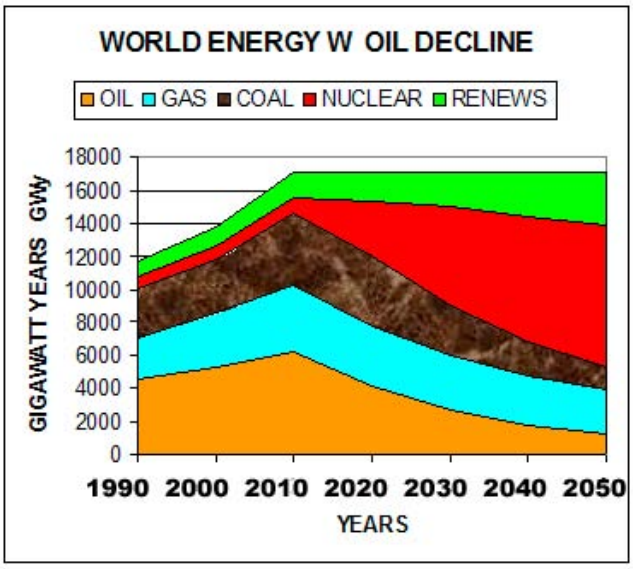


Fig. I.1 The decline of oil, the suppression of coal usage and the expense of natural gas lead to an energy gap of 7000 GWy by 2050. Nuclear power must increase to 3000 GWy and renewable energy 1000 GWy would maintain globale energy supplies at the 2010 level.

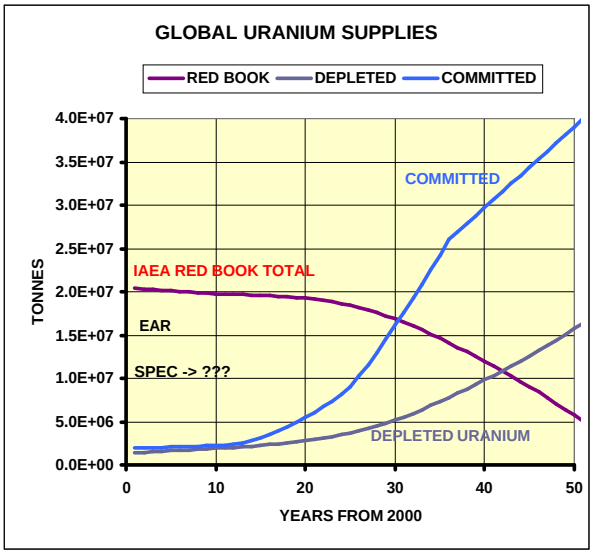


Fig. II.3 The resource of 20Mt of natural Uranium, predicted by the IAEA declines as reactor fleets are built. Correspondingly the stock of depleted Uranium from enrichment plants grows. The reactors built need a 60 year commitment of Uranium supply. The total commitment exceeds 20Mt by 2035 as Fission uses up all the EAR resources.

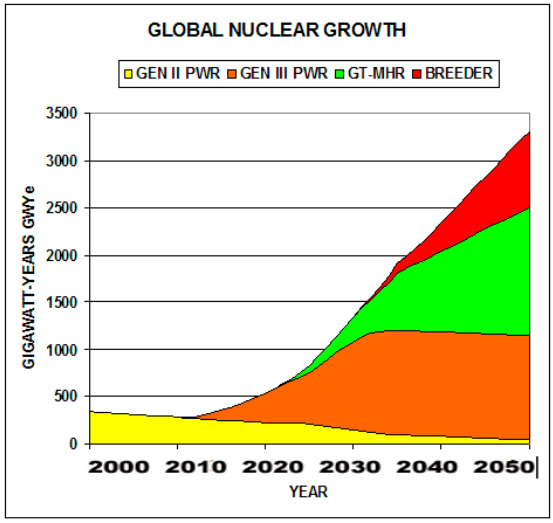


Fig. II.2 Gen III reactors will replace existing Gen II reactors, growing to a fleet of 1200 GWy by 2035. These may be superseded by Gen IV power reactors from 2025 for a fleet of 1800 GWy. Gen IV Fast Breeders will also be deployed from 2030.

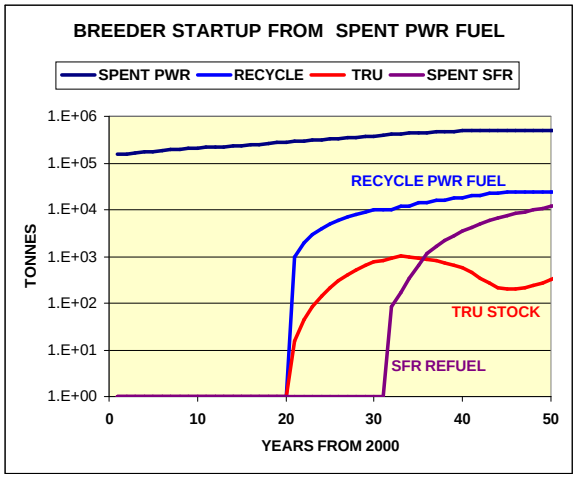


Fig. II.4 Full Recycling of the large stock of spent fuel from the reactor fleets begins in 2020 to build stocks of Trans Uranic fissile fuel to start the Fast Breeder fleet by 2030. The spent fuel from the FBRs is also recycled to fully sustain them with a small excess for FBR fleet growth. The Gen III/IV reactors cannot also be sustained.

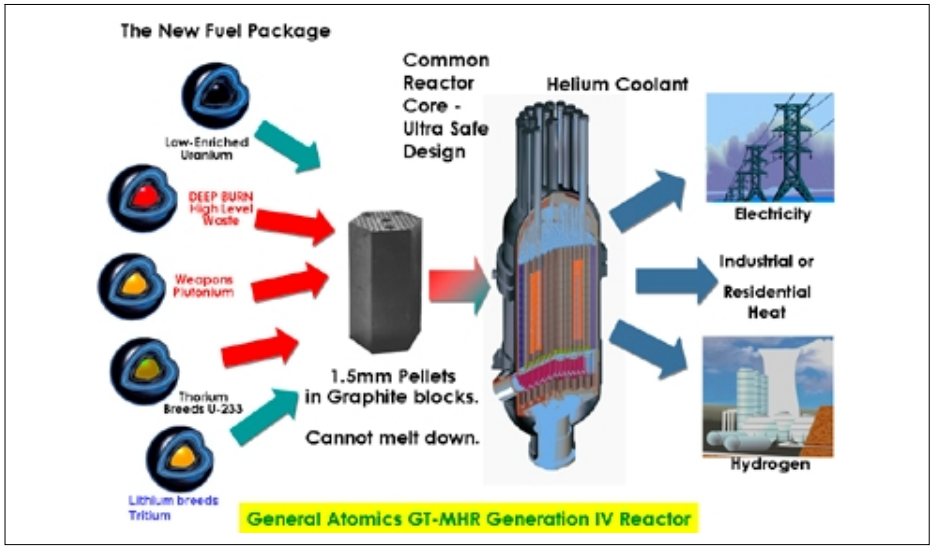


Fig II.1 The General Atomics GT-MHR reactor using triple coated TRISO fuel particles can burn many fuels including Low enriched Uranium, reactor wastes, or weapons Plutonium. It can also create new fission fuel by irradiating Thorium or Fusion fuel by irradiating Lithium.

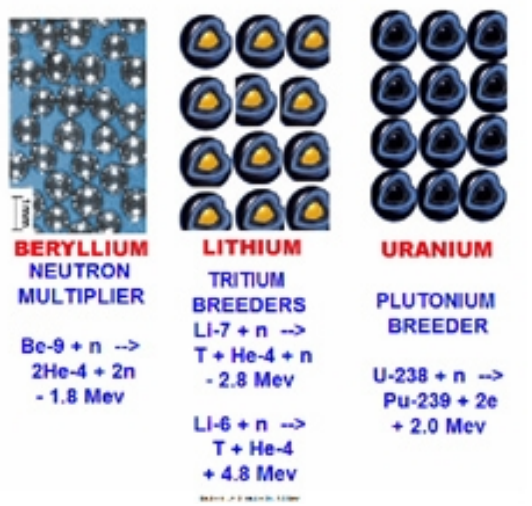


Fig III.1 Breeder blankets for fusion reactors could use TRISO packaging for layers of Lithium and depleted Uranium, using an initial layer of a neutron multiplier like Beryllium. These blankets could support a fusion reactor and 5-10 fission reactors.

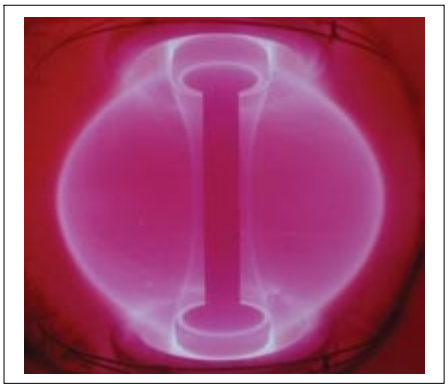


Fig III.2 Compact Spherical Tokamak reactors offer much higher performance than the standard large Tokamak such as ITER. Small versions could be deployed early to support the fission programme. This shows the plasma in the first such Culham experiment, START, 1997.

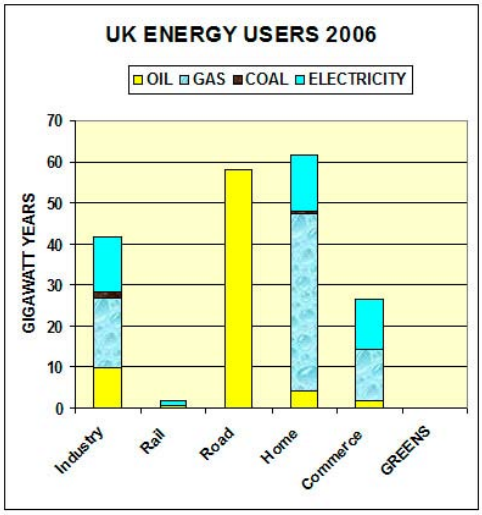


Fig. V.1 Total energy use in the UK. Gas and Oil must be replaced by Nuclear and Wind electricity. The Rail system must be electrified and trebled. Green contributions from rooftop power will never be significant.

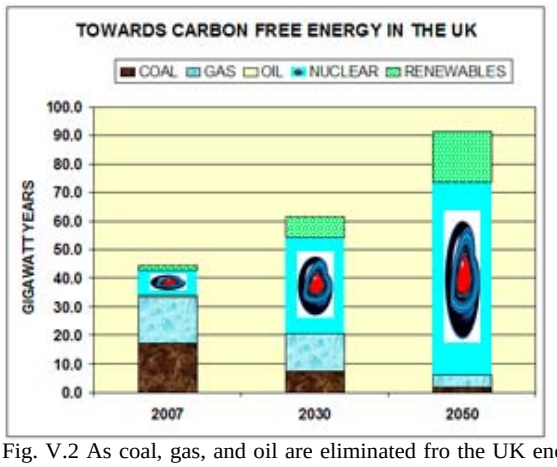


Fig. V.2 As coal, gas, and oil are eliminated fro the UK energy mix, Nuclear and Wind must fill the gaps for Industry, Transport, Commerce, home heating, and agriculture.

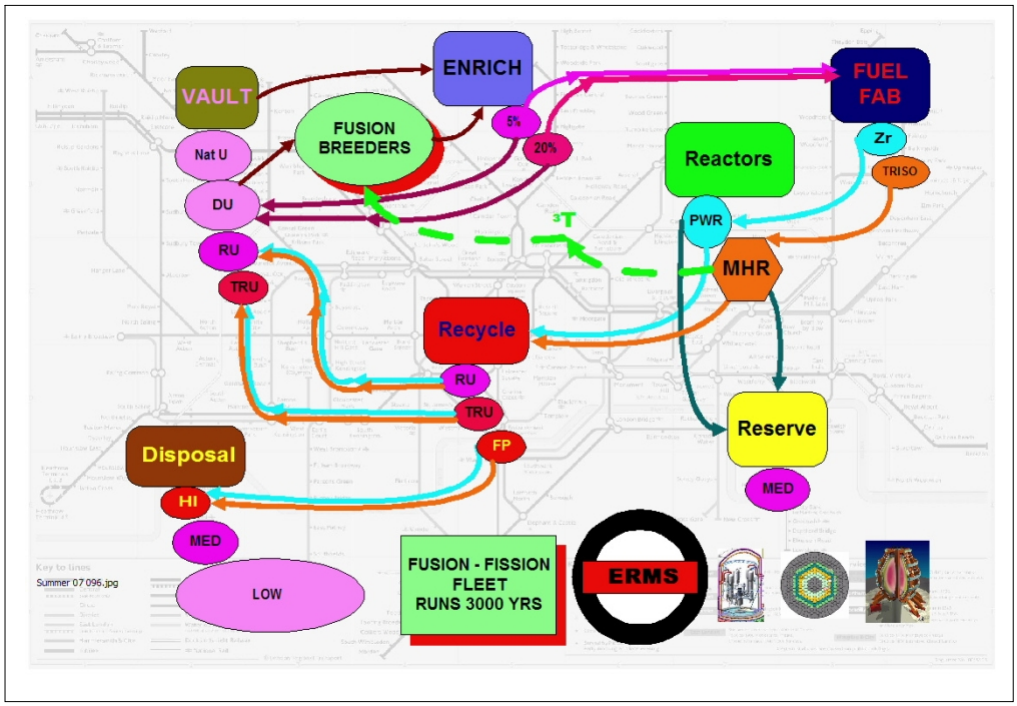


Fig. III.3 A route map of the whole technology for a combined Fission-Fusion future shows only two fission reactor types, the PWR and the MHR. Fusion breeders fill the role of fission breeders which would not be needed. All these facilities work within the ERMS system with no human contact with radioactive materials. Much of it will be Underground.

Key:

VAULT: Natural Uranium, Depleted Uranium 0.02%, Recycled Uranium 1%, TransUranics and Plutonium.

ENRICHMENT: 5% for PWR fuel, 20% for MHR fuels.

FUEL FAB: Zirconium clad rods. TRISO fuel particles in compacts or pebbles.

REACTORS: Pressurised Water, High temperature Helium cooled.

RECYCLE: Spent fuel process, FP Fission products.

DISPOSAL: Hi level FP waste + Pre-ERMS Medium, Low level 'wastes'.

RESERVE: Medium level materials reserved for 300 years. No low level.

APPENDIX A. REACTOR GALLERY

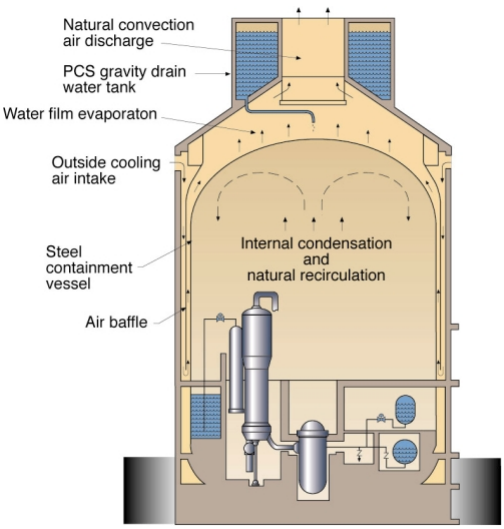
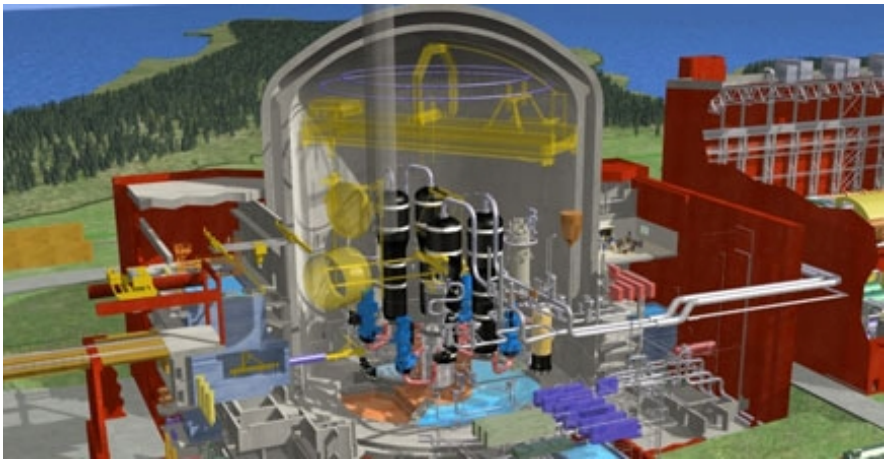
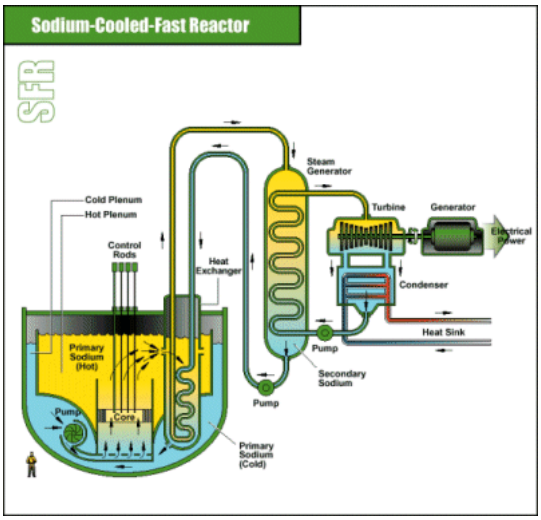


Figure 3. AP600 Passive Containment Cooling System

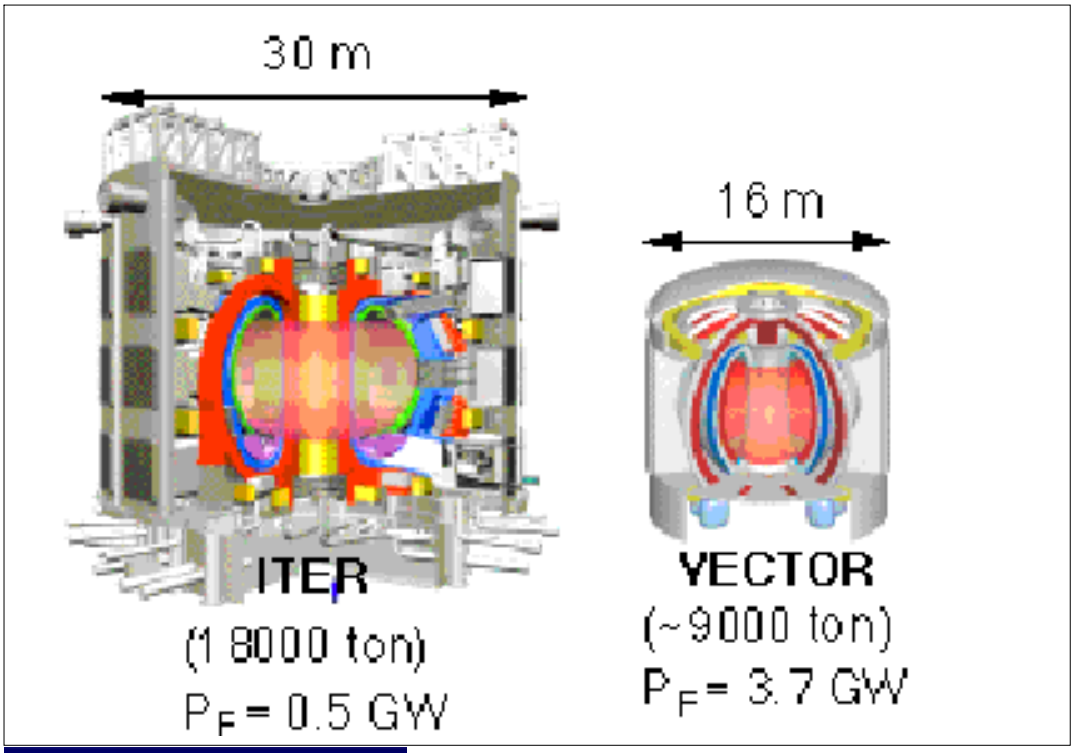
The Westinghouse AP600 and similar AP100 were the first reactors to be approved under the new US programme by the Nuclear Regulatory Agency. The plumbing is greatly simplified and passive safety is offered through the swimming pool of collant at the top which would be released in the event of a coolant failure. Thermal motion in the reactor chamber would prevent any meltdown.



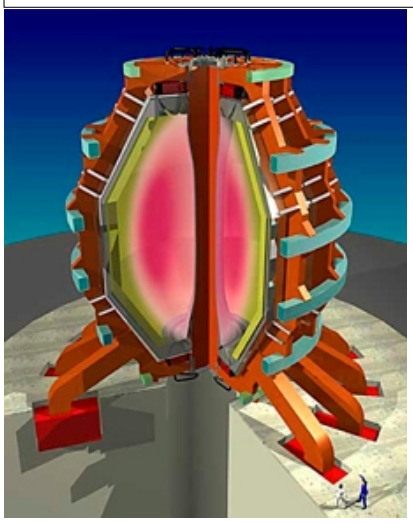
The French EPR takes the multiple systems route to safety, with four completely independent systems which ensure no loss of coolant to a very high probability. The reactor is 50% more powerful than the AP1000. A catchment pool for any meltdown which did occur ensures full containment of all radioactive debris products. France has run the world's safest nuclear power industry.



The General Electric design of a completely safe fast reactor uses a giant pond of liquid molten salt to ensure passive cooling of the compact, very high power density core. GE PRISM parameters are used here to model the Fast Reactor fuel cycle.

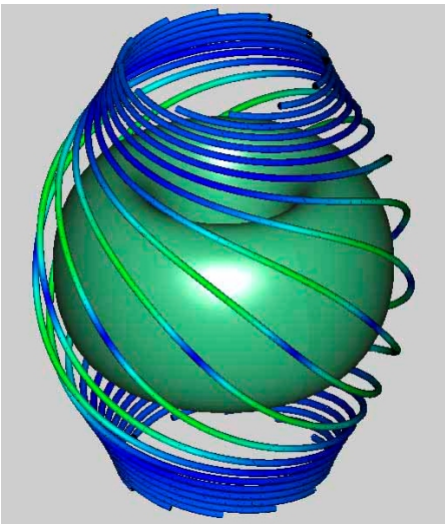


This cartoon shows the shape, relative sizes and fusion power of the international experiment ITER and the Japanese design study for a high power Very Compact Spherical Tokamak reactor, VECTOR.



Compact Spherical Tokamak reactors offer much higher performance than the standard large Tokamak such as ITER. Small versions could be deployed early to support the fission programme.

This reactor design is based on the MAST experiment at Culham. A small 100MW version would be 1/3rd as small and could be operated with currently available technologies.



The compact Spherical Tokamaks have very strongly curved magnetic field lines which defy the use of simple mathematical calculation and require computer simulation to see their properties. The curvature holds a much higher plasma pressure than the ring shaped Tokamak. Inner field wrap the plasma with a high shear between them, helping to suppress fine scale turbulence losses. This simulation is by Hayashi et al. at the Japanese Atomic Energy Research Institute in a collaboration with UKAEA Culham.