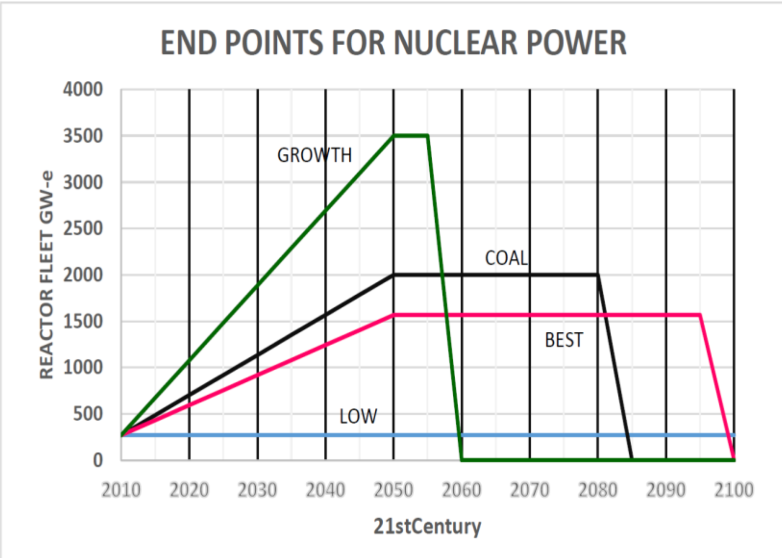
Nuclear Power:

Escaping the Path to Failure

Brendan McNamara, September 2014

Nuclear power could be the primary contributor for reducing Carbon emissions. The present growth rate will be ineffective, but a big expansion using light water cooled reactors will be running out of Uranium by 2050.

The closed fuel cycle, using Breeder Reactors, will use the same resources over many millennia. Politics stands in the way.



The avoidable collapse of Nuclear Power.

Environmentalists for Nuclear Energy – UK

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Overview

Electricity from Nuclear Reactor types developed over the last 75 years could combine to supply 80% of the world's energy for over 10,000 years from apparently tiny supplies of Uranium. Fusion Power is another type which could extend the supply to millions of years, clearly a great triumph for humanity. The emergence of rapid climate change as a world catastrophe has set us a stupendous challenge to change all our energy usage to cut carbon emissions by 80% in the 35 years to 2050. Every carbon free energy source should be assessed for the maximum contribution it could make and the environmental penalties which arise. This has not been done for Nuclear power which could replace the big polluter, Coal, a goal quite within reach by the world energy industry.

The World Energy Council has evaluated the current nuclear growth plans around the world and perceives only a modest increase. The International Energy Agency has written nuclear power out of its scenarios [OECD, 2013]. It is not the role of these bodies to comment on or guide individual government policies so they merely represent selected political consensus views. This leaves only one plan, to cut carbon emissions at any cost by the use of Wind and Solar power, backed up by fossil fuels. The plan has been fully assessed for the USA by the US National Renewable Energy Laboratory [NREL, 2010] but with little consideration of public acceptance.

The Nuclear industry has not done a system modelling exercise on this scale. What it has done is develop safety and performance standards for the newest Generation III+ reactors which satisfy scrupulous regulators as an acceptable basis for rapid nuclear growth. However, this makes very poor use of Uranium resources. Pressurised Water Reactors (PWRs) like the Areva EPR, the Westinghouse-Toshiba AP1000, and the Rosatom VVER 1200, dominate the new commercial market. They burn fuel till fission waste fragments slow the reactor when the "Spent" fuel is removed and set aside for burial. It is easy to show that in any attempt to replace Coal this "Open" fuel in, fuel out cycle will run out of Uranium this century, leaving a legacy of 2 million tonnes of Spent fuel to be buried for millions of years. This is a path to failure and an ugly result.

The alternative "Closed" cycle would recover 99% of all the fuels in Spent fuel and return them to reactors. New generation Breeder reactors would create 10-20% more fuel than they burn and consume all their own high level wastes, plus those from PWRs. Existing Spent fuel stocks, which are a major problem for governments, will all be consumed, obviating any need for Geological Disposal Facilities (GDFs). A global system would have a tiny footprint, run for over 10,000 years, and return spectacular benefits.

So why has the nuclear industry not pursued their best options vigorously? They do feel that they must sell what they have, PWRs, and not get side-tracked by schemes still in need of some development. The nuclear industry may not relish a fight with coal as it is eliminated, whereas Renewables will only put coal and gas on standby, subsidised to still exist. They have actually missed the limit on Uranium supplies, with cover from the World Nuclear Association (WNA) claim that there will never be a problem. They are unsuccessful at keeping the issue of Spent fuel on hold with the promise of GDFs. Western politicians remain baffled by the lack of clarity from the industry and have become their primary obstacle.

We at EfN want to see nuclear energy reach its true potential. We must show how the workings of the Open cycle is only 1% efficient in its use of Uranium and will use up all expected Uranium ores this century, and then demolish the WNA Uranium story. We then outline the features of new, little known Closed cycle reactors which make them so valuable and so near to exploitation. A major objective is to identify the political blocks to maximising the contribution of nuclear power.

I. Natural Uranium

Uranium ore is a mix of two chemically identical isotopes, U-238 (99.3%) and U-235 (0.7%). The main one, U-238, is faintly radioactive and very rarely an atom disintegrates or "fissions" spontaneously, spitting out 2 or 3 hot neutrons as it does so. These cool off to be a seed, captured by an atom of the other isotope, U-235, which promptly fissions, releasing lots of energy and 2-3 more neutrons. With sufficient U-235 nearby, this leads to a chain reaction which can power a nuclear reactor.

Burning one tonne of U-235 gives enough energy to generate a 1000 MegaWatts of electricity for a year, a total output of 1 GigaWatt-year-electricity (1GWy-e). This is pretty much the output of a large modern PWR running with a 90% load factor. To find out how many GWy-e are possible we need only know the total mineable resource on the planet to calculate the number of tonnes of U-235. It is only 161,000t according to the IAEA.

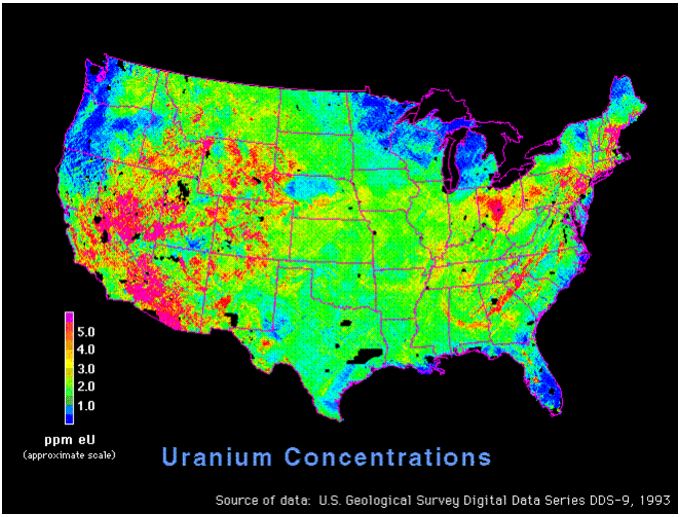
It is not a good idea to separate out a whole tonne of U-235 in one place since the critical mass for a nuclear explosion is only 15kg. So, the PWR uses 20t of fuel rods enriched to only 5% U-235 and 95% U-238 as an annual fuel load.

Uranium-238 has its own trick. It too can absorb a cool neutron to become U-239. This is highly unstable and, in 23min, turns into an isotope of a new element, Plutonium-239. This is a more energetic fissile fuel than U-235, with a critical mass of 5kg. It is made and partly burned in every PWR, to be thrown away and buried in the Open cycle.

How many reactors do we need to match the primary energy from Coal? World Coal now delivers **2000** GWy-e of energy for electricity, steel, cement and chemical by-products [BP, 2014], but total demands are likely to grow by 40-50% as world population rises above 9Bn. A more appropriate target for nuclear power would be **3500** GWy-e by 2050. About 6400 coal generators typically produce ~500MW-e with a load factor of 50%. Most of these may be swapped for nuclear as they retire before 2050. The coal industry will of course resist this. BP shows that the total world coal resources would last only 113 years if burned at the current rate, putting 2.7Tn tonnes of CO_2 into the atmosphere.

I. Uranium Resources

The USGS map of Uranium Concentrations shows how comprehensive their search was, finding a substantial resource of 5.6Mt. In the 1950s the government issued free Geiger counters to would be explorers. The USA currently imports 95% of its Uranium with most of its mines inactive. Other countries have not been so meticulous but every mining geologist knows what to look for.



The IAEA, OECD, and NEA periodically publish their authoritative Red Book analysis on mineable Uranium [IAEA, 2011]. This lists "Found" mines and reserves, "Reasonably Assured Resources" (RAR) in similar geologies, "Inferred Resources" if we look harder, and "Prognosticated" and "Speculative" resources in unexplored regions. The 40+ Reporting countries also estimate the mining costs per kg of Uranium from their sources. Total production is currently 58,000t/yr. Coal mines now produce ~1 Bnt/yr. Our Chart 2 below shows the world totals for each cost range and Uncertainty level. The "Speculative" resources are the highest.

There is a total of only 161,000t U-235 in mined Uranium as indicated by the red caps on each stack. It is not necessary or cost effective to extract all the U-235 from a batch of Uranium. Instead, enrichment is stopped with ~0.2% of U-235 in the tailings, which are set aside and called "Depleted Uranium" (DU). Thus, only **~0.5%,** or **115,000** t, is available from the ores for fresh reactor fuel.

The IAEA Red Book completes the tally of possible fuels with some reported resources of 6MT of the non-fissile metal, Thorium. It has a single isotope, Thorium-232, and like U-238 can breed another fissile Uranium isotope, U-233, which has long disappeared from the planet. A reactor is the only way to make tonnes of U-233. Just the declared resource would be good for **6** million GW-e reactor years, though 60 Mt might be found.

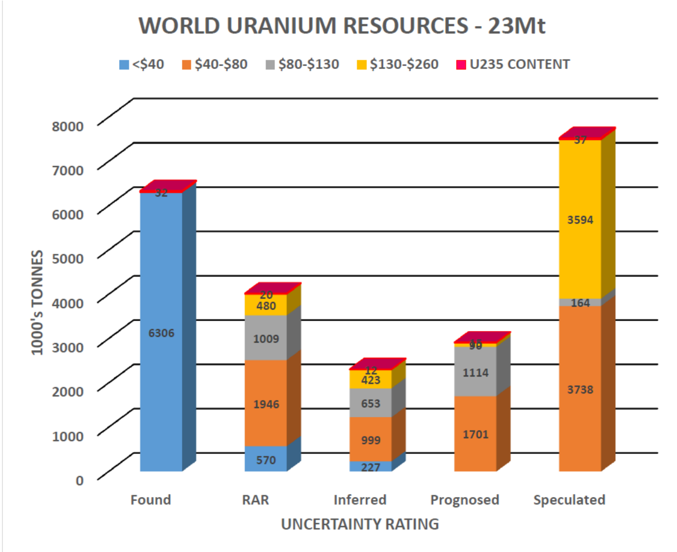


Chart 1. IAEA Red Book Uranium Resources.

It might appear that there are lots of fissile fuels, but only U-235 lives on in ores. The other fissile isotopes, U-233 and Pu-239, must all be made in reactors. The IAEA has accounted for the only natural resources, Uranium and Thorium.

III. The present Path to Failure

It is easy to calculate what would happen with the Open cycle. Global nuclear electricity production was about **270** GWy-e in 2010. There are now some 73 large reactors under construction and 299 proposed around the world. A programme to match the 2000 GW-e of Coal by 2050 would need an increase of 43 GW-e every year. However, by 2050 all the Found, RAR, and Inferred Uranium sources would have been exhausted. The 2000GW-e fleet would then consume the rest of the 23MT Uranium by 2080 (Chart 2).

The bolder “Growth” target of 3500 GW-e to match rising energy needs would collapse by 2060. The “Best” way to avoid a lot of early reactor retirements is to target only 1567 GW-e which would displace 75% of present coal use but allow that fleet to run till 2100. It takes 10 years to bring a new Uranium mine to production, so rapid exploration is required.

The Low case, just replacing existing reactors, could continue till 2430 but has no impact on coal or global warming. Each programme has the same result of creating **2.3Mt** of Spent Fuel and leaving **21.7Mt** of Depleted Uranium squandered.

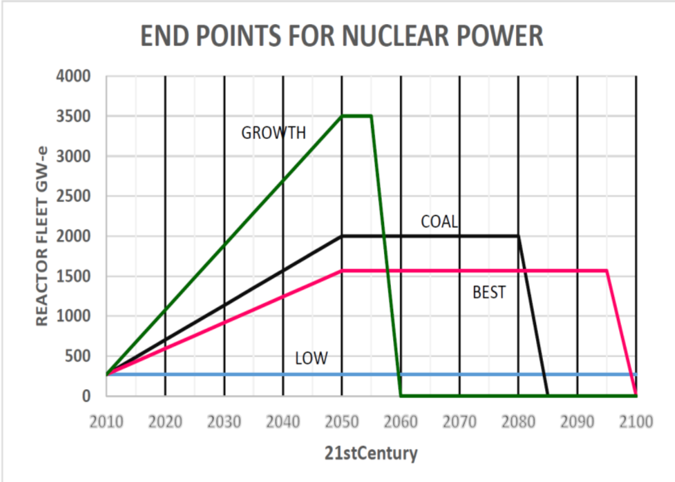


Chart 2. The avoidable collapse of Nuclear Power.

It takes **190** tonnes of natural Uranium to make the **20t** fuel load of 5% enriched PWR fuel, leaving **170t** of DU. The world has accumulated 1.2Mt of DU which breeders could turn into fissile Pu-239. The world reserves of Oil are 230 Billion tonnes. The DU energy content is equivalent to 8800 Bt Oil and is already the largest standing energy resource on the planet! The UK already owns enough DU to run a Closed cycle all-electric Britain for 500 years [McNamara, 2006, 2007], but not when it is buried or sold as waste as the UK is doing. Proper use of this would make the UK independent of Russian coal and gas imports.

The PWR of course breeds some Pu-239 from the U-238 in the fuel rods. It only achieves a breeding ratio of 60% or a 3% fissile content in Spent fuel, which is to be buried. The world inventory is 176000 t, containing 5,280 t of fissile fuels.

It is almost incomprehensible that such gigantic energy resources could be abandoned this way.

IV. The Endless Uranium Supply fallacy.

The industry is represented by its World Nuclear Association which contradicts the IAEA and promotes the idea there will never be a shortage of Uranium [WNA, 2014]. In a muddled set of arguments, deeply buried in their Library, they deride those who predict any limit as followers of the 'Limits to Growth' fallacy. Of course, the limit to CO2 in the atmosphere just turned up. To show how large the Uranium limit may be they cite the vast quantities in seawater. With 1t of U-235 in 400 billion tonnes of seawater it is not a real resource, unlike the fusion fuel Deuterium, at 1t in 58,000t of water, which is extracted today from rainwater. Future technologies could extract Uranium from ever poorer ores, but at a diminishing return on effort. They say that discovery of good ores will grow exponentially with price and 10 times more will be found for every price doubling. This extrapolates to 2000 times more at 10 times the price, so this model quickly makes no sense. Did the USA somehow miss the presence of 11 billion tonnes? The reality, which will certainly last to 2050 and beyond, comes from the IAEA data. The 2014 edition of the Red Book was issued in September. The total has decreased a little but confidence in resources around existing mines has increased. We are now mining from 7.6Mt declared Found, have a pretty good idea about another 7.6Mt RAR, and guess that there is at least another 7.6Mt out there. The WNA have no grounds to say that gigantic deposits will be found before 2050. Owners need an assured fuel supply for the 50-60 working life of their reactors, so ignoring Open cycle limits on a strong programme would be a gamble by 2035.

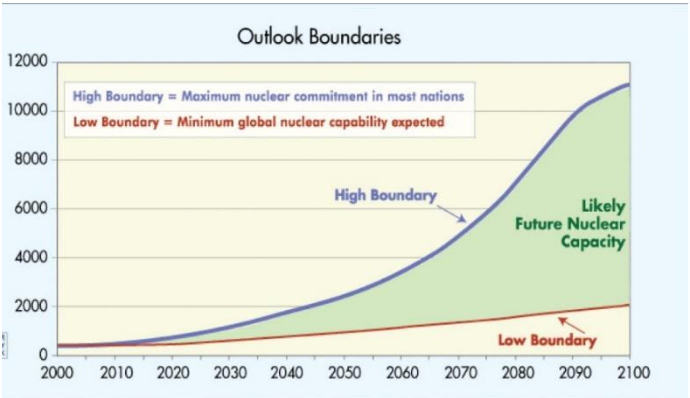


Chart 3. WNA limits to Pessimism and Optimism. GW-e vs Year

The WNA is not equipped to match the NREL assessment of renewables. Chart 3 shows their casual attempt at projecting nuclear futures this century. The WNA Outlook 'Low Boundary' case uses up all IAEA resources around 2100, with modest impact on coal by 2050. Their 'High Boundary', like our Coal target, uses up all assured resources around 2050.

The Closed cycle changes everything. Only 1t is burned per GWy-e and 99% of everything else is recycled, so mined natural Uranium is only needed at 1t per GWy-e, not 190t. Mining will be a loser and drop by 90% from today's level, but could run for thousands of years.

V. Leading Closed Cycle Reactors

Closed cycle reactors were much more complex to develop and have a chequered history. Most use a densely packed metallic fuel enriched to 20% of fissiles and cooled by liquid metals. The early designs were more difficult to control than PWRs so the research proceeded slowly and carefully. Slow progress left them open to budget cutters but 3 of these metal fuelled reactors are now ready for deployment, meeting the same stringent safety requirements as PWRS. There are now no technical reasons why the Closed cycle cannot be fully implemented to use the entire 23Mt of Uranium listed by the IAEA.

The UK was the first civilian programme to follow the Closed cycle with their MAGNOX reactors. The magnesium cladding for their fuel rods disintegrates after use, so the fuel had to be recycled. A mix of Plutonium isotopes, unsuitable for weapons, was recovered for eventual use in Fast Reactors, but they were cancelled. The UK was left with a stockpile of over 110 t of Plutonium fuel.

The Russian approach [RT,2014] has not stumbled and the design of a big, commercial fast reactor, the BN-1200 is now being finalised. The special recycling methods required for fast reactor metallic fuels still need industrialisation with robotic handling. Each recycling plant will serve 50 reactors. Russia will recycle their old weapons Plutonium as fuel for their current BN-800 model.

The US Department of Energy has had a malign effect on closed cycle technology over the last 25 years. The Argonne National Laboratory was tasked with development of civilian reactors. ANL developed the "Integral Fast Reactor" and the recycling methods to the point of building a prototype. It met a sorry fate when USDoE suffocated it with bureaucratic incompetence. DoE decided to create all the facilities of the Closed cycle in a hugely expensive industrial network, like NASA's, before building the prototype [Till & Chang, 2011]. The project cost soared, produced little, and was axed. ANL was reduced to a skeleton laboratory. GE-Hitachi have picked up the research and developed the commercially viable S-PRISM Fast Breeder Reactor [GE-Hitachi, 2014]. As DoE has lost interest, GE-Hitachi has set aside its offer to consume the US stocks of Spent fuel. Instead, they have proposed to build their first one in the UK to burn a fuel blend of the UK's 110t Plutonium stockpile with DU , but bury the Spent fuel. The stockpile would be far better used to start a closed cycle UK fleet of S-PRISMs.

South Korea has a project, PRIDE [S. KOREA,2014], to industrialise the recycling, but the US opposed this (2011) on the grounds that it could lead to weapons proliferation and was close to North Korea. The position has now shifted to a USDoE agreement for S. Korea to be given all the recycling knowledge from ANL and to build the first Integral Fast Reactor. No such nuclear transfer or collaboration has ever been enacted with any other country. Why would the USDoE set up S. Korea as a competitor to GE-Hitachi? The US obsession with weapons proliferation dominates their thinking. Their 'Swords to Ploughshares' stunt purchased old weapons Plutonium from Russia to be burned in their Open cycle PWRs. None of the material has been processed and the special MOX fuel plant has been put on hold [CONGRESS,2014].

The magnificent concept of the Molten Salt Thorium Breeder Reactor was well tested at the USDoE Oak Ridge National Laboratory (ORNL) but never made it out. The molten salt mix, which is both fuel and coolant at 5% enrichment, is easier to handle than the solid PWR fuels. Its own Closed cycle allows for continual refuelling and waste removal as the salt is pumped around. This amazing reactor cannot melt or burn, is completely safe against loss of coolant and no reactor would be lost to an engineering fault. These reactors are still on the drawing board. China has a new laboratory of over 400 scientists working on a 25 year reactor and built-in reprocessing technologies programme. The project has now been accelerated to a 10 year time frame which could impact before 2050. [Xu, 2014]

There is one more fast reactor to consider: Fusion, which fuses Deuterium and Tritium isotopes of Hydrogen to throw out a Helium nucleus and an ultra-fast neutron. Given the slow history of Fusion it seems counter-intuitive, but a small, 50MW Fusion core, surrounded by a molten salt blanket with Depleted Uranium is a powerful breeder since a kilo of neutrons makes 239 kilos of Plutonium. The necessary Fusion technologies work today [Tokamak Energy,2014], the separation of fuel from this molten salt is simple, so this is entirely feasible and could start to fill the gap by 2030. [McNamara 2008]. Fusion could use DU for direct Plutonium breeding and partner PWRs for many decades.

Our guess at the order in which these contenders will get to market: RosAtom BN-1200, GE-Hitachi S-Prism, Small Fusion Breeder, Thorium breeder, but it is more like a steeplechase than a horse race.

The Closed cycle is a big winner in many ways:

(i) 3,500 reactors only needs a mix of 3,500t of mined Uranium and Thorium per year.
(ii) We have centuries to discover Uranium and Thorium resources.
(iii) The total nuclear energy footprint for the USA is a tiny 156 reactor sites, at 4 GW-e each, and 12 recycling plants.
(iv) Recycling the world's 176,000t stock of Spent fuel will yield merely 1,000t of two radioactive wastes, Caesium and Strontium, needing storage for 500 years. The rest has many uses. [McNamara, 2013]

VII . Political Obstacles to Direction Change

The industry has been pushed into this calamitous corner by successive US governments under Carter, Reagan, Bush and Clinton, halting work on the Closed cycle. Carter banned recycling after the Three Mile Island accident which killed nobody and released insignificant radiation. All the TMI players were at fault but, for similar reasons, Japan went on to lose 3 more old US reactors at Fukushima. Again, no harm from radiation was caused, as documented by the International Commission on Radiological Protection [ICRP,2014], [Allison, 2009]. The USA and the IAEA are tenacious in pursuit of potential proliferation issues but, collectively with vendors like GE and other nuclear organisations, do not pursue real safety breaches. Reagan dismantled much of the Fusion energy programme to divert resources to Star Wars, a technically unworkable scheme. The decline of Fusion in the USA continues today.

The US position has influenced the EU so that Germany is closing nuclear plants in favour of coal, French socialists propose to close the most successful nuclear industry in the world, and the UK is turning slowly back to nuclear.

France and the USA built most of the world's reactors between 1970 and 1990 at a rate of 14 per year. At 18 GW-e per year the USA can replace its aging fleet and reach 625 GW-e, including 100 Breeder Reactors, to end coal by 2050. However, changing direction rapidly has limitations. Top of the list are:

(i) The nuclear industry has failed to make its case.
(ii) It could take a full 8 year term of the next US government to authorise the Recycling and Fast Reactor projects. Similar delays may occur in the EU.
(iii) The Nuclear Regulatory Commission (2013) bureaucrats declare that it could take 20 years to develop the regulations. They have no mission or funds to regulate Fast reactors or advanced recycling.
(iv) Scientists find it hard to be heard. One quote – on GM organisms – is typical: The belief of the new President of the EU Commission, Jean-Claude Juncker, is that: ' … The EU Commission should be in a position to give the view of democratically elected governments at least the same weight as scientific advice …'

China is pushing hard with a Thorium data sharing agreement with ORNL, licences for PWR technology from Areva and Westinghouse for their Chinese designs, and a strong Fusion programme aiming to bypass the international project, ITER. China has set the standard but they will not build 50 reactors a year world-wide.

Our politicians must find alternative advisors, uproot their obstacles to nuclear energy, restore national nuclear laboratories, and change the public image. The knowledge and skills are there and the energy industry, including nuclear, is expert at managing projects of this magnitude. There is not a mountain to climb, just a better direction to go in. The USA looks like a lost cause, leaving others to seize the commercial opportunity valued in $Trillions.

What is shown here is that the Open cycle must be abandoned by everyone to escape the Path to Failure. The Closed cycle prospectus is compelling but persuading the voting population to lose their acquired fears of nuclear power and radiation will be hard. Only public opinion has the power to persuade politicians to move quickly.

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Xu Hongjie,China, 2013, Thorium: Google YouTube and these words to see the Chinese video.

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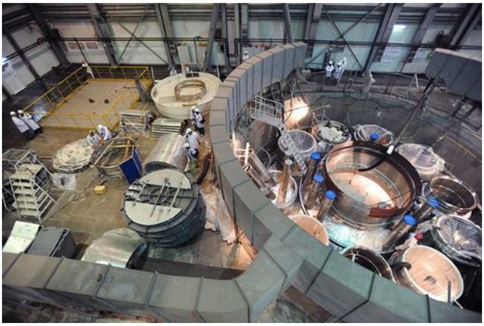
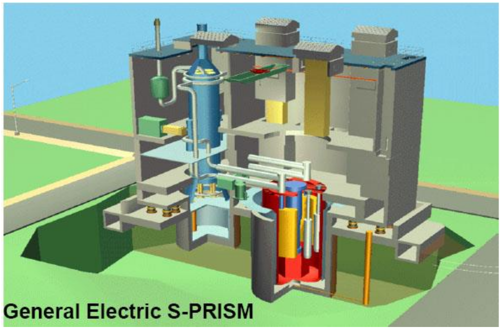
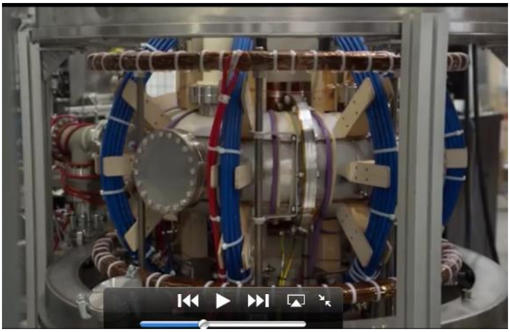
CLOSED CYCLE REACTORS



RosAtom: BN-800 Sodium cooled Fast Reactor



General Electric S-PRISM



Tokamak Energy: 1st. Small Tokamak with

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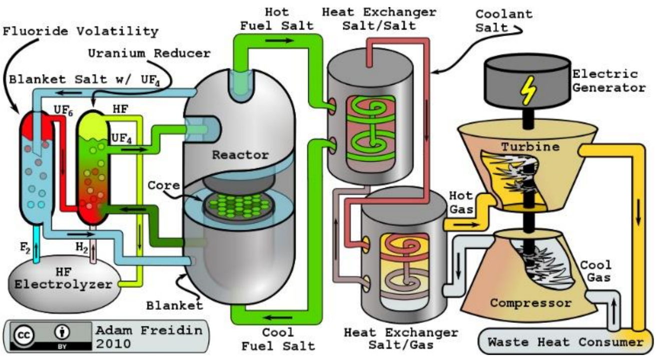

Thorium Molten Salt Breeder with Recycling.