FUNFI: A WORKSHOP ON FUSION-FISSION SYSTEMS. VARENNA 2011.

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A recent Workshop in Varenna on Fusion for Neutrons &Sub-critical Fission (FUNFI) gave a good snapshot of the global state of play in Fusion and its contributions to Fission Nuclear Energy. This report has a wider context than the scope of the meeting and is addressed to people with a technical background who may not be familiar with Fusion or Fission in any detail

Entrance to the Villa Monastero.

I. OVERVIEW

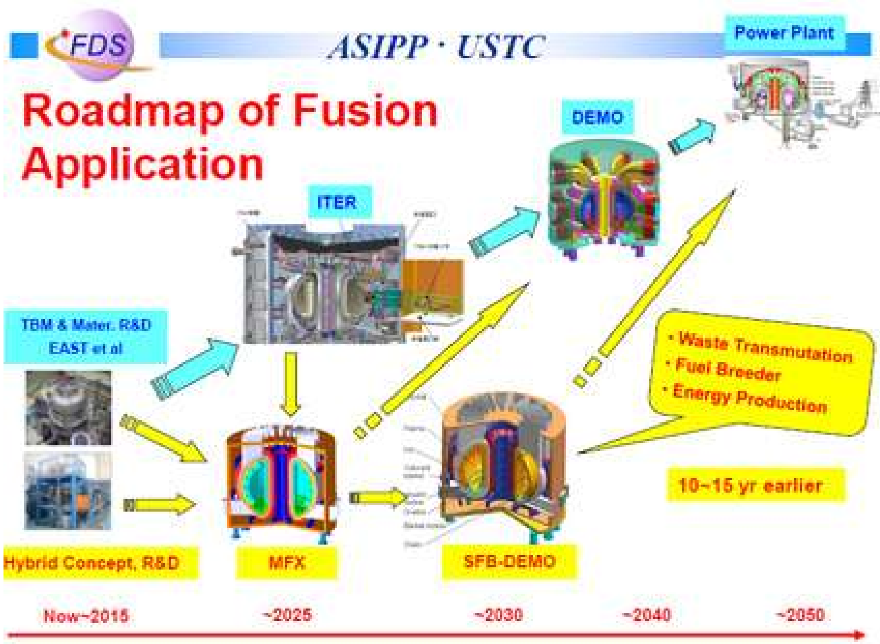
The 62 participants came from the EU, Russia , India, China and the USA. China will clearly be the world leader in Fusion technologies by 2030 because it is actively building many experimental systems. China is also building 3 Nuclear Reactors per year for the next decade, the highest build rate in the world, not matched since the French built their nuclear system in the 1970-80s. Many of the participants did not have a working knowledge of both Fusion and Fission so a lot was learned by all in this cross disciplinary workshop.

. An important background theme was the potential for Weapons Proliferation from any of these nuclear projects. Hans Blix, the head of the IAEA Iraq inspection team was a key speaker on these unresolved issues.

Only a small personal selection of the flood of topics from Varenna is discussed here.

1.1 Fusion Futures

The leading Fusion machine is the Tokamak with scores of systems around the world. The leading system is JET at Culham Laboratory near Oxford which achieved energy breakeven in 1997. The international follow on from that, ITER, is being built in France to produce 500MW of Fusion power. It is intended to lead to a DEMO by 2040 and a commercially viable Fusion Power Plant by about 2050.



The US Fusion programme is flat-lining with one large aging Tokamak at General Atomics in San Diego and a small Spherical Tokamak, NSTX, at Princeton.

Other innovation in the EU has a weakly funded Spherical Tokamak at Culham and an elegant Stellarator, Wendlestein-VII, in Germany.

ITER is absorbing most of the new Fusion funding in the world and the inevitable cost rises from an internationally managed effort are seen as a disappointment by some politicians – but everything else in the world costs more.

The funding prospects for Fusion are fragile in this economy so a lot of effort has gone into theoretical and computational engineering studies of several unique applications which will solve some major Fission. These have been known for decades but sophisticated computing and a very extensive knowledge of over 8500 neutron cross sections makes the modeling far more convincing.

Fusion has 20 times the neutron output of an equivalent Fission plant, all of which can be available for transmuting or fissioning elements. Much of the workshop was about the design and performance of the so called Hybrid Fusion-Fission systems, each of which is also a power plant. The Fusion core of these Hybrids is much smaller than that for a Power Plant and so may be built sooner. All Fusion reactors must also breed their own Tritium fusion fuel, the heaviest isotope of hydrogen, from Lithium. Hybrid designs all do this

The diagram above. from the FDS group in China, illustrates the prospects and an accelerated 'low road' to a major Fusion impact in this half century, but it may not yet represent the funding flow.

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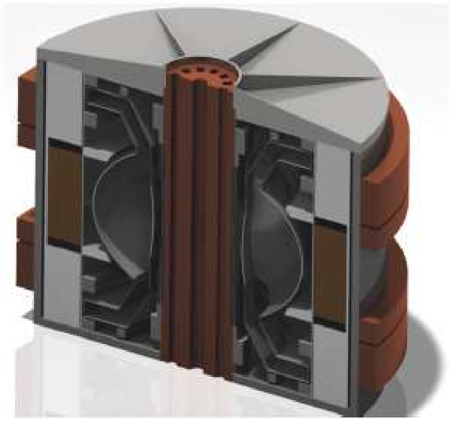
II. Fusion-Fission Hybrids

2.1 Actinide Burners: The most valuable Hybrids may be for burning new and existing radioactive fuels from Spent Fuel, Plutonium and the Minor Actinides Neptunium, Americium, and Curium. This would remove the need for large Geological Disposal Facilities (GDFs) and evade the huge responsibility of simply burying them. Many designscan run entirely on what is otherwise described as High Level Waste.



A design from MIT is shown here with both the fusion core and the surrounding, solid fuelled fission reactor inside the outer magnetic coils. With 200 to 800MW of Fusion and 2000MW of Fission, the machine could burn Actinides from 20 conventional reactors or from legacy Spent Fuel. In this design the Fusion core output must be increased as the fission fuel burns.

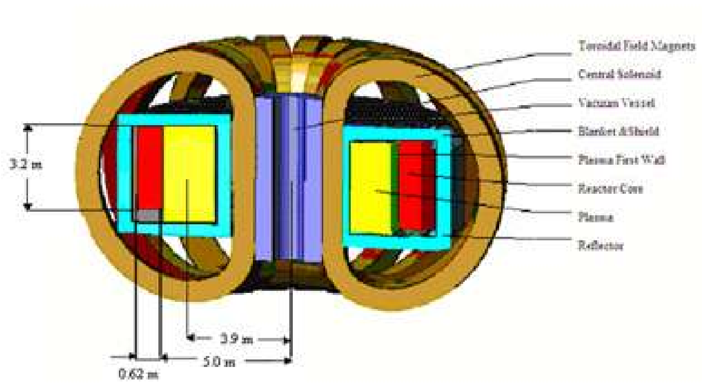
Such Burner designs far outstrip the capabilities of Fast Fission Reactors alone.

2.2 Fuel Breeders: The second Hybrid version would breed enough of the two principal nuclear fuels, Plutonium or Uranium-233 for 4-5 fission plants. Breeding Plutonium from our huge stocks of Depleted Uranium can refuel fission reactors. The UK owns enough DU to fuel an all electric Britain for 500 years.

It is widely stated that there is and always will be adequate Uranium supplies on the planet. However, only nuclear energy can meet the looming demand but a rapid growth in nuclear power could outstrip the discovery and mining of Uranium ores by 2035. Renewable energy from Wind and Solar is proving to be far more expensive, and even unaffordable, than current supply and will not meet its expectations by 2050. Carbon Capture and Storage (CCS) is looking increasingly unaffordable with energy companies pulling out of projects which are not fully subsidized. Coal use must therefore be cut. The affordable solution is a much larger nuclear programme than that projected by all the energy agencies, putting pressure on Uranium supply this century. **The UK really needs about 40GW of nuclear energy by 2050 to meet emissions and economic targets.**

Breeding fissile U-233 from Thorium-232 is necessary to give a clean start, without Actinides, for new Thorium Molten Salt reactors, after which they breed their own U-233. An alternative would be to start Thorium breeders on weapons grade or recovered reactor grade Plutonium diluted into the molten salt. The Plutonium and other actinides which would be created are burned out as the reactor runs and no further Plutonium is bred. **This is a better use of stockpiled Plutonium than making MOX for Light Water Reactors.**

2.3 Sub-Critical Reactors: The third Hybrid version would use the very fast neutrons from a Fusion core to drive a surrounding Fission reactor .This means that the fast fission reactor is made completely safe from criticality accidents and would burn much of its own waste. A leading proponent of Hybrids is Weston Stacey and his School of Plasma Engineering at Georgia Tech, Atlanta. Their SABR design runs an actual Sodium cooled Fast Reactor, in sub-critical mode. This could use all the Actinides from 3 thermal reactors as fuel or burn just the minor Actinides, after removal of the Plutonium, from 25 reactors. Fuel fabrication would have to be developed for such solid fuels. The use of liquid Sodium is a serious fire hazard which makes full containment of radioactive products in the event of an accident much more expensive.



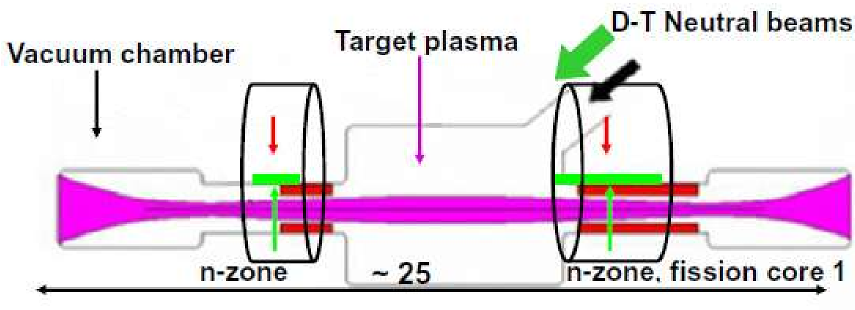
The burning, breeding, and power production rates from such systems are quite spectacular and would be economically sound. This justifies the effort to combine the apparently different technologies of Fusion and Fission in a Hybrid system. However, the systems all depend upon plasma technologies and reactor materials to be tested in ITER, which will not be completed till after 2035. Further work on Hybrid designs is a useful way to evaluate the required technologies to be developed. The Hybrid studies also justify the development of small versions of such plants as soon as possible to open this path.

III. Early Fusion Prospects

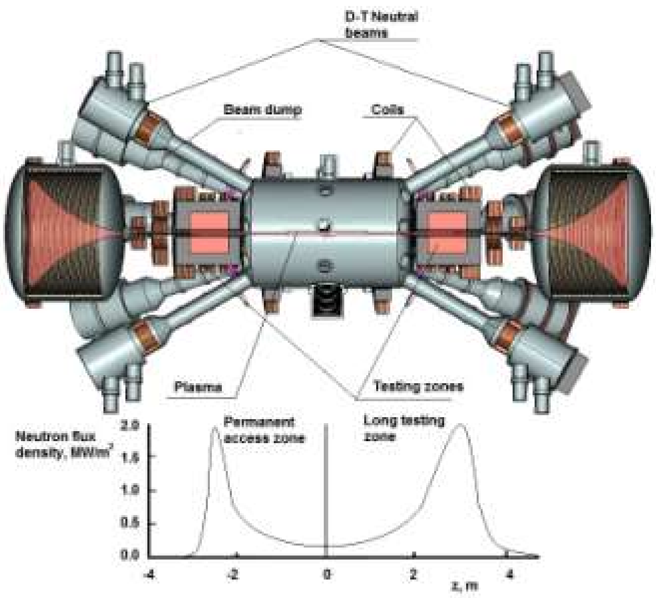
We know a great deal about plasma physics, plasma technologies, fission, radioactive materials, reactor materials and the neutronics of all the elements. Smaller, simpler fusion systems can be built now, with existing capabilities, to do all of the things discussed above, but on a smaller and less economic scale. This should produce an array of new results which would be much more convincing than wondrous prospects for the second half of the century. The performance of existing technologies can be raised from the 10-100s of seconds used in experiments today to a level of hours or even continuous running. Real systems need to be run for days, months and years to reveal all the more subtle problems of corrosion, wear and real life engineering.

The two front runners at the present time are the Gas Dynamic Trap at Novosibirsk in Siberia, and the Small Spherical Tokamak designs being developed by Tokamak Solutions in the UK. Proponents of Hybrids – Bill Stacey, the GDT – Alex Ivanov, and Spherical Tokamaks – Mikhail Gryaznevich, are pictured here.

3.1 Gas Dynamic Trap: The **GDT** is a very simple linear machine with circular superconducting magnets but may not lead to an efficient fusion reactor as it leaks too much energy from the ends. However, it can be made to generate several MW of Fusion energy and a substantial neutron flux for testing materials and blanket systems. It could be the first fusion machine in the world to go into continuous neutron production. This would trial continuous vacuum pumping, continuous Tritium recovery and recycling, efficient neutral beams at 80-150keV, plasma energy recovery systems, and continuous pumping of Helium, liquid metal, and molten salt heat transfer systems. **The consensus of the Workshop was that this project should be pressed forward with some urgency.**



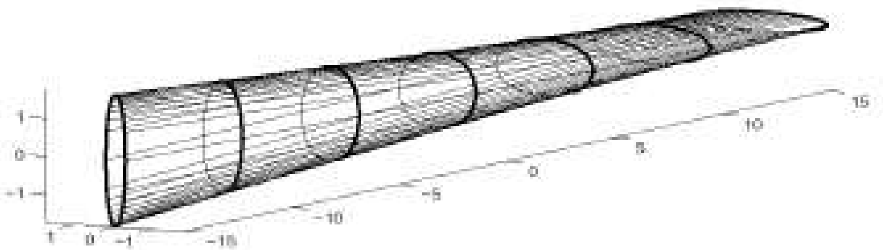
This sketch of the GDT concept shows a pair of simple circular magnet coils which trap ions of Deuterium or Tritium bouncing between them. A cooler plasma column flows out the ends of the central chamber into an expanding weaker magnetic field region to be collected and recycled at the end walls.



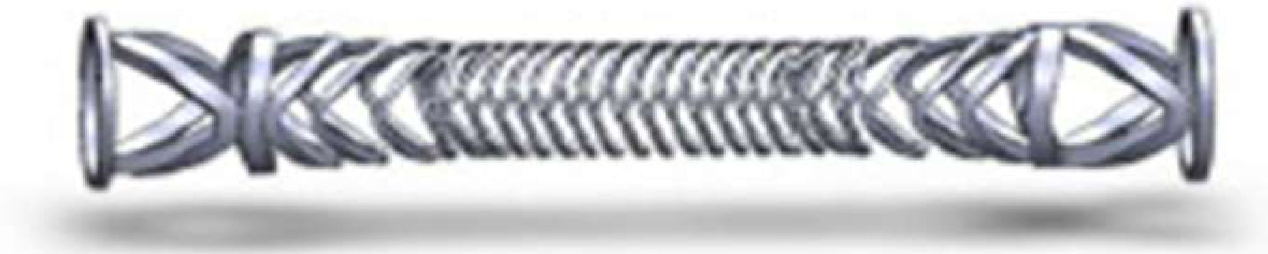
The layout of the GDT reactor is shown here. Large magnetic coils in the central region support the axial magnetic field containing a cool (<500eV) Deuterium target plasma. The angled beams inject Tritium into the chamber. The fuel ions bounce between the 10 times stronger superconducting magnetic field coils and spend much of their time near these mirror coils where most of the fusion takes place. The long plasma column is prevented from spinning into the walls by the electrical connection to the end walls in the magnetic expansion chambers. The outward curvature of the weaker magnetic field there also stabilizes the plasma.

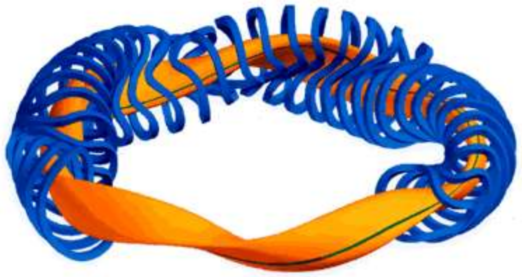
A complete GDT research facility would cost about $400M and produce crucial physics, materials, and engineering results for the fusion community long before ITER. However, the steady plasma losses to the ends means that some 60MW of power is needed to run the beams and other equipment for only 2-3MW of Fusion output and a power multiplier of Q=1/30. This does not scale up directly to a Fusion reactor for electricity production which needs Q>10. In a hybrid machine, most of the power is generated in the Fission blankets so the demands on the efficiency of the core would permit Q>0.15. Various methods to plug the ends and reduce the losses are being tested.

3.2 Mirror Hybrids: The Swedish team at Uppsala (O. Agren et al.) have designed a long mirror system, SLM, where the magnetic field is sculpted with curved elliptical coils to provide stability. Mirror end plugs, heated by microwaves, can reduce the hot ion losses for Q~0.4 if the electron temperature can be held at 2keV. . I was gratified to see that the theory of omnigenous plasma equilibrium in such systems by Larry Hall and myself (1975) remains useful.



Here is the plasma shape and the coil set for this system. The 'omnigenous' property means that all plasma particles on a magnetic surface as shown will remain on it. Unlike the simple mirror, the average magnetic pressure on these surfaces increases radially, making the plasma stable.

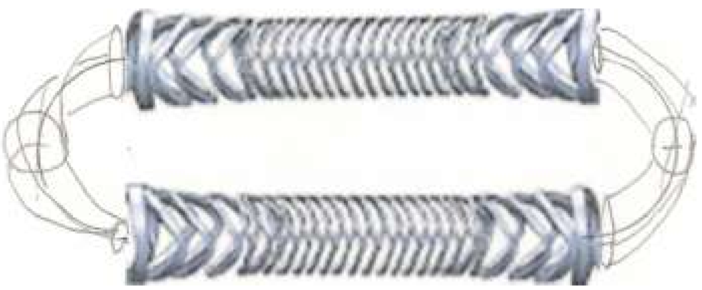




The essential simplicity of a linear system has great advantages for the design and operation of Fission blankets. If better end plugging could achieve Q~1 then an economic system could be an early competitor.

Or can the ends be connected? The Wendelstein X-7 is a toroidal machine, called a Stellarator, using sculptured coils, as shown, twisting the field lines around but without the need of a plasma current. This design creates a series of omnigenous mirror trap regions linked together. Many problems for driving large currents in a Tokamak plasma are eliminated, but the coil set is complex in this Stellarator-Mirror device..

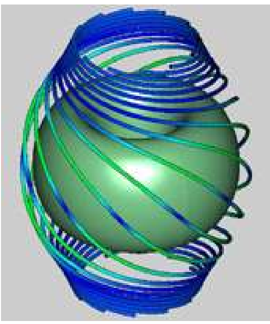
Could a double set of the SLM coils, oriented opposite to each other, be linked at the ends with another sculpted coil set to twist the field lines round by 90^0 each as the flux tube is bent around between them? In two trips around the circuit all the field lines would be closed and the bad magnetic curvature on an outer connection would be more than cancelled on by good curvature on an inner swing. The end losses from each Mirror set are recirculated and a much larger Q (10?) can be expected. The notion is sketched below:



Another approach by V. Moiseenko suggests a standard Stellarator with a large Mirror Trap in the circuit.

Suffice to say, the Mirror Fusion approach is not yet dead and can prove of great value in the programme.

3.3 The Spherical Tokamak: At 1/30th of the plasma volume, this is a compact version of the large Tokamaks like JET but with comparable toroidal plasma currents (1-5 million amps) and confining magnetic fields (1-5 Tesla). The result is that the magnetic fields are wrapped much more tightly around the plasma, giving better confinement and stability. The energy gain runs from Q~0.1 to Q= 3 or10 at the highest parameters. A computer plot of a single field line (blue) threading through the plasma centre)green) is shown:



At the low values of current and field a hot (3keV) target D-T plasma can be driven with a 2-3MW neutral beam of Tritium to make a very powerful 1-2MW neutron source. The machine is much more complex than the GDT but has far superior plasma confinement. An ST neutron source is on the direct path to significant small Fusion reactors or fusion cores. The required investment is in the £200-300k range. Like the GDT project, the technologies have to be lifted to industrial standards.

At the higher parameter values the ST is capable of producing 25-100MW of Fusion power at which levels they can breed fuels and transmute nuclear wastes on a useful scale. The investment rises substantially as all the necessary technologies are brought together. Some £500M is appropriate in a 10 year programme.

The physical size of the plasma containment vessels are comparable to the MAST experiment at Culham, UK, as shown. When external blankets and larger superconducting coils are added the reactor is somewhat larger than this experiment.

Tokamak Solutions UK has designed a number of STs in collaboration with the Kurchatov Institute, Moscow. Experiments are under way to build and test a magnetic coil using High Temperature Superconductors (liquid Nitrogen cooled.)

Several of the Hybrid Fusion reactor concepts are based on somewhat larger STs. It will be part of the Tokamak Solutions' development to investigate advanced reactor materials.

R. Srinivasan from India has long been proposing a Spherical Tokamaks. He described plans for a Fusion Test Reactor similar to ones considered by Tokamak Solutions. The Indian economy may be more capable of funding such a project than is the UK.

IV. Fusion and Fission Technologies

The ITER programme is already addressing many of the requirements, but on a scale appropriate to ITER. The neutral beams are being designed to run at 1000keV using a different beam technology, not the 80-150keV needed by the GDT or STs. The ITER wall materials for the plasma chamber have to withstand up to 10 times the fusion neutron flux of the GDF/DT machines which can use existing materials.

The designs of blankets for tritium breeding, fission fuel breeding, or waste burning have more in common. The Chinese programme is already making eight detailed studies of pumping systems for Lithium-Lead liquid metal coolants.

Another set of papers (Duran, Orsitto, Kallne, Croci, Nocente) discussed the need for new diagnostic devices which could measure the key parameters of a Fusion Hybrid in the high neutron fluxes and temperatures at which they will work. The environment is more demanding than that of a Fission reactor and also requires monitoring of plasma losses, wall damage, flows of metallic conducting coolants in strong magnetic fields, and so on for the fusion core. Fusion development continues to invest in whole careers of innovation and advanced engineering over many supporting technologies.

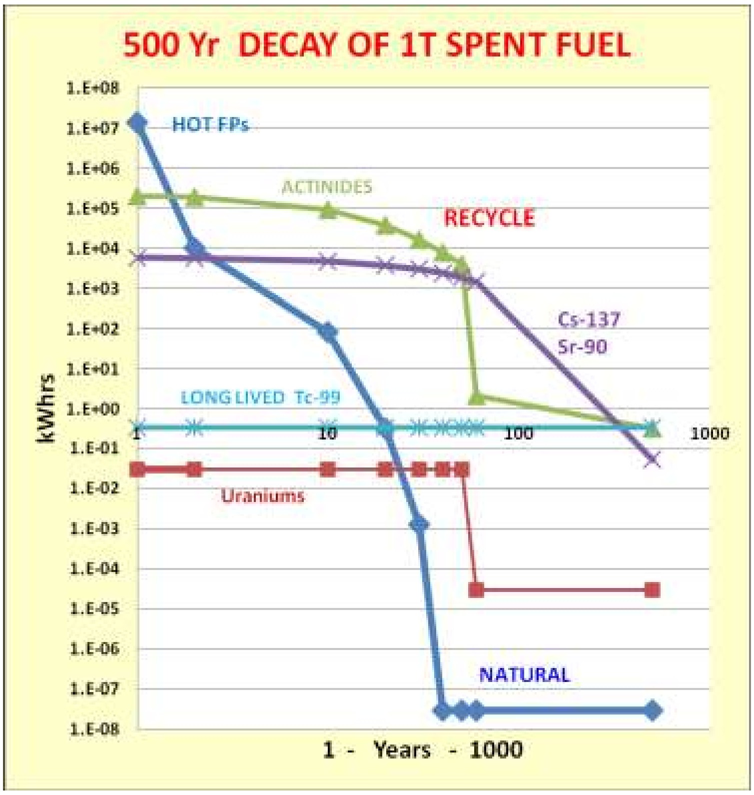
V. Reactor Neutronics and Spent Fuels

M. Salvatores gave a clear outline of the basics of the production and use of neutrons in Fission reactors for the largely Fusion audience. He gave the standard picture of the radioactivity in Spent Fuel showing Plutonium and the Minor Actinides as a hazard for a million years. This picture changes dramatically with recycling and reuse of Spent Fuel, leaving very little to be buried for more than 1000 years. I believe this to be a really important observation (Ed Sayre, ‘Commercial Value of Used Nuclear Fuel’ 2009) and introduced it to the meeting.

So, what about the notorious questions of Spent Fuel? This has stacked up in cooling ponds around the world because the US and others decided not to do Recycling. **This leaves only one option for handling of the radioactive materials – burial in a Geological Disposal Site. While this will work, it is the most expensive option.**

What is Spent Fuel? In the Uranium cycle the solid fuel rods consist of Uranium Oxide, enriched to 3-5% with the fissile isotope U-235. A 1000MW (1 Gigawatt) reactor consumes the equivalent of 1 tonne of U235 per year, or about **30 milligrams a second**. Uranium fission produces an average of 2.53 neutrons, which maintain a controlled chain reaction, and also breed some Plutonium and then some higher Actinides from the natural ^{92}U238 included in the fuel rods. The Plutonium is also a fissile fuel and so burns to contribute about 1/3 of the power. Fission shatters the Uranium or Plutonium nuclei into pairs of Fission Products, yielding multiple isotopes of lighter elements such as ^{39}Yttrium + ^{53}Iodine. Many of these isotopes are radioactive but with very variable energy output and decay rates.

The hazard from radiation finally depends on how much energy is absorbed by a recipient. The heat output from Spent Fuel isotopes is a good measure of potential hazard.



What would recycling do for us and when? Each tonne of Spent Fuel has produced a steady ~35MW of heat for 2-3 years. Each tonne can be separated into 5 streams, none of which need to be buried forever. The decay of all the radioactive materials in 1 tonne of Spent Fuel is shown in my chart here. This takes Ed Sayre's inventory of real Spent Fuel and rolls it back 50 years and forward to 500 years.

1. The major stream is the ~955kg of Uraniums, including 944kg of U238 and about 1% of unburned U235, which is set aside for future fuel breeding if recycled at 50 years. It is a little more radioactive than Depleted Uranium. **This is eventually worth about £1Bn in electricity generated.**

2. The hottest radioactives are the ~35kg of Fission Products. These are what cause a meltdown in light water reactors within a day after loss of all cooling. And yet, in 2 years, they have cooled by a factor of 100. In 50 years they all turn into natural and non radioactive elements and are not seen in Sayre's inventory. Other data on Iodine and other short lived isotopes in fuel in the reactors gives the initial content.

   Almost all their radiation is in the form of hot electrons (β_- particles) which do not even penetrate a sheet of paper. Each decay moves an isotope up the periodic table by one. Iodine becomes the noble gas Xenon. The blue line falls off the chart at 50 years. This 35kg contains precious metals like Rhodium and rare earths for electronics. **When separated, these Fission Products have a total value at today's prices of about £15-20M. The initial cost of the fresh fuel is about £1.5M.**

3. The next hottest set the ~8 kg of Plutonium and other Actinides created by neutron absorption in the U-238. They have long lives and remain radioactive for up to 1M years. They are the major long term heat load to be managed in a GDF. With Recycling they can be burned as fuel in suitable reactors for **£5M of electricity.** Making solid Actinide fuel is complicated by the different histories of each fuel rod and their variations in isotope content, and by the significant radioactivity. If the Plutonium is separated out the task of making MOX fuel (Plutonium Oxide) is easier, as the French are doing.

   We show them recycled out of the Spent Fuel stock and off to a fuel store to be used in future reactors, The separation processes are good to 99.9%, 1:1000, and the remaining traces shown are in the processing solvents and the system itself. They still decay by 1/10 in 1000 years as the highest actinides, Curium and Americium have shorter lives. Only 2g of Pu is left behind this way.

4. The last really hot set is the ~5kg of awkward isotopes in the FPs which have half lives of 30-100 years and remain highly active for up to 500 years as shown. The well known ones are Cesium-137 and Strontium-90. Cesium-137 has a half life of ~30 years. In 10 half lives, ~300 years, the amount remaining drops by (1/2)^10 = 1/1024. In 600 years a kilo of Cs-137 will have dropped to 1 milligram in half kilo of the neighbouring isotope, Barium-137. Unfortunately, the Barium spits out a powerful 2.8MeV gamma ray before achieving its natural state. It takes metres of shielding to absorb these γ rays. This is still a tiny amount of waste which needs safe burial – but not for geological time scales. The only use for these isotopes is as along lived, but radioactive heat source.

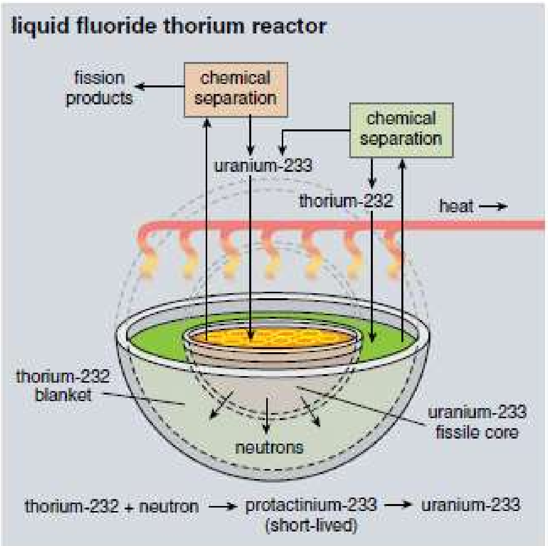
5. Finally, we show the steady behaviour of the very Long lived isotopes. Technetium-99 dominates the million year radiation, but it is always low enough for the material to be used in industrial

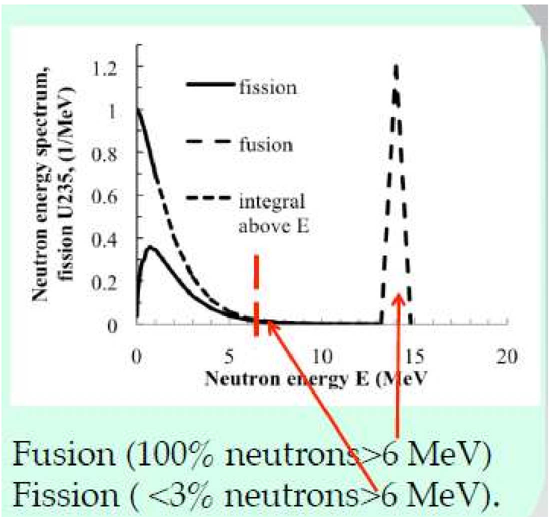
products. Many others, like Indium, have half lives up to 10,000 times the age of the universe. The very long lived isotopes are no significant hazard.

In the UK , Mark Higson, CEO of the Office for Nuclear Development firmly defends the use of a GDF with no recycling and no contribution to any R&D for new systems. This simple approach is forced by the need to overcome media and Green opposition to nuclear power. The first spent fuel would enter the GDF by 2050 so there is time to set up recycling. Either way, the problem of Nuclear Waste has perfectly viable solutions.

VI. Fusion and the Thorium Fuel Cycle.

It is worth giving more detail on the Thorium story: The Thorium cycle starts with the only available isotope, Thorium 232 which is more plentiful than Uranium. When irradiated by neutrons, Thorium can capture one and decay into Uranium-233, another fissile isotope with a half life of 1.6 million years. This is short enough that there is no U-233 found naturally on the planet. The breeding rate for Th-232 to U-233 is 2.7 times faster than that for U-238 to Pu-239. The net neutron production from breeding and fission of U-233 by a second neutron is 2.3 against 2.17 for Plutonium. This makes the Liquid Fluoride Thorium Reactor (LFTR) able to breed all its own fuel.





The favoured designs use molten salt mixtures at ~750^{0}C, with Lithium, Beryllium, Thorium and U-233, as both the reactor fuel and its own coolant. Graphite blocks can be placed in the reactor vessel to slow down the fission neutrons for a high fission rate. The salt does not burn in air, steam, or pure oxygen and is not soluble in water. It freezes at 350^{0}C and so leaks would be self sealing or at least not flow away. The reactor system has no flammable materials or internal structure which could collapse.

Here we show a 2 fluid version by Hargraves and Moir. The outer blanket is a Thorium salt which breeds the U-233. This is collected from the circulating liquid by bubbling Fluorine through it. This 'oxidises' the UF4 to the volatile Uranium Hexafluoride, UF6 for addition to reactor salt containing no Thorium. The same step of Fluorine bubbling will recover all the unburned U-233 from the reactor salt, separating it from the build up of Fission Products.

Since it would take a chain of 6 neutron absorptions to build up U-233 to Pu-239 the Thorium reactor breeds almost no Plutonium at all. The Spent Fuel is 10,000 times less active than that from a PWR after The Cesium and Strontium are removed. With liquid fuels it is possible to continually extract many FPs and refuel the reactor. **So, the LFTR is clearly one of several of the World's Safest Reactors which cannot burn or melt down, breeds its own fuel and burns most of its own wastes. It is the sort of reactor that Germany, Belgium and Italy may order when they realise that windmills are not affordable or sensible as a national power supply.**

This leaves the problem of start up. A fissile fuel like U-235 or Pu-239, diluted by U-238, is required for the first fuel load. Higher Actinides are then produced as well. This spoils the story somewhat as it will take several decades to burn these out and achieve a pure Thorium-U-233 salt system.

There is another concern: A short chain of neutron absorptions, and an occasional hit by a fast neutron to knock out 2 neutrons, an (n,2n) reaction, generates about 2% of the Uranium as U-232. This has a poor fission rate and a half life of 69 years. The decay, when it happens, produces a chain of 6 hot alpha particles (helium nuclei) and a final 2.6MeV γ ray. The molten salt fuel is dangerous to handle, which is a serious obstacle for anyone wishing to steal some of it, but requiring robotic machines to do all processing and repair of equipment.

Fusion is one important source of neutrons which does not rely on Uranium. Fusion could breed U-233 directly from Thorium in a molten salt blanket, giving a clean start for several LFTRs. In addition, Fusion produces far more very hot neutrons than fission, as shown, which therefore exercise the (n,2n) more strongly to make more of the Uranium into U-232.

Moir considered a full scale Fusion-Thorium Hybrid Breeder in which fission is suppressed and up to 23 LFTRs can be supported. When operated for decades the system produces up to 5% of the Uranium as U-232. This is sufficient to make the γ radiation lethal in a short time. Weapons Proliferation from this starting point would be unfeasible and easily detectable.

A small Spherical Tokamak reactor would be able to breed initial fuel for a small LFTR long before 2050 when large Hybrids might be built. Prototypes of the LFTR and the Spherical Tokamak Breeder could be built on the same time scale of 10-15 years.

India now (05/11/11)plans to build an Advanced Heavy Water cooled Thorium reactor. This is not a Molten Salt reactor and does not have any of the safety, refuelling or recycling properties offered by the MSR.

VII. WEAPONS PROLIFERATION & FUSION

The final topic discussed here is Proliferation which turned up many times. In a rapidly changing world this has become more of a concern as many countries aspire to nuclear energy.

Hans Blix, head of the IAEA Weapons Inspection team in Iraq finished the meeting with his discourse on the failure to make any significant progress towards disarmament. Disassembly of aging stockpiles and refurbishment of the remainder with more modern designs is hardly disarmament. Although military spending in the USA doubled between 2000 and 2011, but wars in Iraq and Afghanistan were not won and even when massive cuts are happening in other areas the US is currently unwilling to cut back in this area.

Roland Schenkel, a former IAEA Weapons Inspector, attributes the Fukushima disaster to the well known list of failures to regularly review safety measures, failure to upgrade equipment to prevent Hydrogen explosions or power supply failures, lack of prescriptive regulation by the government, and a poor safety culture by TEPCO**. Back in the UK, Mark Weightman of the Health & Safety Executive who headed an IAEA inquiry team to Fukushima drew the same conclusions. The UK Regulatory system will be guided by this and new nuclear build will be safe in this regime.**

To these I would add the failure of General Electric and Babcocks to enforce the upgrade of safety equipment as deployed elsewhere on reactors they designed and built. In addition, they laid low during the entire disaster and contributed nothing visible to the world in the way of advice or guidance. I would also say that the IAEA made periodic inspections in Japan but only to check compliance with Proliferation measures. Finally, the Japanese government turned away many offers of help in getting mobile power to the site. Destruction of all surrounding infrastructure would not have prevented beach or helicopter landings of equipment.

What has now happened is that all countries are reviewing their existing nuclear plants and plans.

Schenkel's paper gave a comprehensive list of issues and possible solutions for all the principal reactor systems or proposals. The final question is, how can all this be enforced in 30-50 countries with differing regulatory systems and expertise? He proposed the following set of steps to be supervised by IAEA.

How to improve legal/regulatory framework?
Integrate lessons learnt from Fukushima in legally binding
IAEA safety standards
Require legally binding international benchmarks(peer reviews) of
Design safety reviews
Independence, competence and functioning of national regulators
Operational Safety Reviews
Peer inspections with follow up/ compliance inspections
Charge IAEA with overall co-ordination
To foster implementation of recommendations, reports should also be sent to
national parliaments

A problem with this solution is that the IAEA is tightly constrained by the UN Security Council and by the USA and becomes as ineffective as anything else when it most matters. The world has many vividly different political, religious, language and social systems which do not respond well to centralised control. Any real Safety regime for nuclear energy should be adapted to this.

My own paper on the topic does just this. The ideas are simple and based on a 'Neighbourhood Watch' scheme where groups of countries have their own inspectors on frequent or permanent duty at all regional nuclear sites. Compliance with common sense, experience and safety demands should not require enforcement by military action. Neighbours have many ways to coerce a regional partner to maintain the highest levels of safe operation. More than security, most populations are far more concerned about Safety and this can supercede proliferation issues and stop Proliferation from the civil nuclear energy programmes at the same time. Here is the outline slide:

NESST : Nuclear Energy Safety & Security Treaty

Divorcing Nuclear Energy from Nuclear Weapons

REGIONAL AGREEMENTS

on 24 X 7 Safety and Security for Fission & Fusion.

Graded, proportional, non-violent PENALTIES

for NESST violations.

Efffective use of CHOKE POINTS in the fuel cycles.

ENFORCED SAFETY PROCEDURES

NESST STOPS PROLIFERATION

The ultimate arbiters when real political problems arise would still be the IAEA and the UN but with powerful regional support. Clearly, Proliferation is more about politics than technology. **China and Taiwan have just signed an agreement on reactor safety.**

One final quotation, that illustrates cultural biases, is from an abstract by Rob Goldston, former Director of Princeton Plasma Physics Laboratory and a consultant on Weapons Proliferation:

"In a scenario of breakout from safeguards, a fusion power plant has no fissile material at the time when inspectors are expelled. It can be rendered incapable of producing such material through a missile strike, with no risk of release of radioactive material."

VIII. CONCLUSIONS

FUNFI was a small meeting which covered many of the issues of present and future nuclear systems. The location was calm and inspiring and showed no signs of an economy in difficulty. The organisers and staff were always helpful. **The leader of the Chinese team, Yican Wu, proposed that China should host the next FUNFI meeting.**

The meeting left out many possibilities, like Laser Fusion and Small Fission Reactors, but the story would have been similar with more chapters. Nuclear Energy has many new and spectacular developments yet to happen. It can do all the things we would most hope for from an energy system, especially by stabilising energy prices for centuries.

The Proceedings of the meeting will be published in 2012 by the American Institute for Physics in their Conference series.