RISKS, INNOVATION & FUNDING FOR FUSION TECHNOLOGIES

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I. INTRODUCTION

The RISK of losing the entire investment in any advanced technology declines as innovation and knowledge growth moves forward. In the case of the Fusion of Hydrogen and other light elements, discovered by Mark Oliphant in 1934 at Cambridge using ion accelerators, the investment was tiny, the ingenuity high, and the results spectacular. The energy release is 70% higher, per tonne of fuel, than for Uranium. The universe is full of light elements that power the stars, so the ultimate rewards are clearly boundless. There was little relevant technology base to produce a reactor which could steadily burn a Hydrogen plasma of fully ionised fuel.

Only governments could afford to bet on human ingenuity and invest where everything had yet to be discovered or invented. The big prize of electricity from Fusion is now in sight for 2050 and beyond but new advances offer low hanging fruit in the form of other valuable applications of Fusion in the near future. Here we will show how 70 years of Fusion research has built up a knowledge and engineering base which is now ready for exploitation at an acceptable risk for advanced technology projects. Some hundred billion dollars worth of government research is available for early applications which can be worth hundreds of billions. We will outline the flow of investment and reward needed to make this happen.

The first, simplest, but undesirable application was the H-bomb. The designers all turned to civilian needs for electric power and developed a swathe of devices to make and confine million degree plasmas, but their efforts were held secret. The first UK toroidal device, with a large current flow to heat and compress the plasma, was built by Thoneman and Ware in 1946 at Oxford. The risk of failure was maybe 99% but the results were sufficient to justify larger machines. The principal Fusion goals and technical STEPS were worked out, the most important being to confine the plasma for long enough and hot enough and dense enough to release more nuclear energy than it took to run the plasma or breakeven. The most promising approaches were with large magnetic fields to hold the plasma, large currents or energy injection to heat the plasma, and confinement long enough to maintain the right density.

Each STEP achieved would lower the Risk, but nature did not yield success easily. Solids stay put, liquids flow together, air blows erratically, but plasmas have a multitude of ways to wriggle or leap across magnetic fields. Technology was not enough and plasmas had to be fully understood to gain control.

In 1958 at the first classified meeting between Britain, France, Russia and the USA, the Russians admitted that Fusion would not provide quick answers. They declassified everything, to the horror of the US participants, and Fusion became an international effort. Every STEP achieved benefitted all the players, along with the steady increase in KNOWLEDGE of plasma behaviour.

This also means that new versions of fusion machines now stand on a huge basis of technology, engineering, and understanding. The RISKS are regarded as low enough to invest $10-20Bn on a fully working fusion reactor. The International Thermonuclear Experimental Reactor (ITER) is to engineer all the components for a 500MW reactor. This is the final step before a Demonstration of a complete commercial Fusion electricity plant by 2040. ITER is now under construction at Caderache in France. All this engineering can now be applied to alternative fusion applications for commercial exploitation well before electricity generation becomes a reality.

Governments have now placed all their eggs in this one last basket. It will be up to Corporations and private enterprise to commercialise the results.

II. RISKS vs KNOWLEDGE

This is a lengthy story, all compressed into the chart below. It shows the steady flow of invention and discovery and major STEPS forward, reducing RISK as KNOWLEDGE increases. The residual unpredictable 5% risk is from political and financial obstacles to any large programme,

Chart I shows the knowledge contributions of three of the multiple approaches to Controlled Fusion. Only one has survived the funding cuts and so is the best option to spin off early uses for Fusion neutrons. The thickness of the lines indicates the contributions from the scores of Mirror machines and hundreds of Tokamaks.

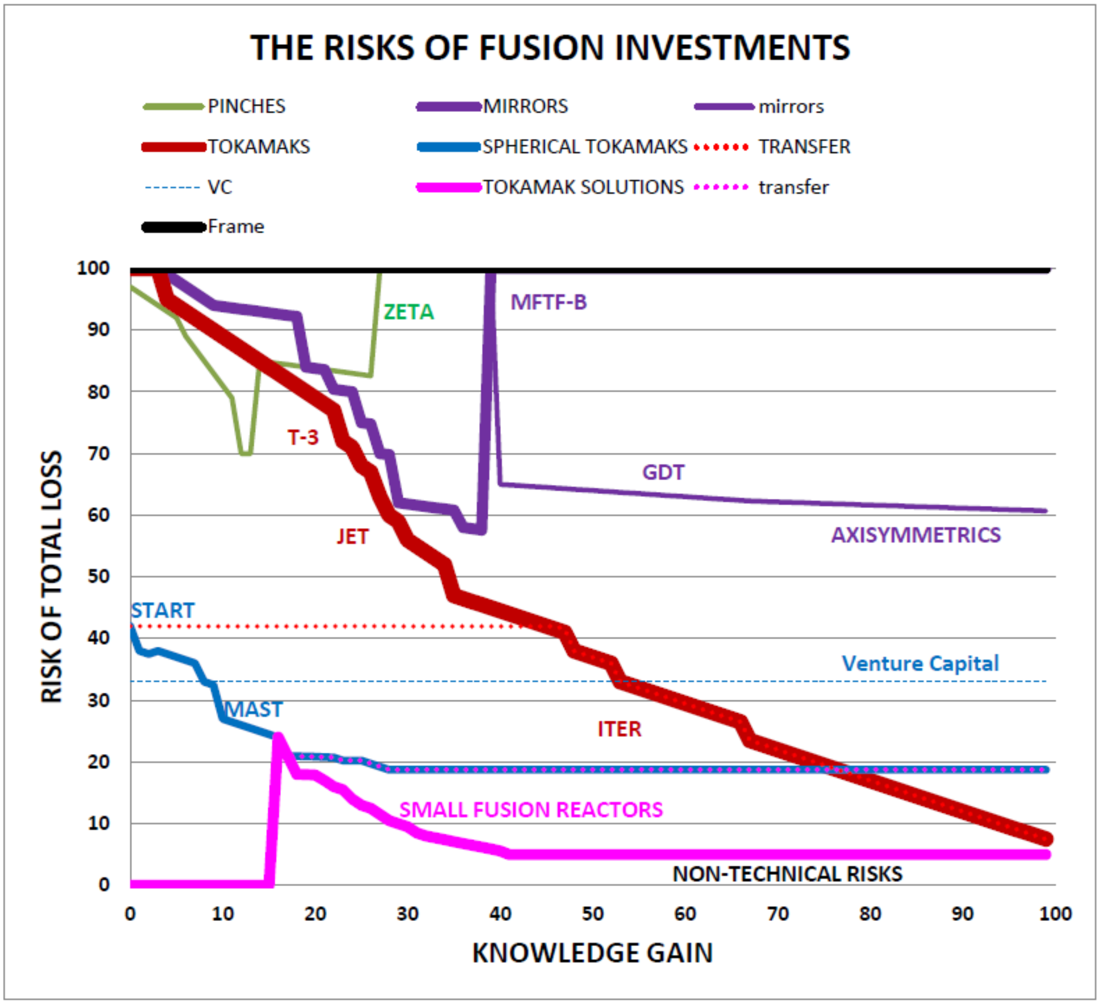

Chart I. RISK vs KNOWLEDGE

(1) PINCHES

There are several Pinch fusion devices. The toroidal pinch by Thoneman and Ware led to the largest machine of its day, ZETA, in 1955 at Harwell. It soon produced neutrons from fusion reactions in the Deuterium plasma. Somewhat unreliable temperature measurements were made by sticking a couple of wire electrodes into the plasma (a 'plasma probe') to draw a small current. News of the neutrons leaked and a premature 'mission accomplished' statement was issued. The RISK dropped hugely, but it was later realised that the plasma was too cool for fusion and also quite unstable. Fluctuations had acted as accelerators to produce a few hot Deuterons and fusion reactions. Total embarrassment for the whole Fusion community. The RISK went back up.

Learning from failure, ZETA continued and the team invented a new technique of temperature measurement by Laser scattering which became a world standard. The project closed in 1962, RISK=100% loss.

The promise was still high and Britain invested in a large, purpose built laboratory at Culham, to investigate Fusion and Space Plasma Physics. This was much smarter than the red brick AEA labs at Harwell and Aldermaston.

(2) TOKAMAKS

Invented by H-bomb designers Tamm and Sakharov, these have become to the world's leading fusion machine. In 1968, the latest machine at the Kurchatov Laboratory, T-3, hit an unprecedented 10 million degrees. Culham sent a small team to the Kurchatov to make laser measurements of the temperature. The breakthrough was confirmed and the whole world started building small Tokamaks. The Tokamaks hit many of the key STEPS like Clean plasmas, Stable Confinement, and Current controls.

The big STEPS are seen in the chart as sharp drops in Risk, sharable with other projects.

In 1970 the Culham Director, Bas Pease, decided to push the Fusion ambition faster by designing a very large Tokamak with internal collaboration between the other EU laboratories. EURATOM had to agree to the proposal. The Joint European Torus (JET) was built by 1980 at Culham after a long delay as politicians argued about which country should host the facility. It achieved the big STEP of breakeven fusion energy in 1999. The machine was then radioactive and had to be maintained by man-like robots. This was another major nuclear technology STEP.

Fusion RISK had reached the 1 in 3 success level accepted by Venture Capitalists for investment in shopping malls.

The world wide results produced a Scaling Law which combines their data to predict the required size, magnetic field, and current needed to make electricity. Design of ITER began in 1992 and went through two iterations to the final design being built now.

There is one remaining huge STEP for the ITER programme. The flood of hot fusion neutrons from the plasma must deposit its heat in a surrounding Blanket with cooling loops to drive turbines. The cool neutrons must also be finally absorbed in molten Lithium Fluoride salts to breed fresh fusion fuel, the heaviest Hydrogen isotope, Tritium. The blanket design depends upon supercomputer neutronics calculations, the standard thermal hydraulics of cooling systems, and the chemistry for control of corrosion by the salts.

(3) MIRRORS

The simplest static confinement device is a straight magnetic field squeezed tight by coils at each end of the plasma chamber. Hydrogen ions spiralling along the field lines are reflected by the strong mirror fields – mostly. Plasma confinement was marginal for Fusion electricity. Every country had a mirror programme at the start. These were all quickly unstable and the plasma would wobble sideways into the walls. Additional parallel coils stabilised this by making the total magnetic pressure a minimum at the plasma centre. This was a big STEP, backed by a new theorem that all Minimium-B systems would be stable.

A device was invented in 1970 to inject a high current of neutral Hydrogen atoms into a Minimum-B mirror at Livermore. This made a plasma at 100 million degrees, sufficient for thermonuclear fusion to take place. A really big STEP adopted by most labs and devices around the world.

The confinement problem was solved by adding an additional, very high field, mirror chamber at each end of a long central chamber. These were to contain 800 million degree plasmas which would stopper the ends of the central reactor chamber. This is called a Tandem Mirror.

A very large tandem mirror machine, MFTF-B, was built to match the Tokamak performance at JET. The Livermore group developed complex superconducting magnets run at liquid Helium temperatures around 2 degrees Kelvin. These were commissioned and met their goals.

In 1984, MFTF-B was commissioned and immediately closed by Ronald Reagan in a general cutback on Fusion research in favour of the ill-fated Star Wars project. The RISK had gone to a 100% loss.

Some other mirror programmes have survived and Russia continues to do fusion research with machines like the Gas Dynamic trap (GDT) in Novosibirsk. This has few significant technical barriers to becoming a powerful neutron source for materials testing. This change of mission will provide a resource great value to Fusion.

New Axisymmetric Tandem Mirror designs could one day become the preferred large Fusion Reactor.

(4) SPHERICAL TOKAMAKS

Most Tokamaks have an aspect ratio of minor to major radii like a bicycle tyre. By compressing the design towards a sphere with a hole in the middle one adds a lot more curvature to the field lines which reduces the fine scale turbulence and cuts plasma losses.

The START machine was built very cheaply from recycled components by the UK Fusion programme at Culham, 1991. It proved that the configuration worked, gave this more ideal plasma shape, and could be run at a much higher plasma pressure for the same field strength. Many small Spherical Tokamaks were built around the world.

The machine started from zero knowledge of its performance and some uncertainty that a stable plasma torus would even form. As indicated by a dotted line on Chart I it drew on the accumulated Tokamak Knowledge. A larger machine, MAST, was designed to run at much higher plasma current, and was eventually funded at a modest level. This performed well in 2000 and, in collaboration with a similar effort at Princeton, showed that performance should increase more rapidly with magnetic field strength than the standard Tokamak scaling. The new machines were making big STEPS forward.

Fusion funding outside the ITER programme continues to dwindle. It has taken 5 years to secure funds for an upgrade to MAST and that is spread thinly over five years. A more ambitious upgrade for the Princeton NSTX machine is in progress.

New Urgency & New Missions.

In the last decade, the problems of Global Warming, the decline of Cheap Oil, the rise of wind power which needs gas fired back up, and the appearance of even more carbon fuels in shale gas and oil and undersea methyl hydrates make the use of safe nuclear power and accelerated Fusion development necessary. A likely doubling or tripling in nuclear power by 2030 will put considerable pressure on Uranium sources. The latest UK plan for nuclear energy predicts up to 75GW of nuclear power by 2050.

The Spherical Tokamak performance is good enough to support 5-50MW of Fusion power, using existing materials and industrial strength versions of current laboratory systems for heating and fuelling. It will not make much electricity but the neutrons can transmute any elements.

Other approaches have been revived with modern technologies using a reversed field pinch (Lockheed), Boron fusion (Lawrenceville), electrostatic confinement (Crossfire), or plasma compressed by a spinning wall of lead forced inwards by pneumatic pumps (General Fusion). All have similar short and long term goals to build Small Fusion Reactors (SMRs).

The Spherical Tokamak Spin-off

In 2007 a small group based at Culham moved to build a Spherical Tokamak machine to serve as powerful neutron sources for reactor materials evaluation, making new medical isotopes, and research in fast neutron physics. A spin-off company, Tokamak Solutions UK, was formed by 2010.

For each such spin-off, later developments will allow larger models to serve as breeders of reactor fuel from Depleted Uranium, breeders of Uranium fuel from Thorium to give Thorium reactors a clean start, or burners of high end nuclear wastes. One kg of fusion fuel can produce 44 kg of reactor fuel from Depleted Uranium, so the potential gains are extraordinary.

A Development Scenario

This group of commercial Fusion enterprises could deliver very valuable services to nuclear energy within 20 years. This is a long time for commercial investment, so the steps must generate a combination of income, intellectual property, and much greater value to each round of investors. The shared technology steps for each, over the next 20 years are to

(i) Design a suitable first machine to trial all the technologies together and produce useful neutron output.
(ii) Industrialise current injectors, heaters, accelerators, and RF sources to reactor grade.
(iii) Develop high temperature superconducting coil sets which can operate at liquid nitrogen temperatures.
(iv) Build and operate a Prototype, SFR-1 for basic tasks in materials research.
(v) Build and operate a full scale Demonstrator, SFR-2, of all the technologies to be commercialised.

(vi) Sell a commercial version, SFR-3, in the nuclear energy market from 2035.

(vii) Build and operate the first Hybrid Fusion-Fission reactor, FF-Hybrid for nuclear electricity.

Following the RISK/KNOWLEDGE curves, the VALUE of any investment will rise with huge jumps as the major STEPS are achieved, matching the jumps in funding required for the next phases. Investors will be able to stay with the programme or sell on to those able to support the much more valuable follow-on steps.

III. INVESTMENTS & VALUES

The massive value in Fusion technologies has been built by £100Bn of government investment, but the US and EU Fusion budgets have been cut back heavily since 1984 and are now concentrated on the ITER project. The US has closed most of the larger machines. The UK has relegated Fusion from a government project to an academic research programme funded through the Science Research Council budgets. Chart II shows the US Fusion budgets for the Office of Fusion Energy (Magnetic Fusion) and the Inertial Confinement Facility (Laser Fusion). The ICF at Livermore is also promoted as a simulator of weapons physics.

China and Russia continue to invest large amounts into ambitious Fusion projects. Both have declared that they hope to bypass ITER, using much of the new technology, to build Hybrid Fusion-Fission reactors. These are much less demanding than a pure Fusion machine but make for a very safe Fission Reactor blanket. Their ambitions remain on a grand scale.

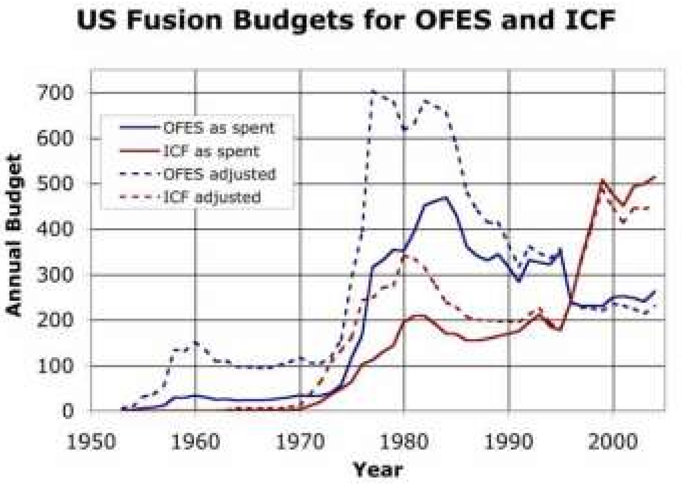

Chart II. The decline and fall of US Fusion.

It is time for private enterprise to pick up the almost completed story. Several companies are using the knowledge base to reinvent earlier devices for a much higher performance level.

SMALL FUSION REACTORS BY 2025

The new Fusion enterprises are able to benefit from the transfer of government funded research into a series of commercial Small Fusion Reactors. Only two development steps are needed to upgrade and integrate known technologies into a modest prototype and follow on with a full scale demonstrator of an operational plant.

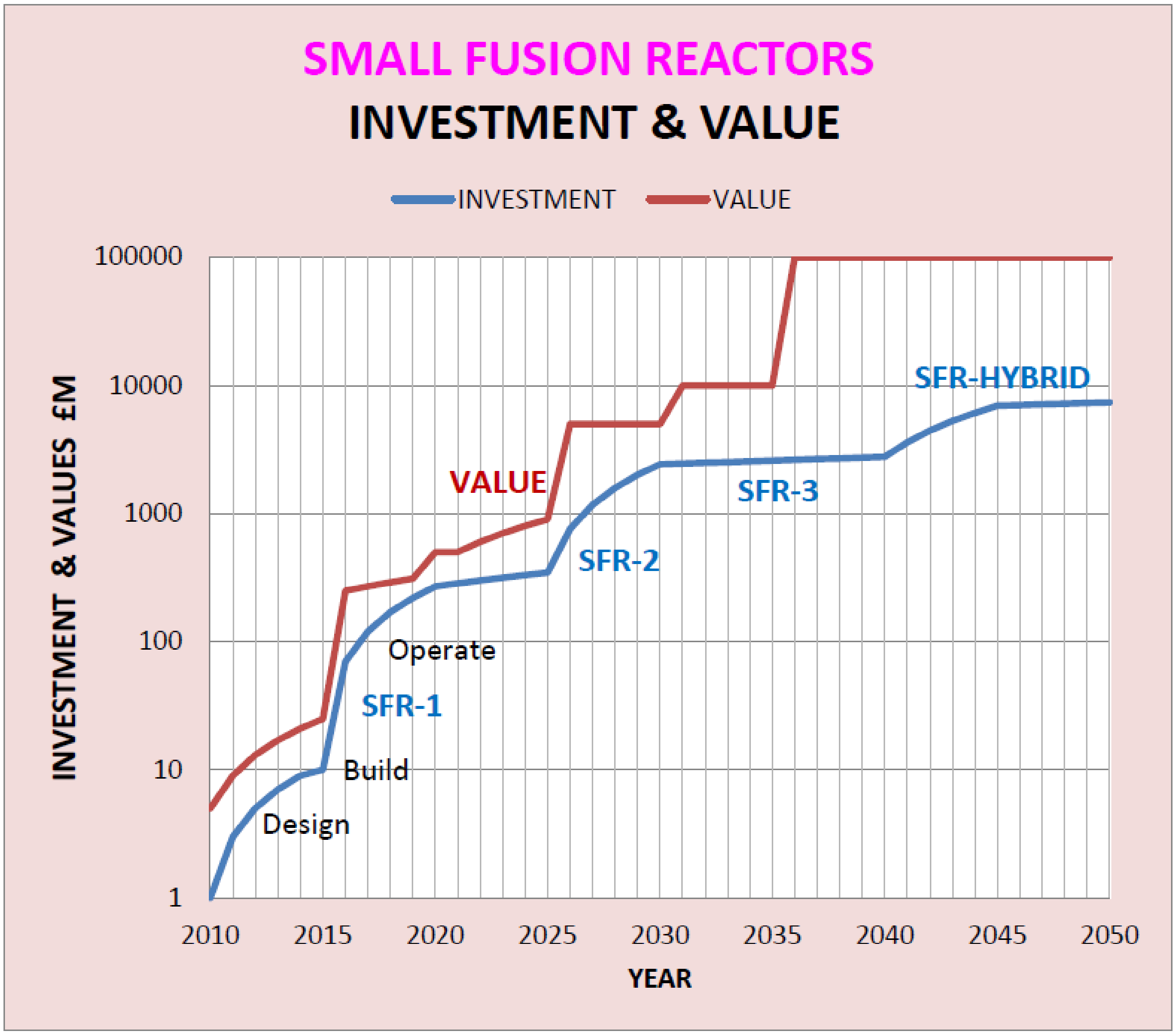

Chart III. A £10Bn Investment for a £1Tn Business. Note the logarithmic £M scale for Values.

Chart III shows the projected movements of the cumulative investment and the market size or valuations at each stage. After some £100Bn of global investment in Fusion this needs an investment of only £10Bn to enter a £Trillion world energy market. The total investment is small enough to be raised directly from energy investor groups without any borrowings from financial markets.

The project phases are described in generic form as overlapping 5 year cycles to design, build, operate and sell the successive plants. An avalanche of patents by all the project partners will protect the new engineering knowledge for investors. The plants will run for many years and pay their way as platforms for training and continued developments.

A project starts with an implicit Value of £10M or more, the cost of drawing up the design for the first Prototype. Collaboration with companies who will supply the industrial strength components creates substantial IP. One such, with Oxford Instruments, has already produced High Temperature Superconducting coils for a small Tokamak test bed. Such coils are critical to the operating costs of most SFRs.

The completed design and completed network of partners and suppliers is then worth the £300M needed to build and operate SFR-1.

Nuclear facilities are bound by local government regulations and by required agreements with the IAEA on nuclear materials and safety. Several SFR build sites have been identified in Europe and elsewhere which will allow rapid planning approvals. The countries who offer sites will benefit from the training in these technologies which will be part of the build and operation.

As SFR-1 becomes operational, the project value leaps to the £2Bn baseline for SFR-2. The design team will design SFR-2 during the operation of SFR-1 to provide a rapid follow on as goals are met.

The SFR-2 will develop all the most valuable blanket applications to allow for a family of separate plants for different purposes. Marketing of these products will run together with the operation of SFR-2. The next Value point is for the expected sales of many plants at £3-4Bn each.

The design and build cycles continue with progress to small Hybrid Fusion-Fission reactors producing base load electricity. The Project Market valuation becomes £Trillions. This can happen in the latter half of this century, creating dynastic fortunes for the strongest investors. Our world civilisation has to solve many other problems on the way, so this is a most optimistic view.

IV. FINALE

We are able to give such a detailed sketch of a possible future path for Fusion technologies only because of the huge knowledge base and technical capability which now exists.

Other nuclear pathways, such as the Molten Salt Thorium Breeder, can also benefit from the achievements of the Fusion effort. The recycling and transmutation of nuclear wastes becomes essential and practicable with Fusion-Fission hybrids.

Governments have been notoriously poor at technology transfer which requires training, not just the study of published work. Slow, poorly funded research dissipates experience which must be relearned later. Private enterprise tends to narrow its focus and therefore miss relevant innovations. Good management of the new Fusion efforts should capture expertise as well as Knowledge.

The website, www.EfN-UK.org, hosts a wide discussion of the Economics and Politics of Energy and a balanced selection of reports on the technologies for Fusion, Nuclear and Renewable energy resources. External links to relevant organisations give access to far more information and interaction on all topics. The site is highly interactive with comments, blogs, and rapid publications services for all.