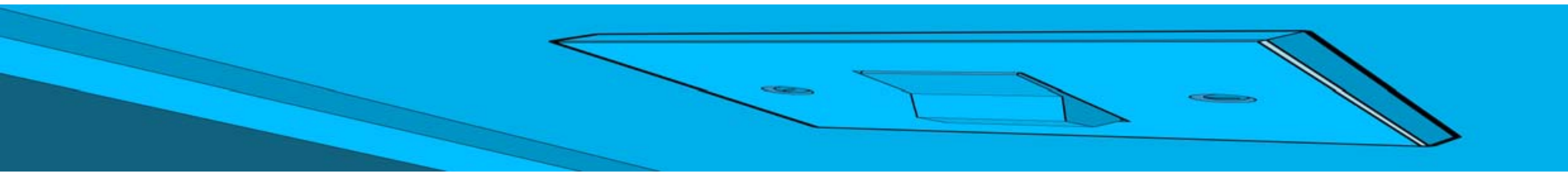

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Sustainable Hydrogen Production: A role for Fusion?

A workshop exploring the potential for large scale Hydrogen production through methods other than electrolysis

Meeting Report
April 11th-12th 2007
Culham Science Centre and Worcester College, University of Oxford

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UKAEA's Culham Division in Oxfordshire, UK is the national centre for fusion research, hosting the European flagship experiment JET on behalf of partners across Europe and with its own unique research programme. The search for commercial fusion power at Culham is part of a global drive to produce electrical power from the process that powers the sun. www.fusion.org.uk

The Energy Security Initiative is a multi-disciplinary collaboration between the University of Cambridge and the Massachusetts Institute of Technology, under the auspices of the Cambridge-MIT Institute. The aim of the initiative is to provide a neutral space for discussion, analysis and research focused on the key issues in international energy security. The initiative works with stakeholders to develop solutions to energy security challenges at national and international levels. Collaborations with companies, governments and universities beyond Cambridge and MIT is a key component of the initiative’s strategy for delivering value to its diverse stakeholders. http://www.energysecurityinitiative.org/

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Sustainable Hydrogen Production: a role for Fusion?

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Day 1 – Wednesday 11th April

1.1 Welcome and introduction to Fusion, Sir Chris Llewellyn Smith, UKAEA Culham Division

Dr Bill Nuttall, of the **University of Cambridge**, thanked everyone for coming to the conference, and gave special mention to those who had travelled far, before introducing **Prof. Sir Chris Llewellyn Smith** who took the stage to discuss the **UKAEA**'s vision of **The Path to Fusion Power**. Before describing the work that took place at Culham, Sir Chris apologised for his absence from the rest of the conference. He was to go to the European Commission to detail the same argument he was about to layout before us, namely that due to the reality of climate change, alternative energy supplies needed to be fast-tracked.

The Path to Fusion Power started from the fact that fusion works. It powers the sun and stars, and the Joint European Torus (**JET**) which is currently the world's largest fusion device, hosted by the UKAEA at **Culham**, has produced 16MW of fusion power. The big question is when fusion can be made to work reliably and economically. A major barrier is that very large devices are needed to demonstrate net fusion power production. Even JET consumes more power than it produces, but the next step device **ITER**, described later, which is twice as big as JET in every dimension, should produce at least ten times as much fusion power as the power needed to heat the fuel.

The most promising reaction for power production on earth is the fusion of Deuterium (**D**) and Tritium (**T**), which are heavy isotopes of Hydrogen containing one and two neutrons respectively. To produce fusion in "magnetic confinement" devices such as JET and ITER, a low density gas of D and T must be heated to over 100 million ^{0}C. At a few thousand ^{0}C inter-atomic collisions strip the electrons from the D and T nuclei, and the gas becomes a "plasma" of separately moving nuclei and electrons. At 100 million ^{0}C some of the D and T nuclei have sufficient energy to overcome their mutual electrical repulsion and approach each other closely enough that fusion can occur.

The first challenge is to heat a large volume (perhaps 2000 m^3 in a fusion power plant) of D and T to over 100 million ^{0}C. Contact between the dilute gas and solid wall would cool down the gas and extinguish the fusion reaction. The gas must therefore be insulated from the wall by using magnetic fields which guide electrically charged particles. This is achieved in a ring-doughnut shaped "magnetic bottle" known as a tokamak. The challenge of containing a hot D-T plasma has been met in JET and other devices to a degree which would make it possible to construct a fusion power station, albeit with low performance. The performance can however be improved by increasing the pressure: doubling the pressure doubles the density, at fixed temperature, which in turn quadruples the fusion reaction rate. However, as the pressure is increased the plasma tends to become unstable and escape the magnetic bottle. Current tokamak research is focussed on avoiding and controlling instabilities. Every year plasma performance improves, and there is optimism that over the next two decades the level required for an efficient fusion power station will be reached.

The products of the DT reaction are high energy neutrons and Helium (**He**) ions. The charged He ions are trapped in the "magnetic bottle" and slowed down by colliding with the DT fuel. This keeps the plasma hot, allowing further fusion reactions to take place. Indeed, it is possible for the reaction to sustain itself in this way, a regime in which the plasma is said to be "burning".

The neutrons, not being charged, are not steered by magnetic fields and escape into the wall where they slow down and eventually come to a stop, transferring their energy to the wall which is heated up. The heat will then be removed through cooling circuits and used to generate electricity, or perhaps to produce hydrogen. The flux of high energy neutrons into the wall is several MW per square metre, and **the second challenge** is to identify materials, from which to construct the wall, that will stand up to this bombardment for long periods.

Fusion reactors will be complex devices, and **the third challenge** will be to design reactors that are easy to build, and will work reliably and be easy to operate and maintain.

The energy released in a fusion reaction is 17.6MeV (shared 14.1MeV/3.5MeV between the neutron and the Helium ion that are generated in the reaction). This is some 10 million times more than the energy released in a typical chemical reaction, and correspondingly while a 1GW coal power station would consume 10,000 tonnes of coal in a day, a fusion power station would consume only 1kg of D and T.

In terms of energy security, it is important to consider where the fuel - the Deuterium and Tritium - comes from, and how easily it is obtained. Deuterium atoms are direct remnants of the Big Bang and widely available and abundant; there is one among every 6,700 Hydrogen atoms in the universe, and they can be extracted from water at negligible cost. However, Tritium has a half-life of 12.3 years (meaning that every twelve and a bit years half of it decays), so it is not naturally abundant. Fortunately, it can be generated from Lithium (Li) through a reaction induced by the neutrons, generated by fusion, that produces Tritium and Helium. Lithium is a common metal, found all over the World and not restricted to a few regions, like oil for instance. There is enough Li easily available from rock to power the world through fusion for hundreds of years. For the longer term, Li is present in and can be extracted relatively cheaply from sea water, where there is enough to provide the world's energy needs for millions of years.

So the raw fusion fuels are Li and water. A small amount of Tritium would be required initially as kindling, to fuse with Deuterium, to get a fusion reactor going. Subsequently, sufficient Tritium would be produced to keep the device running (and provide kindling for restarts and/or new fusion reactors) by reactions between the neutrons produced in fusion and Li placed in the walls of the device that capture the neutrons. The Li in one laptop battery and the D in 40 litres of water, would – allowing for inefficiencies – provide 200,000 kWh of electricity; this is enough to support the lifestyle of a member of the UK population (i.e. their personal electricity use, and their share of electricity consumption by industry, commerce, public transport etc.) for thirty years, with no air pollution or CO_2 production. This huge potential is reason enough to continue development unless a barrier is met.

In JET the hot gas is confined in a torus ('ring-doughnut' shape) with a volume of $100m^3$, whereas in **ITER**, the next step fusion device to be built in Cadarache, France, the volume will be close to $1000m^3$. Magnets surround the torus and, together with an electric current of several million amps that is driven through the plasma around the torus, create the 'magnetic bottle' that confines the plasma.

Around the walls of the torus in a fusion power station there will be a 'blanket' containing Lithium and the cooling circuits that will be used to extract the heat. In a power plant the plasma will contain 10-20 postage stamps worth of matter taking up a volume of some 2000m^3, at a millionth of atmospheric density, but at a million times atmospheric temperature, leading to an overall pressure of about 1 atmosphere.

Early power plants will be built using relatively familiar materials that are thought very likely to be able to survive in fusion power station conditions, but will have working temperatures limited to 400-500°C. The 2nd Law of Thermodynamics implies that higher temperatures lead to greater efficiency in converting thermal energy to electricity. As for other thermal power plants, it is hoped that materials than can work at higher temperatures will be developed, such as Silicon Carbide (**SiC**) ceramics that might be capable of withstanding up to 1100°C. For the production of Hydrogen approximately 800°C is needed to thermo-chemically "crack water".

The benefits of fusion were then discussed. Near unlimited fuel and no air pollution or CO_2 production are certainly advantageous, as are the intrinsic safety aspects. The biggest danger would come from a Tritium release, which however even in the worst-case scenario would probably not require evacuation of the surrounding area. There is no radioactive 'ash' or long-lived waste. However, the blankets surrounding the device would become radioactive due to the neutron irradiation. This effect can be minimised by choosing low-activation materials, so that any radioactive species produced would have short half-lives, on the order of 10 years, and so decay away quickly, allowing all components to be recycled after 100 years – so no permanent repositories are required, as the waste decays on a human, rather than a geological, timescale.

The history of fusion research, from the early machines in the 1950s, to the emergence of the Russian Tokamak in the late 1960s, was summarised, culminating in the JET project in the UK and the forthcoming ITER device in France.

The dynamic mindset of fusion research was then explained. Originally, the plan was to build ITER, and if it proved successful, only then start to worry about the materials. However, progress in recent decades strongly suggests that ITER will work as expected; this expectation follows from semi-empirical scaling laws that successfully interpolate between different devices (e.g. the similarly shaped COMPASS-D, ASDEX-U which is twice as big in every dimension, and JET which is twice as big again) and can be used to extrapolate to ITER, which is twice as big as JET. The current plan of action is therefore to develop the new materials in parallel to building ITER.

The next-step is to build ITER, which should produce ten times as much fusion energy as that used to heat the plasma, and - as close to simultaneously as allowed by the available funding - to build the International Fusion Materials Irradiation Facility (**IFMIF**). The step from ITER to a power station will be smaller than that from JET to ITER, although the huge challenge of building systems that will operate reliably for long periods will have to be faced. The ITER parties house half the World's population, and it is a truly international venture to find a global solution to a global problem. Final design and prototyping for IFMIF is being carried out jointly by the EU and Japan.

Two positive developments in plasma physics have increased optimism about fusion: the discovery of a self-generated 'bootstrap' current, which reduces the power needed to keep tokamaks operating, and 'high confinement modes' in which the edge of the plasma acts as an insulating barrier allowing higher pressure and a greater fusion reaction rate. On the other hand it is possible in principle, although thought very unlikely, that 'burning' plasmas, which will be studied in ITER for the first time, might exhibit new instabilities or be unable to sustain boot-strap currents (in which case long pulses rather than continuous operation would be a fall back, or the use of an alternative configuration called a stellarator in which a plasma current is not required).

Less-developed alternatives to the traditional doughnut-shaped Tokamak are also under investigation: stellerators (which have a highly complicated vessel geometry) and Spherical Tokamaks (**ST**s), which are shaped more like a cored apple. The two World-leading STs are MAST, located in Culham, and NSTX in Princeton in the USA. Machines like MAST make more efficient use of their magnetic field, allowing adequate plasma pressure with much lower currents in the magnets. This could make it possible to operate round the clock without superconducting magnets, which would be a big advantage in terms of cost and decreased complexity – but STs face other challenges such as bigger heat fluxes. JET's magnets are made of copper and can only be operated for a minute because they become hot. Power plant magnets will have to run for much longer periods of time, and in the case of conventional tokamaks would have to be superconducting – which requires that they be made of special materials through which current flows without resistance when they are cooled down to close to absolute zero.

The materials that make up the wall and blanket of a future fusion power plant will be exposed to up to $2MWm^{-2}$ from the 14.1 MeV neutrons produced by the fusion reaction in the plasma. This leads to displacement cascades in the material where atoms are knocked out of their positions and go on to knock out further atoms. These displacements lead to many different phenomena, including swelling. The majority of displaced atoms return sooner or later to regular positions in the lattice, but some remain as defects. The neutrons also lead to the production of Hydrogen and Helium in the materials, as occurs also in fission reactors but at a much lower rate. Hydrogen atoms are small and are expected to make their way out of the material. Helium atoms are larger and less mobile, but could migrate and accumulate at the grain-boundaries of the crystals that form the material. This would lead to embrittlement and further swelling, caused by the agglomeration of Helium to form bubbles. By using alloys with carefully chosen minor species it is hoped to minimise the diffusion of Helium and displaced atoms. IFMIF is required to simulate the neutrons produced by fusion and identify materials in which diffusion is inhibited.

A recent European Fusion Power Plant Conceptual Study (**PPCS**) explored devices ranging from those achievable in the near term, to those requiring significant development in materials, plasma performance and fusion technology. The Study investigated the economics of the different designs, and found costs for fusion generated electricity that look comparable to the costs for low carbon alternatives. Fusion costs decrease with output: each of the machines modelled produced $1.5GW_e$, which is the around the largest output from a single source with which grid operators feel comfortable. Fusion would therefore be suitable for providing power to major population centres. Capital costs dominate the cost of fusion power and operating costs are low. Perhaps during off-peak times fusion power could used to produce Hydrogen – either though thermo-chemical cracking of water or by electrolysis.

The Fast-Track approach to fusion involves in parallel exploiting ITER and investigating materials at IFMIF, with the aim of building the first prototype power plant, DEMO. Construction of ITER was delayed for political reasons, but is now beginning, and it is hoped that construction of IFMIF will follow immediately the R&D being carried out by the EU and Japan is finished. Assuming about 10 years to build ITER, a further 10 years to study power-plant relevant scenarios at

ITER and materials at IFMIF, and then a further 10 years to build DEMO, electricity production by fusion should be demonstrated in about 30 years. Large scale deployment of fusion should then be beginning around the middle of the century.

The question is often asked whether fusion could be developed faster if more money were available. Sir Chris was to visit the **European Commission** on the Friday of the conference to discuss his answer to just that question, which he believes is ‘yes’. With increased funding the current research could be reinforced with extra projects, reducing the risk of potential delays. The idea had been put forward that perhaps a DEMO could be built without waiting for full results from ITER and IFMIF, although they are certainly required for the development of an efficient and optimised fusion power plant. While it would be inefficient, with un-optimised materials, an ‘early DEMO’ would provide a focus for R&D, and bring industry more fully on board, thereby most importantly introducing a culture of designing for ‘buildability, reliability, operability and maintainability’.

To keep the funding issue in context, $1.5 billion p.a. is spent worldwide on fusion research, which (e.g.) is less than the funding available for High Energy Particle physics. Generally, publicly funded energy R&D needs to be increased. Amazingly, it is less than half what it was in real terms in 1980 and is running at less than 0.25% of the World energy market, which is worth some $4.5 trillion p.a.

There is no ‘silver bullet’ that could solve the very challenging problem of meeting the world’s rising energy needs in an environmentally responsible manner. A ‘cocktail’, or portfolio, of measures is needed, including reducing energy use, greater efficiency in using energy, renewables, carbon capture and storage at fossil-fuel-burning power stations and factories, and nuclear fission. Fusion has the potential to be a major part of the portfolio, and must be developed as one of very few alternatives for large-scale production of base-load power. Clive Cookson of the Financial Times was quoted as saying, ‘Even if ITER goes well over budget and cost $1 billion a year to build, it will be well worth it for even a 20% chance of another major energy option’. Sir Chris concluded by saying that this was surely right, although he thought that 20% was very pessimistic.

The question was asked whether the development of STs, as an outside competitor with large potential, could be pushed forward. Sir Chris responded by saying that only about 3% of the fusion budget was spent on ST research, which was well justified in view of their attractive features. MAST had been built on a shoestring budget, and neither MAST nor NSTX could reach steady sate plasma conditions with high power. More funding was now needed to upgrade MAST, to see whether steady state can be achieved and address the other crucial questions that will determine whether STs have a future.

An inquiry was then made about removal of the He ‘ash’ once it has given up its energy to heat the plasma, which is necessary to prevent it diluting the D-T fuel and eventually extinguishing the fusion reaction. Sir Chris described how the magnetic configuration in modern tokamaks leads impurities, such as He, to a device called the divertor that acts as a sort of exhaust and takes them out of the plasma.

It was noted that, so far, there had been no mention of **Inertial Confinement Fusion**. Little work was currently pursued in Europe on inertial fusion, although scientists from the Rutherford Appleton Laboratory had made important advances in collaboration with Japanese groups. Inertial confinement operates in a different regime to the magnetically confined fusion that had been described, instead using a high density but low volume pellet of DT fuel. Lasers are focused onto the plastic coating of this pellet, which ablates and sends a pressure wave inwards, compressing the fuel. Inertial fusion faces a number of challenges, including developing suitable high power lasers that can fire five times a second, rather than once every twenty minutes as at present, and reducing the cost of the pellets and the tubes that surround them, and serve to focus the radiation pressure, from some $500 each to some 10 cents. Materials issues similar, but not identical, to those that confront magnetic fusion will then have to be faced.

The comment was made that the arguments presented had been very persuasive, but how would one go about convincing the ‘man on the street’? Reliability is the hardest question to answer, and it was acknowledged that no one could prove that fusion would deliver - but if we had seen Mr. Bleriot fly across the channel in 1909, it would have been difficult then to convince the ‘man in the street’ of the concept of a Jumbo Jet. The truth is that technology moves on, and the involvement of industry is required (as represented by many of the attendees) to spur this development forward. Although fusion is not well known to the public, there is growing knowledge and appreciation of its potential, and it is relatively easy to convince people that fusion development should be very vigorously pursued even if success is not 100% certain.

1.2 Hydrogen vision, Prof Peter Edwards, University of Oxford

After tours of the JET and MAST facilities at the Culham Science Centre, **Prof. Peter Edwards** of the **University of Oxford** discussed what he saw to be the ‘Hydrogen **Vision**’, and the possible role of fusion in it. He initially addressed the societal drivers in a move towards a Hydrogen economy, namely the increasing demands for energy as well as climate change and air quality. While Hydrogen on its own would not be a panacea to the global dilemma of increased demand versus decreasing resources, he believed that it has a strong part to play in the future energy mix.

Is there a UK Hydrogen vision? **Greg Vaughan**, of the **DTI**, and **Dr. Geoff Dutton**, of **HyWays** (not in attendance), have looked at how the UK fits into the European perspective. The **DTI** energy team highlighted four aspects of a Hydrogen economy with regards to this country. Firstly, the benefit to the public good in terms of better air-quality in urban centres and regionally, and also the economic opportunities it would create. Secondly, the UK’s current approach is to keep the Hydrogen option open. Thirdly, that alignment with the EU should be an aim, so that joint initiatives can be pursued with regards to Hydrogen fuel-cell technology, and fourthly, to support these developments and initiatives.

The UK’s priorities lie in transport, as this sector is a major contributor to CO_2 emissions. A spot light is needed on Hydrogen and fuel cells, both for transport and power generation. In the UK regional supplies are crucial. The hard facts that need to be figured out are: how much Hydrogen in needed (or how much produced and stored), and where will the energy for the Hydrogen production come from? Hydrogen itself is just an energy carrier like electricity, albeit more easily stored, but still requires an energy input. What are the ‘hard products’ of a Hydrogen economy going to be, i.e. what form will the Hydrogen be stored in – as a liquid, gas or a solid?

It can be envisaged that the heat from a nuclear fission reactor, from the Sun, or from a fusion device could be used to split water into its constituent elements - Hydrogen and Oxygen. Currently, 80% of the World’s Hydrogen comes from the steam reformation of methane. This Hydrogen can then be used in adapted combustion engines, where it would lead to zero primary pollutants and no Greenhouse Gases.

Current Hydrogen fuel cell technology is moving away from the simple platinum catalyst processes towards more advanced concepts such as the proton exchange membrane (a Hydrogen atom's nucleus is just a proton) that will be more suitable for transportation purposes and, for instance, laptop batteries. The amazing growth in the Hydrogen industry across the rest of the World was commented upon, as demonstrated by the Hydrogen Fuel Cell Expo in Tokyo. Hydrogen's applications are far ranging, from the current fleets of buses to ships and providing the electricity - if not the combustion - requirements of aeroplanes by 2020.

In the **2004 Zuckerman Lecture**, **Hioyuki Yoshikawa** is noted to have said, 'Sustainable development is like a simultaneous equation – difficult to solve', and this equally applies to Hydrogen. Production, storage, utilisation, public acceptance and economics all have to be accounted for. The barriers are current production methods and vehicle on-board storage.

Today, the three main production methods are steam Methane reformation, partial oxidation of hydrocarbons, and water electrolysis. In obtaining Hydrogen from fossil fuels, CO_2 is released, so this method has marginal effects on trying to tackle the energy challenges faced. When obtaining Hydrogen through electrolysis, a primary energy source is required, and the effects this has on the environment need to be taken into account.

CO_2 capture and storage have been put forth as part of the solution to the above problem, but concerns remain about sequestration and it should be approached with caution: is it safe? What are the long-term problems? But the effect of Carbon Dioxide upon our planet is real, and the **Royal Society** have just released a report detailing the increasing acidity of the World's oceans due to a build up of atmospheric CO_2. It is clear from this, and more, that action needs to be taken now, before large and irreversible damage is done to the oceans. Alternatives to ground sequestration are being investigated in Oxford laboratories, including the possibility of sequestering CO_2 into hydrocarbon chains by reacting it with Hydrogen. These hydrocarbons can then be stored. This process is known as Carbon elaboration.

Hydrogen itself can be stored in many different ways: at high pressure; cryogenically; or in a solid-state material. This latter option is described as the 'perfect' storage medium, but the biggest problem associated with this method is the absorption and release of the Hydrogen, and that it requires certain conditions that currently make it an unfavourable option for a car that must possess a 300-350 km driving range. It can be said that, overall, large-scale storage is cheap, while on a small scale it is expensive.

In terms of transport, the current storage options are either gas or liquid. Hydrogen gas is stored under high pressure, at 350-750 bar, requiring fibre-reinforced composite containers. When storing it as a liquid, there is a 30-40% loss in efficiency due to the energy taken up by the liquefaction process, although this percentage is constantly coming down so could lead to a highly effective storage process very soon. However, gas and liquid storage solutions remain fairly bulky.

Nanocrystalline powders such as Mg_2NiH_4 and $LaNi_5H_6$, which are used in submarines, offer small, solid state, Hydrogen storage that also has the attractive feature of being reversible, i.e. once depleted they can easily be recharged with

Hydrogen. Unfortunately they are very heavy, especially relative to the Hydrogen energy carrier. The ideal elements to which the Hydrogen would be bound would posses a small atomic weight. After chemical considerations are taken into account, this leaves only a few choices left near the beginning of the Periodic Table. Finding the right combination of these light elements is the grand challenge of Hydrogen storage. Some recent solutions have been $Li_9BH_4(NH_2)_3$, which is made up of light elements (unfortunately the Hydrogen release is irreversible) and $LiNH_2$ (which if heated up leads to the release of ammonia).

In summary, the current vision for the UK is an incremental Hydrogen economy - analyses of demand allocations scenarios are currently underway. Hydrogen will initially be obtained from fossil fuels, and the CO_2 generated will be sequestered away, whilst the Hydrogen will be stored as a liquid or gas and used in combustion engines. This vision has a marginal effect on energy security. A step-change in the Hydrogen economy would require technological advances: specifically the capability to thermochemically ‘crack’ water; the solid-state storage of the Hydrogen; and the subsequent use of the Hydrogen in fuel cells to generate electricity. These advances would lead to a much bigger payoff in terms of both energy and security.

The question was posed that - if the Hydrogen is stored in the solid-state - is the release rate limited (from the point of view of fuelling a vehicle)? This was answered by acknowledging that this was indeed one of the challenges faced. The heavy Lanthanum Nickel Hydrides have very good kinetics, unlike some of the new, lighter materials. However, it is possible to use catalysts to speed up the rate of Hydrogen absorption and release. Some materials have the property of giving up the Hydrogen quickly, but are slow to regenerate. At the moment those with good kinetics tend to be too heavy.

It was quipped by an attendee whether the idea of storing Hydrogen as a fuel for combustion on a Jumbo Jet was a joke. In response to this it was stated by that engines that ran on Hydrogen had been investigated in the Tupolev ‘Cryoplane’. This raised the issue of just how safe would an aeroplane be with cryogenically stored Hydrogen on board. As an aviation fuel, Kerosene is hard to beat, but that Hydrogen has a place in providing the on-board electricity in an aircraft. Suffice it to say that inroads are being made on ground transportation at present.

It was asked whether the Carbon elaboration process could be further ‘elaborated’ upon. The Carbon sequestration method poses the danger of creating an underground stockpile of CO_2 gas. If lots of Hydrogen could be generated in a sustainable manner, through clever catalysis this could be linked with CO_2, and lead to the production of diesel. So in effect the CO_2 is being recycled by elaboration in a hydrocarbon chain.

1.3 Automotive demand for bulk hydrogen, John Hollis, BMW

The **Automotive demand for bulk Hydrogen** was then addressed by **John Hollis** from **BMW**, under the theme **Hydrogen, Fuel for Future Propulsion Technologies**. He went on to talk about how BMW is looking at Hydrogen in this context. Over the years political focus has moved from air quality to climate change. Security of supply is now an issue too. In terms of the technological advances associated with air quality, in European countries such as Germany or the UK, despite an increase in driving, the concentration of all pollutants, carbon monoxide, sulphur dioxide, nitrous oxides, benzene and particulate matter have all dramatically reduced in the last thirty years. The focus of attention has moved to Global Warming and CO2 emissions.

Currently, there are limited international political indicators in terms of quantifying practical CO2 targets. BMW's interpretation is that there needs to be a long term reduction of around 70%.

Since 1998, cars in the European Union have been subject to a Voluntary Agreement to reduce the amount of carbon dioxide they emit and considerable progress has been made. But there are limits as to what can be achieved whilst using carbon–rich fossil fuels. Even with substantially improved engine technologies, over a period of decades, improvements are likely to be eventually negated by growth in traffic.

If Carbon outputs are to be reduced then it is logical to consider using fuels without carbon. Hydrogen is such a fuel. The strategy at BMW is that if a 70% reduction in CO_2 is required then we must think about hydrogen as the long term fuel. After more than twenty five years of research and development, BMW has now launched a production car with an internal combustion engine running on liquid hydrogen.

By obtaining liquid Hydrogen through renewable energy sources it is expected that an 80% reduction in CO_2 can be achieved. CO2 being only required for the manufacture of the equipment to produce the hydrogen and virtually none being created in vehicle operation.

In the short term, Hydrogen will be most cheaply obtained from natural gas. In the medium term, an environmental improvement can be achieved if such Hydrogen were progressively mixed with Hydrogen from renewable sources as capacity is developed.

BMW has taken the internal combustion engine, which has been under development for over a century, and converted it to run on hydrogen. It has produced a bi-fuel car, running either on conventional petrol or Hydrogen, in order to give it independence during a period when the hydrogen infrastructure is being built up. The Hydrogen is stored as a liquid, but is heated up to a gas before it is combusted in the engine.

A comparison of internal combustion engines with fuel cell vehicles was shown, indicating advantages and disadvantages of each technology. BMW believes that both technologies will have their uses in the future. When it will be possible to use pure hydrogen in the internal combustion engine (when there is enough infrastructure for mono-fuel operation), BMW expects to make very significant improvements in the efficiency of the engine.

The **BMW H-7** has had some modifications to enable it to run as a dual-fuel car. Running on petrol, the engine has a direct injection system, whilst on hydrogen, a parallel injection system mixes the fuel with air in the inlet manifold. Parts of the chassis are made from lighter materials than standard to compensate for the weight of the second (liquid hydrogen) tank. The vehicle develops 240 hp, and can be driven with similar characteristics as a petrol-driven car, at up to 140mph (speed electronically limited).

There are many infrastructure changes that have to be put in place for a successful Hydrogen economy to function. A demonstration project is currently underway in Berlin, with fuelling for both internal combustion-engined vehicles and fuel cell vehicles, storing the on-board hydrogen as liquid or as a compressed gas. BMW has chosen to use liquid Hydrogen as this leads to a smaller fuel tank and a greater range.

The BMW H-7 project uses technologies that are currently available. The car is being treated as a normal production vehicle. BMW is going to produce 100 vehicles which will be used for demonstration purposes. The purpose of the H-7 is to change the current mindset about the practicability of using hydrogen as a fuel.

Nevertheless, the Hydrogen-market potential is likely to take several decades before it will come to fruition. This will depend on the urgency with which Global Warming is viewed and the impact that CO2 is considered to have on global warming.

A questioner observed that if a car stored its Hydrogen cryogenically, there would be constant loses of Hydrogen as it boils off. It was noted that the tank was highly insulated, like a super-thermos flask – if it was filled with hot coffee, it would take 80 days for the coffee to cool down sufficiently to drink. Currently there is an extended period before any boil-off takes place and there are a number of future developments available that would extend this period even further. Additionally BMW has fitted a catalyser to convert any boil-off hydrogen to water vapour.

The inquiry was made that if Hydrogen is to be obtained from water, where would it be generated? Offshore? In a Hydrogen economy there will be many thousands of different places where transport will require access to the fuel – perhaps the Hydrogen will be generated offshore and shipped to the regions where it is required.

1.4 Political consensus on climate change, Sir Crispin Tickell

An after-dinner speech was given by **Sir Crispin Tickell** on the subject of how to gain political consensus on climate change. Sir Crispin began his speech with reference to the fact that he had just returned from a conference in the United States whose theme was the future of energy systems of all kinds in the next thousand years. His own view is that energy is unlikely to be the main problem facing the human species on the assumption that it still exists. Rather it will be human numbers, and the vulnerability of cities.

The conference looked into many exotic energy possibilities, including: hydrogen generation for fuel cells from coal gasification; solar energy both terrestrial and from space; geothermal; tide and wave, with new seawater technology; nuclear, whether fission (especially pebble-bed) or fusion (ITER). He mentioned that hydrogen was not the most popular source of energy at the conference, not least because of the amount of CO2 normally required to generate it, and the problems of storage. Most attendees thought that fuel cells could be powered in other ways.

Sir Crispin then went on to describe how the whole debate about climate change with its implications for energy policy has been transformed by:

- the Stern review of 30 October 2006
- the IPCC science report of 2 February 2007
- the IPCC impacts report of 6 April 2007

He pointed out that the forthcoming Energy White Paper would join this list. He added that in the meantime the Government has published a Climate Change bill, and is raising the general issue in the UN Security Council. The UN Secretary General recently spoke of the possibility of holding "a high level meeting" on climate change during the General Assembly in September.

Sir Crispin then turned to climate change referring to the fact that the current epoch has been well labelled the Anthropocene:

- climate destabilization rather than climate change: from weather patterns world-wide to acidification of the oceans, to sea-level rise, to extinction of vulnerable species;
- the effect on humans with the likelihood of new threats to health, and substantial increase in migration, in the northern hemisphere mostly from south to north.

He pointed out that Britain and northern Europe generally may be relatively privileged. At present Northern Europe already faces more of a problem over adaptation to change than over mitigation of it for future generations. Yet somehow the transition from a high to a low carbon economy needs to be made. So the race is on to look at, and invest in:

- the various forms of renewable energy
- energy from nuclear sources
    - fission, and the case for pebble-bed (requiring only 9% of uranium 235 and with heat levels capable of generating hydrogen)
    - fusion driven by theoretically limitless sources of supply (tritium and deuterium)

Sir Crispin drew his speech to a close by setting out what could be done:

Internationally:

- Kyoto 1 & 2
- the Gleneagles process
- management of the likely security problems through the Security Council

All this may lead to carbon cap and trading, possibly with sanctions against offenders as in the WTO. A comprehensive solution would be to create some special international body for the purpose, preferably a World Environment Organization to act as an umbrella for the numerous environmental agreements already in existence.

Nationally:

- each government has its own responsibilities, particularly governments in industrial countries who unwittingly created the problem in the first place. They have to set in place a sensible market system within the framework of the public interest, with incentives and disincentives to match;
- in fact business and industry are already getting the message, more in some countries than in others;
- we have to recognise that new technologies are important, but can never solve the problem on their own;

Sir Crispin ended his speech with mention of the Virgin Challenge Prize, for which he is one of the judges: US$25 million for commercially viable methods of extracting greenhouse gases from the atmosphere.

Day 2 – Thursday 12th April

Professor Jim Skea, Research Director of the **UKERC**, introduced the second day of the conference on this “utterly fascinating” topic, held in **Worcester College**, Oxford. The idea of an ‘energy island’ reminded him of **IIASA** (International Institute for Applied Systems Analysis, a research organisation based in Austria) meetings in the 1980s. The concept of energy islands was promoted as early as 1969 by **C. Marchetti**, who envisioned as coal, oil and gas production peaked they would be replaced by nuclear fission, and eventually by fusion. Originally at the **Joint Research Council** in Ispra, Italy, Marchetti moved to **Euratom** where he invented the idea of the Hydrogen economy. Thirty-eight years later we are moving towards the reality of that vision.

1.5 Why fusion for hydrogen? Dr William Nuttall, University of Cambridge

Why fusion for Hydrogen? was addressed by **Dr William ‘Bill’ Nuttall** of the **University of Cambridge**, who noted that the work he was about to present was undertaken as part of the **Cambridge-MIT Energy Security Initiative**, and supported by the European Commission’s FP6 project Coordinating Energy Security of Supply Activities (CESSA). The driver behind the pursuit of Hydrogen as an energy carrier is climate change. The decarbonisation of electricity generation, while not easy, is fairly straightforward. It is transport that poses the greatest challenge. Transport consumes 39% of the global energy supplies, around 75 million barrels of oils a day from the World’s one million oil wells.

Hydrogen is an energy vector, not a resource (or fuel), but rather a pure energy carrier like electricity. As such it requires an energy source to create it. Today, Hydrogen is primarily obtained from the steam reformation of methane. Relying on methane is not an improvement in energy security and unless the process is coupled to Carbon Capture and Storage it has little positive impact on climate change.

Scientific American describes fusion as possessing huge amounts of potential. In their 2006 feature on alternative energy **Joan Ogden** described the high hopes for Hydrogen production through electrolysis, with details of the supply chain showing tankers of liquid Hydrogen being transported or pumped through pipes. In the long term the magazine discussed the possibility of using nuclear process heat to generate Hydrogen.

A possible solution is the production of Hydrogen through the high-temperature thermochemical cracking of water, which requires a temperature of about 800°C (if a Sulphur-Iodine cycle is used). This heat could be achieved through focusing mirrors in desert regions, or through nuclear fission or fusion elsewhere. A project developer would have to think carefully about the public perception of having boiling Sulphuric acid next to a fission reactor, while no such problem would exist for a fusion plant. This marriage of fusion and Hydrogen was inspired by the work of **General Atomics**.

With regards to the economics of the project, the kind of monetary risks involved are similar to those encountered by the oil majors in their daily business. Unlike an electricity company for instance, oil majors are not risk-averse. The previous day, Sir Chris Llewellyn Smith said it would take upwards of forty years before fusion was capable of providing base load electricity. Generating electricity comes with significant challenges: the fusion device must operate in the steady-state with only short shutdown periods, all this while still maintaining high reliability. The decarbonisation of electricity generation can come from other means. All these competitive challenges can be avoided if fusion instead concentrates on the generation of Hydrogen. For instance, if a fusion power plant trips and shuts down – say from a false Tritium release alarm – suddenly 2.0GWe have been lost from the grid, but the plant requires 400MW from somewhere to restart.

In the UK there is insufficient solar radiation to drive a solar furnace. With regards to the idea of using fission to provide the heat to generate Hydrogen, fusion reactors have more intrinsic safety and are cleaner than even Generation IV fission reactors. They would be much more easily embraced by a safety-regulator. A 'Fusion Island' producing Hydrogen has excellent security advantages – it just needs workers, a little electricity, and perhaps some Helium (but more on the latter of those three later).

The Fusion Island vision is that the project might be achieved 10 years before fusion is ready to take on the base-load of electricity generation. The Hydrogen could then be shipped in cryogenic liquid form. The 'island' could easily be a platform. Operating offshore has benefits. The product could then be sold, and the ships that transport it powered by off-gassed Hydrogen.

Dr. Bartek Glowacki's (University of Cambridge) idea of using liquid-Hydrogen cooled MgB_2 (**Magnesium Diboride**) for the superconducting magnets was then introduced. These operate at 20K, much warmer than the **Niobium-Tin** superconducting magnets conventionally envisioned. The MgB_2 would require no He (which is obtained from natural gas). Some Hydrogen would also be kept on-site, and could be used with a gas turbine to power the liquefiers, or to charge up flywheels to fire the next plasma pulse.

The link was then made to the willingness of industry to invest in the Fusion Island project. Compared to fusion for electricity, with fusion for Hydrogen reliability is not such an issue. There would be no problem with the fusion device operating in pulsed mode. The by-product of the water splitting, liquid Oxygen, could also be sold. The oxygen could be shipped out to be burnt with fossil fuels – oxyfuel combustion – and would of course be shipped in a separate tanker to the Hydrogen. Oxyfuel combustion of fossil fuels leads to lower NO_x production and a pure CO_2 stream (therefore an amine cycle is no longer needed to strip the CO_2 from the fossil fuel combustion products).

There is also the possibility of making and selling ammonia (a potential Hydrogen carrier).

The Fusion Island project needs to fit in with some sort of business strategy. The benefits are that there is no need to establish exceptional reliability. The announcement that DEMO may be built soon is exciting in terms of the project. Real Options techniques may be incorporated into the design to make it more attractive for business. The groundwork has already been done by **M A Cardin** (MIT). It is hoped to work on the project for the next 3 years and then take it forward. The oil majors are used to the type of risks involved, they live work and deal with hostile environments.

In summary, Hydrogen is arguably the best first use for fusion. It is easier, faster, cheaper and better matched to market pull than electricity-based ambitions. Also Fusion will be arguably one of the best ways to make hydrogen being large-scale, safe, clean, secure and suitable for all locations. Fission could also be used to generate Hydrogen. Many of the attendees would be aware of how safe fission is, especially Generation IV, but safety regulators might have a different opinion when fission is combined with challenging chemical processes. In terms of ‘Princeton Wedges’, fusion for Hydrogen has a lot of potential in bringing down the amount of CO_2 released. Dr. Nuttall concluded by thanking UKAEA Fusion, CESSA, CMI, The Engineer magazine, and the EEEGR for its 2006 Innovation Award (Third Place).

1.6 Thermochemical water-splitting and the US nuclear hydrogen programme, Lloyd Brown, General Atomics

Dr. Lloyd Brown from **General Atomics** (GA) then discussed **Thermochemical water-splitting and the US nuclear Hydrogen programme**. The focus was on the Sulphur Iodine cycle for the thermochemical splitting of water, work on which has been going on since 1979. There were three main topics. Firstly the nuclear Hydrogen process and how fusion fits in. In 1972 the Gas Research Institute made projections that by the year 2000 there would be upwards of a thousand fusion power stations. Things did not quite work out that way, but the market is still there.

The ‘other-way’ of obtaining Hydrogen is electrolysis. Using a LWR (Light Water Reactor) the process is approximately 24% efficient, which increases to 36% for a high temperature reactor. The thermochemical splitting of water on the other hand offers efficiencies of up to 50%. The two methods can actually be combined, high-temperature electrolysis and hybrid thermochemical cycles. The most efficient processes involve high temperature reactors, whether they are fission or fusion. The US Department of Energy (DOE) has been looking at coupling GIV Fission electricity production to Hydrogen generation.

The United States has many Hydrogen production methodologies. Using fossil fuels leads to the production of CO_2 that could be sequestered away underground. The Solar Hydrogen Generation Research project looks at harnessing the Sun’s heat to generate Hydrogen. There is also the National Hydrogen Initiative, which brings together national laboratories and universities. High temperature fusion has the potential to be more effective, but possesses unique problems such as Tritium and high-energy neutrons.

The GIV fission modular Helium cooled reactor concept was then considered as a means of generating heat to produce Hydrogen. Operating at higher temperatures, the plant’s efficiency could increase to over 47%. Derivatives of this concept, such as the passively safe Gas Turbine Modular Helium Reactor (GT-MHR), have a process temperature of 900°C, suitable for thermochemical Hydrogen production. The competitor to this reactor is the Pebble Bed Modular Reactor (PBMR), capable of 2-300MW_{th}. The phrase ‘bigger is better’, often applied in this conference to fusion, does not apply to the PBMR as the passive safety features put a limit on the size of the reactor.

The turbine section of these nuclear fission power plants could be replaced with an intermediate heat exchanger, which could link the reactor to a Hydrogen production plant. The next generation of new (fission) plants could demonstrate Hydrogen production through the hybrid method of thermochemical ‘cracking’ and high temperature electrolysis. If 60 MW_{th} of heat were available for Hydrogen production, this would lead to 20 tonnes of the product produced per day. The Hydrogen produced must meet fuel cell standards – that produced from fossil fuel tends to have a high content of carbon monoxide.

High temperature electrolysis is also known as steam electrolysis. Hydrogen gas is produced, and with some extra work oxygen gas can also be extracted from the electrolyte. The largest ceramic heat electrolysis cell is currently $10cm^2$, so some 5 million of these would be needed for a Hydrogen plant to be practicable, which is much more than is present in current setups. In standard electrolysis the platinum electrodes require a high over potential, so more electricity is required to operate them than would be expected. High temperature electrolysis on the other hand, without platinum electrodes, has the potential to function with much less electricity.

The hybrid Sulphur cycle splits Sulphuric acid into water, Sulphur dioxide and oxygen. Then, via low temperature electrolysis, the water and Sulphur dioxide are recombined to give Sulphuric acid and Hydrogen. This is simpler than pure thermochemical electrolysis, using much larger (and more expensive) electrolysis cells.

The Sulphur-Iodine cycle was invented at General Atomics in the 1970s, and involves three chemical reactions. Water, Sulphuric acid and Iodine are reacted together to give Hydrogen-Iodine and Sulphuric acid. This involves the well-known Bunsen reaction. The challenge is how to separate the Hydrogen-Iodine from the Sulphuric acid – this requires energy. By including an excess of Iodine in the reactants, the products will enter a two-phase regime from which they can more easily be separated. Unlike traditional electrolysis, the Sulphur-Iodine cycle reaction rate depends on volume, not area, so scales up more efficiently. Investigation into this reaction has proceeded intermittently over the past thirty years, and between 1974 and 1986 GA performed plant cost estimates using fission, fusion and solar power as the heat source. Indications are that in the near future the Sulphur-Iodine cycle will be best matched to high-temperature Helium cooled fission reactors. Solar power is capable of using solid reactants that are unsuitable for nuclear reactors.

The next step is an integrated engineering demonstration with appropriate engineering materials, operating at 20-80bar. These high pressures are required because if it were to be coupled to a high temperature Helium cooled reactor, which operates at 70 bar, there must be minimal pressure difference. An investigation rig is due to be assembled in San Diego this Summer, with hopefully results by September 2007.

1.7 Thermochemical processes, Prof Ray Allen, University of Sheffield

Professor Ray Allen of **Sheffield University** then discussed the broad subject of **Thermochemical Cycles**. He began by pointing out that what was about to be covered complimented the previous speaker's presentation, and the acknowledgement was made that General Atomics has been working on thermochemical cycles for quite some time. Firstly, the macrodynamics of Hydrogen production were to be discussed, followed by an evaluation of the **HyTech** collaborations on the Sulphur-Iodine process and then a few slides on behalf of **Westinghouse** regarding their Hybrid-Sulphur (**HyS**) process.

From the thermochemical perspective, it does not matter where the heat for the process comes from; the greater concern is the actual generation of Hydrogen. All that is required is a feedstock of chemicals and input energy. The decision criteria on which the energy sources are chosen have to be considered: the reduction in CO2 achieved; the land use; costs and efficiencies. Not forgetting the social acceptability, the security of supply and the technology available. These variables have to be weighed up with respect to the efficiency of Hydrogen production. While heat from nuclear power never seems to make the top of the list, it is still a strong contender. The conclusions of the macro-thermodynamic analysis are that that the choice of energy source depends on what value system is used.

The HyTech collaboration come with a big push from the **CEA** (a French government-funded technological research organization), which is mainly looking into the Sulphur-Iodine (**SI**) process, but is also considering HyS to some extent. The first reaction of the SI cycle runs with an excess of Iodine and water, leading to better thermodynamics and resulting in the products forming as immiscible layers. Before this process can be realised fundamental chemical engineering milestones must be achieved and the funding be obtained.

A European reference flow sheet (or process flow diagram) has already been established by the CEA, and they have calculated lower efficiencies than have been quoted elsewhere in the literature. The CEA has also taken an initial look at the coupling of the SI process to an energy source - analysing the safety aspects and the implications of an intermediate heat exchanger - as well as performing an external safety assessment. It has been determined that a low Hydrogen cost is not necessarily associated with a high efficiency - the area of the heat exchanger and the temperatures applied also contribute significantly.

The conclusions made were similar to those of Lloyd Brown: an international collaboration is looking at the thermochemical SI cycle and in terms of research the UK is catching up with the US. Although it is a complex process, the SI cycle should be able to produce Hydrogen efficiently.

The Westinghouse HyS process was then briefly reviewed. The Pebble Bed Modular Reactor (PBMR), as mentioned by **Sir Crispin Tickell** in the after-dinner speech the previous evening, is envisioned as providing the process heat for the Hydrogen plant, and an integrated flowsheet has been developed. There are many collaborators on the pebble bed project, including South Africa. The HyS process is a simpler method, with fewer steps and fewer unknowns. Overall, the sustainability of Hydrogen production through thermochemical processes has not been proven – and fusion may well be a step towards this. Success in the future depends upon further R&D.

1.8 Fusion hydrogen plant concepts, Dr David Ward and Richard Clarke, UKAEA Culham Division

The **UKAEA**’s **Dr. David Ward** and **Richard Clarke**, a fusion scientist and a chemical engineer respectively, then discussed **Fusion as a Future Source of Hydrogen and Other Products**. David Ward’s work involves paper studies of the social and techno-economic aspects of fusion power plants. David began by reiterating Nuttall’s assertions that fusion matched well with Hydrogen production. The need for high-temperature operation seems to be the most important part, and it must be kept in mind that the main fusion fuel, Deuterium, is an isotope of Hydrogen. There are also enormous reserves of Lithium - the average rock contains enough Lithium to have 20 times the amount of energy as coal, if put to fusion uses. Additionally, the costs of the fusion project will be reduced through R&D.

It was pointed out that, as Sir Chris Llewellyn Smith said the previous day, with regard to power plant cost comparisons fusion could have infinite error bars, as it might not work. The results of cost estimates suggest that fusion will produce electricity in a sensible price range, but the figures generated should not be taken too literally. The audience was reminded that the JET project led to ITER, and ITER will lead to DEMO, which has currently been designed with superconducting magnetic coils.

The key concepts of the European Power Plant Conceptual Study (PPCS) were then discussed. Outside of the vacuum vessel of the device is the ordinary World, which is well known and understood. Inside is the fusion World. Superconducting magnetic coils will be required, which are complex to manufacture, but the costs are continually coming down. At the base of the plasma chamber is a divertor to draw out the Helium ‘ash’, a sort of exhaust system for the fusion machine.

The PPCS investigated four designs – A, B, C and D – going from current technology at one end to more exotic and futuristic machines at the other. PPCS-A is based on technology that may be too old, the design being rather conservative. It would only be useful for generating electricity that could then be used in electrolysis. ITER will be testing some of the ideas of B, C and D. However, B still has problems with coolant pumping power. Model C is dual cooled by liquid LiPb and He, with SiC/SiC inserts, and operates up to 700°C (just within the range where Hydrogen production efficiency in the thermochemical cycle begins to pick up). The final of the four, Model D, is not ‘science-fiction’ as it has been referred to in the past – admittedly, much work needs to be done on the engineering side, but it would better be described as being manufactured from aerospace materials, using SiC/SiC as the main material.

Is enough being done? David Ward gave his personal take on Energy R&D. The spend on renewables is very small (less than 2%) in relation to what is spent in the energy market, despite what the public perception might be. However the global public sector spend on energy R&D is much lower still at around 0.2% of the energy market. It is unlikely that such a very low level of R&D will transform the global energy market to a low carbon system.

Richard Clarke then raised some ideas for the forthcoming discussions, beginning with integrated energy cycles. In terms of a Hydrogen plant associated with a fission or fusion device, the Oxygen produced could be used in clean coal combustion cycles, and the Hydrogen used in transport. Thinking downstream, the Hydrogen could be stored as ammonia, for which there is already a well-established global market and safety infrastructure. The company **Amminex** have developed Hydrammines^{TM}, where ammonia (NH_3) is absorbed into base-chloride molecules for storage. These can then be packaged in a way that exceeds the US DOE 2015 H_2 energy density targets, and are also safe to come into contact with. This is an alternative route of getting bulk Hydrogen into the market.

Argonne National Laboratory has looked into the practicality of a solids-based copper-chlorine thermochemical water splitting cycle working at 550°C. These efforts should be monitored because as things stand the 800°C required for SI requires PPCS model C, the technology for which is not yet available. **Garry Voss** of the UKAEA has developed a divertor that uses solid beads to remove the heat flux incident upon it, illustrating that solids can indeed be handled at high temperatures. Also, the **Australian National University** has investigated NH_3 based solar energy storage, and has planned a $10MW_e$ demonstration plant. Richard Clarke then shared a ‘back of the envelope’ concept on how to combine NH_3 with Fusion Island. Ammonia could be the product that is shipped, being synthesized from Hydrogen with nitrogen separated from air - although this latter step has not been investigated fully.

In conclusion, fusion has many desirable environmental and safety characteristics, and includes the potential for high temperature operation. Energy islands based on water splitting and ammonia should certainly be discussed further.

Before the break-up for the plenary session a brief question and answer session was conducted with the speakers from the morning’s talks. It was commented that the EU had estimated transport related Hydrogen demand would begin properly by 2020 – so, have there been any calculations of the volume of Hydrogen that Fusion Island could produce? The response was made that it depended on the scale of the SI process and the size of the Tokamak, but an estimation had been made of 100,000 tonnes of Hydrogen gas (H_2) produced per year from a $1GW_{th}$ plant.

It was recalled that more than one speaker was not concerned with where the heat came from, whilst it had also been said that the quality of heat varies between different reactors. How are the up-stream and down-stream linked? It was stated that answering these questions was one of the aims of the meeting. If Hydrogen is considered important, then perhaps the fusion program can change direction to provide devices that deliver the right temperatures and quality of heat.

If fusion had the capability of delivering the heat, there would be the opportunities for synergies with other industries. It was added that, from the academic perspective, it is better to operate at higher temperatures. The efficiency of the SI reaction varies very little between 700 and 1000°C, but if fusion operation was at low temperatures then it would be necessary to use standard electrolysis - in which case the fusion plant may as well just make electricity.

The issue of fusion in the context of the fission-based nuclear industry was brought up. The evolution of technology leads to the implementation of infrastructure. The technology should be made to work for electricity first, and then demonstrate Hydrogen production if it is considered viable. It was replied that the horizons of fusion are far ahead, so it could still be designed to deliver something other than electricity, and it was further argued that if Hydrogen was produced straightaway instead of electricity there would be a market for it – the oil industry needs it to make diesel, and they would be willing to buy a functional nuclear reactor with an integrated Hydrogen plant if it could be proved to run economically.

It was asked: if Hydrogen is produced, can it not just be burnt? It could be combusted in Hydrogen generators to make electricity for developing countries - wouldn't this approach have a large impact globally? In response it was said that Hydrogen is a premium product like oil, and while oil was once burnt for power generation it is now put to better uses, as Hydrogen would be. However, burning the stored Hydrogen could be used to generate electricity in periods of intermittency. In conclusion, it was added that there is little point using fusion to generate Hydrogen if the Hydrogen is then later used only to generate electricity.

1.9 Breakout Session 1: Nuclear Heat: which machines match to Hydrogen? Professor Joe Minervini from MIT, who introduced the key questions, chaired this session. Notes were taken by Michael O'Brien, UKAEA.

1. Is there a cycle T that matches TCWS to fusion efficiently?
2. Are the safety aspects of Hydrogen and fusion compatible?
3. With LH_2 and H_2 as working fluids, are fuel cells and LH_2 cooled magnets possible? Is it feasible to have an energy island?
4. Is cyclical operation a help or a hindrance to the achievement of an early fusion-Hydrogen plant?
5. What machine features would change (shape, divertors, stress…)?

Beginning with the first key question, one participant commented that he was not too happy with some of the fusion device temperatures that had been mentioned so far, and it should be noted that there is little gain in efficiency between 700 and 1100°C. At the lower end a larger reactor is required, leading to more exotic materials, not just a bigger heat exchanger. Although the pure Sulphur-Iodine cycle is not a Carnot process, it is limited in terms of overall efficiency by the top temperature achievable.

It was further mentioned that at 700°C, bigger SI cycles are required, which increases the cost. Using oxygen-separation membranes, the equilibrium of the reaction can be shifted to the right, which would help increase the efficiency of lower temperature operation.

To this it was added that from the fission perspective the High Temperature Gas Cooled Reactor (HTGCR) was capable of operating at 1000°C, although there are materials problems associated with this. South Africa is developing the Pebble Bed Modular Reactor, which is achievable in terms of materials as it operates at 900°C. The Very-HTGCR, at 1500°C leads to different materials issues still.

The question was raised whether the temperature really mattered. In 10 years time the Canadian gas market will have collapsed. Hydrogen will be required to turn the oil from the tar sands of Alberta into diesel. Fission or fusion could provide power to generate the Hydrogen needed.

The comments made so far about fusion were interpreted by one participant to mean that the technology was far into the future, in which case Hydrogen would have to be obtained from hydrocarbons and the CO_2 produced sequestered. Fission could be used to fill the gap until fusion becomes a commercial reality. The temperature is only a problem if the fusion issue is forced through.

According to another attendee, discussions with oil companies had indicated that they want Hydrogen now, but they are not willing to buy the technology and would rather go to a merchant provider. Nuclear is an option, but it is up against gas, which is cheaper.
It was reiterated that the gas market is going to be in significant trouble 10 years from now. In response it was noted that the oil industry wanted a solution that used current technology.

Turning back towards the question of fusion, it was acknowledged that the temperature is a serious challenge. The other questions that needed to be dealt with were the impact of pulsed operation and the magnetic technologies used - bearing in mind the costs. The Fusion Island project had been looking into ways to fund research into answering the question of temperature over the next three years.

So far only steady state fusion power had been considered, what about pulsed operation? It was revealed that heat cycle changes could lead to instabilities in the system. This being a possibility, the heat exchanger is required to stay at a constant temperature. But how ‘steady’ does steady state have to be? In order to answer this question the heat transients at start-up and shutdown need to be analysed. However, cycles of at least a few hours would be necessary, but the requirements are different depending on whether the SI or Westinghouse Hybrid-Sulphur cycle is used. It is important that the Iodine in the cycle is not allowed to cool down.

It was pointed out that high-temperature salts could be used to maintain the heat in the wall - the bigger problem was not having the high temperature output.

PPCS Model C, which combines liquid Lithium-Lead and Helium cooling, would be suitable, but is not close to being built. In response it was pointed out that neither are PBMRs. The comment was made that if we want to match the fusion process to Hydrogen production, they we need to think of the energy spectrum not just the temperature. There are many varieties of chemical plasmas that could be reacted in a chamber, and research is still at an early stage. It was further pointed out that continually cycling the vessel's temperature would lead to fatigue and possible material failure, so it may be necessary to maintain the temperature of the walls by injecting heat to keep the components warm between cycles.

It was asked that the timescales of the various technologies be kept in mind, as it will take a long time to get a fusion reactor into the market. If we are serious about Hydrogen, it was proposed our first option should be nuclear fission, as we have that technology now. The Hydrogen economy will continue growing incrementally, so we must start straight away in order to contribute significantly in the future. One attendee agreed with Sir Chris Llewellyn Smith that designing and building DEMO now, even though it would not be efficient or optimised, would be an excellent way of proving fusion worked. Another participant suggested fusion could learn a lesson from fission – in order to get the HTGR built they simply froze the design and 'got on with it'. It was hypothesised what would happen if a Hydrogen plant was built around fission heat quality - would this block out the option of using fusion in the future?

Fission power still suffers from poor public perceptions of safety, so it may be difficult to combine new nuclear fission build with the linked construction of a Hydrogen chemical plant. Generation III nuclear fission power for electricity, while winnable, will be difficult and controversial and we should not forget that fact. Those matters will, of course, come long before issues relating to nuclear Hydrogen. The counter was made that fusion requires fission to win the minds of the public on the wider perception of 'nuclear' power. To this it was added that the UK public perception is based on ancient history, and that the public must be told about the future models and their safety characteristics – progress seems to be going ahead in other countries but not in the UK. All this was put in context by one attendee who said that events – climate change and fuel prices – would overtake the public perceptions of safety. It was acknowledged that in a changing World economy the fusion project could be eliminated, whilst fission was still capable of running for hundreds if not thousands of years.

It was reiterated that the government was looking at having Hydrogen vehicles seriously implemented by 2020. Robust work on fuel technology is required. What will drive fusion research? Will it be electricity or Hydrogen? If the Hydrogen project is pursued by other means now, fusion will eventually have to compete. The session was reminded that the conventional trajectory is to have fusion generating low CO_2 base-load electricity for the grid by 2050. Any extra energy generated off-peak could be used to produce Hydrogen. An alternative outlook is that Hydrogen could be an early goal – and if that were the case, what would such a fusion device look like?

The focus then turned to funding, and the likelihood of obtaining private investment. A conversation was recalled regarding the oil companies: if they invest a billion dollars in a project, they are probably expecting to get ten billion out in just a few years. The subject then turned to the way the Hydrogen is stored. The technologies that are in operation now will dictate the infrastructure that is deployed. What will an efficient fusion machine capable of generating Hydrogen look like? How does it compare to the steam-reformation method? It was pointed out that pulsed fusion machines are very different to steady state.

The fusion program is far away from being technically developed, so the issue of Hydrogen is important in deciding the direction fusion research takes.

One attendee speculated whether with the current emphasis on climate change, perhaps fusion could latch on to the political will that is being generated. Another participant shared the opinion that they saw no carbon-neutral route to Hydrogen production in the near future. The UK currently has a carbon capture and sequestration (CCS) program underway, so is interested in low-carbon, not just carbon-neutral, technologies. The 'end game' is a Hydrogen-fuel cell vehicle. It was added that sequestration is a step along the right path, and certainly in-line with the Princeton Wedges portfolio approach to the energy challenge. As things stand, the timescale for moving to a Hydrogen economy is shorter than that for fusion.

1.10 Breakout Session 2: The Products: What Should the Plant Produce? This session was chaired and introduced by Miles Seaman from IChemE and notes were taken by Anthony Webster, UKAEA.

In answer to the question: What should come out of the plant, the group felt it important not to forget it must be something there is a market for. The opinion was expressed that over the relatively long time-scales for fusion development, we would need to keep an eye on what the public and market would want.

Regarding Hydrogen as a potential product

It was felt there was no real market for a Hydrogen economy at present, and that government legislation would be required for one to develop. It was noted that there were problems with Carbon trading, so careful legislation would be needed. In addition, there would be a need to use fossil fuels to "kick-start" the hydrogen economy, before alternative energy sources become available. The difficulties in starting a Hydrogen economy raised the question – will there be a demand for Hydrogen?

Regarding Ammonia as a potential product

There were strong concerns over the safety of Ammonia as a product. It was felt that Hydrogen was far safer, for example if Hydrogen leaks it will rise – which is not the case with liquid Ammonia. It was suggested however that work is being done in industry to find safer transportation methods for Ammonia.

Other potential products

Due to time constraints, there was not much thought given to other potential products.

Assuming the existence of a Hydrogen market/economy, it was felt that:

- It would need to have been kick started by Hydrocarbons.
- It would need synergies with oil/gas companies, e.g. for the provision of plant, infrastructure and investment.
- Regarding liquid Hydrogen as a product: Liquefying Hydrogen is expensive, probably because it typically uses 30-40% of the energy to liquefy and transport it – it was suggested that integration of processes might improve this, but nonetheless there remain serious concerns about whether it would be economically viable to do so.

- Hydrogen is already piped in some areas, and Hydrogen fuelling stations are also already used in some places. So is there really a need to liquefy it?

1.11 Breakout Session 3: Alternatives - other routes to bulk hydrogen. This session was chaired and introduced by Professor Geoff Hammond from University of Bath and notes were taken by Kate Lancaster, Rutherford Appleton Laboratory.

Fusion technology may not be online for 30 years. Alternatives to fusion include solar, wind, biofuels, hydroelectric and fossil fuels. Hydrogen production is currently linked with carbon – a solution is needed without reliance on carbon. The first need for hydrogen may be the hydrocarbon economy. Bulk production must be policy led.

Fusion must be proved to work! As well as demonstrating the capacity to produce hydrogen. Laser fusion may lend itself to hydrogen production over tokamaks.

The biggest current challenge is production through fossil fuels which is associated with the problem of carbon production unless the CO_2 is sequestered. This will be the case for many years to come (based on the rate of fuel burning today).

There may be opportunity to combine fusion for bulk hydrogen production with the local generation technologies. Intermittancy is not a problem for hydrogen generation by renewables.

The strongest challenger to fusion at present is gas reformation and carbon capture, and possibly solar technology. There may be an intermediate stage to hydrogen production which clears out non-viable technologies.

There is currently competition amongst existing gas companies using steam reformation – this could result in a new market.

Solar technology could possibly fragment energy and hydrogen production to a small local scale, resulting in a small energy island. **Dr. Christian Sattler (German Aerospace Centre, DLR)** gave a brief presentation which explained that solar heat can be used to produce hydrogen through various technologies:

- Parabolic troughs – heat up 390 degrees
- Central receiver (molten salt) – up to 565 degrees
- Atmospheric air receivers – up to 750 degrees so far
- Pressurised receivers – 1045 degrees. This technology is good up to 1100-1200 degrees after which there are material limits

Solar towers represent the only viable solar technology for hydrogen production – this technology is amenable to being scaled up and is close to commercial usage.

Cost is crucial, a key issue being who will pay for development of new technologies. People may not invest in the new technologies unless there is a market for it. There needs to be an examination of the costs of all techniques, taking carbon production into account. The long timescale associated with fusion may mean that there is no financial backing.

One thousand 1GW plants are needed to be viable – these will need to be funded by government as private companies are unlikely to invest in this. This partly depends on where the market is when fusion becomes available – it will be an advantage if the market is mature.

1.12 Plenary discussion: How fast could fusion Hydrogen happen? Professor Jim Skea from UKERC chaired this session.

Jim Skea began by comparing the upcoming short film to Al Gore's documentary 'An Inconvenient Truth'. **Dr. Bartek Glowacki's**, mini-film, 'A Certain Truth' went on to discuss the use of MgB_2 superconducting (SC) magnets on Fusion Island, and the possibility of SC energy-storage rings. The current plan for fusion is to have 112 tonnes of Niobium Tin (Nb_3Sn) SC magnets cooled down to 4K using liquid Helium. MgB_2 functions as a SC at temperatures as high as 20K, rather than the 4.2K required for conventional superconductors. This difference would allow for an MgB_2 magnet system to operate with one-tenth of the cooling power needs of a conventional system. Additionally, this also means that it can be cooled with liquid Hydrogen - a product of Fusion Island.

The prompt questions that this discussion was supposed to try and answer were revealed by Prof. Skea, who chose to address them in reverse order.

3. What is the demand for fusion Hydrogen, what are the side projects, and what are the requirements?
2. Is there a consensus that fusion (and/or fission) Hydrogen can be fast tracked?
1. Is fast-track fusion for Hydrogen compatible with the fusion for electricity research program?

It was asked if those from the commercial sector would set out what demand scenarios they envisioned.

Initially it was pointed out that in order for the Hydrogen economy to have a future we must get out of the fossil fuel market. Hydrogen must become a fuel for planes, ships etc. Industries that require Hydrogen are not concerned with the specifics of the method used to generate it. One should bear it in mind that planes being built now will be in service for the next 30 years.

The infrastructure for Hydrogen is forming, as can be seen by the emergence of demonstration sites. By the time fusion comes online, there should already be a fossil fuel lead Hydrogen-economy. It was suggested that the Hydrogen market would begin with fleet and return to base vehicles. With regards to the market that is driving this, if the automotive market finds a cheap source of Hydrogen they will take advantage of it, and these appetites will be channelled into the market. Is aviation a prospect? Perhaps, but only if the passengers are dispensed with so that there is enough room for the fuel!

The comment was made that the Hydrogen economy will emerge a few years from now, and we should begin to see local production of Hydrogen soon. One participant added that he had heard an oil company say the SI cycle involved 'nasty chemical engineering'. In response it was said that the 'nasty chemicals' used in the process added to the costs. According to another attendee, these chemicals are no worse than those already found at any oil refinery.

What would be required if the aim was to decarbonise the UK's transport? The country currently consumes about 80GW of electricity, what happens when this moves to 140GW – how will this be met? If 20GW of renewables can be expected, add to that a planned nuclear build of 20GW, and there's still 100GW to go. How will the various markets compete, and is fast-tracking possible?

We were reminded that Sir Chris Llewellyn Smith could not attend today's session as he was at the European Commission asking just this question. Assuming everything goes as planned, a demonstration power plant could be underway in

30 years, but is there a different route? Can a DEMO be built now? The design could be frozen then the construction could commence.

The question was asked whether anyone could deliver this Hydrogen without fossil fuels. It being the case that ITER will not be demonstrating the appropriate technologies - as it is concentrating too much on the physics aspects - is it feasible that the Hydrogen technology aspects be pursued in parallel with ITER and IFMIF? It was confirmed that there was still some confusion as to the goals of ITER, despite its global coordination. Some countries claim that fusion should be pursued for the science, whilst others like the UK argue that fusion is for energy. If Europe tasked that DEMO be built now, fusion for energy could be focused on exclusively, and only energy relevant technologies would be developed.

It was pointed out that the energy supply chain should also be considered from the Government's perspective. Oil and gas revenues provide some 25% of the UK's corporation tax. How will this translate into the way that fusion works? One participant suggested that if all this were pushed through in the manner of the Manhattan Project, it would still take 10 years for a fast track build. The private sector will not touch fusion until it has seen many years of consistency, then it'll be another 10 years until that funding comes to fruition. The European approach was compared to that of China, where they would start building DEMO next week if they decided to go through with it today. It was added that we needed to force through a major Hydrogen economy ahead of electricity.

An inquiry was made about the coherence of funding from the Government, and how they would react to a fast-track approach. There are worries that if Hydrogen fuel-cell vehicles are deployed, they threaten the automotive internal-combustion engine sector – the UK makes 30% of Europe's engines. As Hydrogen technology develops skills will have to be fed into it. The Government's perception of fusion is that it currently embodies the longest-term option supported by public money (EPSRC). Fuel cell technology and demonstration will be coordinated through knowledge transfer networks. The Government does not want to force a link that does not currently exist between fusion and Hydrogen technologies. Biofuels have been focused on, but Hydrogen is considered to be the fuel for future transport and it is fundamental that the technology be demonstrated. The observation was made that the Government's approach is more coordinated than 3-4 years ago.

The Government's plans to build a National Nuclear Laboratory were brought to the attention of the session, and it was speculated whether there was a possibility that fusion for Hydrogen could be funded through it. For the time being, it was conjectured that fusion would remain the responsibility of the EPSRC.

1.13 Breakout Session 4: Research requirements for Fusion Island. This session was chaired and introduced by William Nuttall from University of Cambridge and notes were taken by Anthony Webster, UKAEA.

It was suggested by the organisers that the session should consider:

1. What could/needed to be done in: Magnets, Reactor Design, Operating Cycles, Chemical Process Cycles, Product Storage, etc?
2. Hydrogen Production Methods – are there any important differences between ITER and DEMO?
3. Materials research needs?

Introduction

The participants in the session clearly represented a wide range of relevant backgrounds. Only a minority of participants were familiar with the details of fusion research.

This led to a rapid discussion and overview of the main concepts behind fusion in Tokamaks such as JET and ITER – this is summarised here.

- The most developed device for production of power plant quantities of energy is the Tokamak. JET and ITER are Tokamaks, and the UK's experiment MAST is a more spherical version of the Tokamak, often described by abbreviating "Spherical Tokamak", to ST.
- It would take 15-100 MW to drive current in a Tokamak, if steady-state power production is required.
- A Tokamak without current drive would operate for a few hours, then they require 10-20 minutes to replace the swing on the transformer, prior to their operation again. This represents the fundamental basis of the idea that it is natural for fusion energy systems to operate on a long-pulse cycle.
- It was suggested that 2 or more Tokamaks could operate together to provide a steady supply of power – although this would clearly double the Tokamak component of plant costs.
- Stellarators are an alternative magnetic confinement device that would operate in steady state. Unfortunately they require extremely complicated coil shapes and arrangements, making them difficult to build, and often work less well than hoped. Nonetheless, Stellarators are being developed in various labs around the world.
- It is much easier to drive current in an ST than in a conventional tokamak. The stronger magnetic field gradients in an ST produce a self-generated current in the plasma, thus requiring less external current drive.
- The efficiency factor Q for fusion power production refers to the plasma, not to planned commercial energy production (e.g. electricity). Q of one corresponds to equal power produced by fusion to that directly heating the plasma. Of this energy four fifths immediately leaves the plasma in the form of fast neutrons. Q=5 maintains sufficient energy within the plasma to sustain fusion. In addition much more energy would be used in the coils, inefficient heating systems etc. than would be produced by fusion. Commercial fusion energy production would probably require a Q in the range 10-30.
- It was suggested that fusion's relatively long development time may lead to a number of plasma, materials, and engineering problems being solved simultaneously.
- The meeting noted that high temperature gas-cooled fission reactors are well suited to the production of the high temperatures required for thermochemistry.
- The meeting heard that the solar thermal community have much experience with heat storage to overcome intermittency of heat generation.

Broad conclusions

Broadly speaking it was felt that the Fusion research requirements are:

A. *Steady State?* Although baseload electricity production clearly requires steady state heat production, even process heat applications of fusion energy benefit from steady state (or near steady state) operations.
B. *Plant Reliability?* A separate, but related, issue is plant reliability. Arguably process heat applications are less commercially sensitive to such risks. Reliability is a key challenge for commercial fusion energy production.

The meeting then addressed two competing research directions:

- Low temperature process heat applications (approx. 500ºC)
- High temperature process heat applications (approx. 800ºC)

Comments regarding fusion power development, based on the experience with fission power development

It was noted that "technology doesn't develop overnight", and proceeds by a combination of both incremental improvements and major steps forward. Based on experience from the development of Fission power, it was suggested that any serious development of Fusion power would involve the development of many different Physics and Engineering concepts, with plants/experiments being designed and operated now. For instance, it was suggested that DEMO would need to be a flexible device, to allow easy fixing, maintenance, adjustments etc. Importantly, regarding fusion for Hydrogen production, it was suggested that we should: *"Let the technically difficult part drive the design, and let the technically simple part follow"*

For the fusion community this suggested that it would be preferable to try and lower the required temperatures for Hydrogen production to 500 degrees Celsius (more preferable from a design perspective), than to request a design allowing 800 degrees Celsius temperatures in the machines walls. However thermochemistry experts pointed out that no viable thermochemical route to hydrogen had yet been identified at these lower temperatures. At these temperatures high temperature electrolysis would be a viable option, but substantial electricity would be required.

Fusion power plant wall temperatures – "1st Wall" & "Blanket"

A fusion reactor's "1st wall" is the thin layer of material nearest to the plasma (a centimetre or so), and is at a much higher temperature than the "Blanket" (of order a metre in thickness). The meeting discussed the materials benefits of having liquid metals in the blanket. The Blanket adsorbs the majority of the neutrons. In most concepts lithium is placed in the blanket so as to permit the production (via interaction of lithium with high energy neutrons) of tritium for further fusion fuel. Deuterium and Tritium are the fuel for Fusion devices, but whereas Deuterium is abundant in sea water, Tritium has a half life of 12.5 years and must be produced in either a fusion (or fission reactor.) Because the neutrons carry 4/5th of the energy produced by the fusion reactions, the blankets are the structures in which the majority of the fusion energy is extracted as heat energy, via a coolant/heat exchanger. In discussing high and low temperature approaches to fusion energy production it is important to note that in each case the first wall temperatures are the same. The difference lies in the blanket temperature. The blanket temperatures are currently limited to roughly 500-600 degrees Celsius, beyond these temperatures present steels would not have sufficiently good structural properties. To achieve 800 ºC structural elements represents a major research challenge for Fusion Island.

The need for a heat exchanger

It is necessary to have a heat exchanger to transfer the heat to the place where Hydrogen would be produced. This is because if the ingredients in the Hydrogen production cycle were irradiated, they would produce highly undesirable by-products. In essence a process heat fusion machine must have a heat exchanger between the fusion plant coolant loop and the chemical or other process requirements. Regarding coolants, the audience were uncertain whether Sodium was a realistic possibility (owing to safety concerns with high temperature aqueous chemistry on the downstream side), Lead was thought to pose difficulties if the heat exchanger were to rupture. For instance with a sulphur-iodine cycle, such a rupture might cause the production of solid lead sulphate in the fusion plant coolant circuit requiring expensive and difficult repair and remediation. Gaseous coolants for heat transfer, such as helium, might be preferable. This would avoid issues of metal activation and hence might avoid the need for primary and secondary coolant circuits within the fusion machine.

Can we avoid neutron activation by using other fusion reactions? (& is it a realistic possibility?)

There are other possible fusion reactions in addition to D-T, some of which produce far less neutrons. It was pointed out that even D-D reactions are likely to produce a certain amount of neutrons by various reaction pathways. However, it is better to think of neutrons as an excellent mechanism for heat dispersal - *“Neutrons for heat-dispersal are the solution, not the problem”.*

If all the fusion energy were needed to be adsorbed on a material surface, there would be serious, possibly overwhelming challenges for materials development. Instead, neutrons take the majority of the fusion power (4/5ths), and distribute it nice and evenly around the walls of the machine. It was also noted that the penetration depth of the neutrons into the machine walls could be changed by altering the density of the coolant in the blanket.

Other fusion reactions would also require far higher operating temperatures for the plasma than are likely to be achieved without significant improvements. Any planned move away from D-T fusion would raise a host of new research challenges. On balance the group believed the difficulty of these challenges would probably outweigh the possible benefits (e.g. no need for tritium production).

Unexpected improvements in “confinement” can change our outlook

It was noted that we have had unexpected improvements in energy confinement in the past. For example the discovery of “H-mode” and “ITBs”), have allowed a 10-20% improvement in energy confinement time. (The multiple of plasma pressure with confinement time gives an indication of how close we are to producing more power by fusion than is needed to heat the plasma. If you can produce a plasma with a pressure of an atmosphere (that is easily done at present), and if you can confine the energy for about 5 seconds (currently it is about 1 second, and the easiest way to increase this is by making the machine larger, an upper bound at fixed machine size is imposed by diffusion), then you will produce more energy by fusion in a 50-50 mix of Deuterium and Tritium than is required to heat the plasma.)

This led to some discussion concerning the ideal scale of a Fusion Island style machine. Plasma physics concerns favour larger machines while economics and process heat needs perhaps suggest smaller machines. Fire-6 and Ignitor were presented as interesting smaller and cheaper concepts, although Fire-6 is on a similar scale to ITER.

It was questioned whether the lower surface area to volume ratio of larger devices might lead to improved machine performance, because of the potential for a smaller fraction of impurities. It was felt that methods such as "baking" (heating) the walls of the machine during its commissioning, have given sufficient control over impurities to make a significant effect unlikely.

To summarise:

The following questions emerged as being important for the development of fusion for hydrogen production:

- What level of availability of fusion energy is required?
- What should the blanket temperature be: 500ºC or 800ºC?
- What should the heat exchange medium be: liquid metal or gas?
- How large should the machine be?

The fusion experts clearly preferred lower temperature approaches, however thermochemistry requires the higher temperature approach.

There was widespread consensus that any early machines would employ D-T fusion.

1.14 Breakout Session 5: Fusion for Hydrogen: is there a business model? This session was chaired and introduced by Patrick Heren from Heren Energy Ltd. Notes were taken by Michael O'Brien, UKAEA.

The key questions were:

1. What is the cost of Hydrogen? When is Hydrogen needed? What will the size of the reactors be – do we want a few large reactors or more smaller ones? Where will the investment come from, what are the incentives and how can they be implemented?
2. Is business modelling required?
3. Who will the partners be?
4. Is there a strategy, and who will drive it?

A different way of thinking is required when dealing with the time-scales at work in this project. If we look ahead 30 years we do not know how the energy market will function, but in terms of markets Hydrogen will certainly be needed for oil refining. One participant recalled how he had been introduced to the idea of Fusion Island. A few weeks ago he had received an email from one of the conference convenors, asking if there was any private (i.e. oil) interest in fusion. They replied by saying that of course there was, but the situation reminded them of the economist John Maynard Keynes peace talks with Germany in 1918-19. Germany was suffering under an allied blockade, and asked if there was anything Keynes could do to get it lifted. Keynes reply was that there was no chance of that happening unless the Germans did something in return, pointing out that it had taken four years, hundreds of ships, thousands of troops, and tens of thousands of bureaucrats to get to this stage, and these people earned their living by maintaining this blockade and weren't about to give it up for the good of the German people. The same analogy can be used for the oil industry. From the private sectors point of view, there is nothing here for them to get their hands on, hence there is no business model.

The question was then rephrased to whether Hydrogen from fusion is a viable business. It was re-stated that currently there was no business model for Hydrogen, neither was there one for fusion, nor for the coupling of Hydrogen to fusion - but the economies of scale concerned with these technologies were great. If we consider fusion devices in the 3-4GW range, the costs can be halved by doubling the amount of electricity they produce, but would we be comfortable with a few plants producing all of Europe's Hydrogen fuel.

It was commented that whether or not the Hydrogen was compressed, the price came in at about €2 per kg using electrolysis and French nuclear generated electricity. In 20 years this might become competitive with Hydrogen generated through the steam reformation of methane, which was less than €1 a kg three years ago. Compare all these costs to that of sequestering carbon, which is €40 per tonne.

It was suggested that if the economics of this depended on India or China, perhaps the business model would evolve differently. One attendee then asked whether there were business models capable of coping with fusion for Hydrogen rather than for electricity. The problem is we do not know when fusion will deliver, or if it will be reliable enough when it delivers. Is there a market at the end of this, even if the Hydrogen produced is inexpensive? We were reminded that the oil industry would always need Hydrogen for refineries.

The scale of the automotive industry's demand for Hydrogen was then discussed. It was pointed out that while Hydrogen is more efficient at delivering energy compared to conventional fossil fuels it is difficult to compare the two. The UK's energy needs are currently supplied by electricity (1/3) and oil (2/3). The electricity industry can be decarbonised, although it won't be easy. The oil and the transport sector will be a bigger challenge. Another attendee reasserted that the costs involved are important, and that the commercial risks need to be analysed, especially if the Hydrogen market begins to emerge before fusion.

CO_2 avoidance should be targeted at coal, and in order to do this it was noted that CO_2 emissions price could be guaranteed to be (for example) €20 per tonne. With this knowledge the fossil fuel industry could begin to accommodate sequestration technology straight away. The energy sector wants price signals, a political message needs to be sent out that Hydrogen prices will become a reality. One participant came to the conclusion that there were too many external factors to set prices. When accounting the finances of Hydrogen generation, the cost of the heat (and whether it comes from fission or fusion) needs to be determined, as well as the economics of the thermochemical cycle. Both fission and fusion are capital-intensive technologies. Even thought there has been over 40 years of experience in fission there are still perceptions of risk that could make or break the industry.

So can the cost of fusion be brought down if R&D is focussed on Hydrogen generation? An inquiry was made regarding the prospect of Laser-Fusion (Inertial Confinement Fusion). The reply was made that this would take even longer to develop than the conventional magnetic confinement approach.

The observation was made that all discussions in Europe resemble the ones being had at this meeting, where people say that they are a bit worried about the security of their gas supply or some such. In countries like China and India they do not have the energy capacity required, and when they talk about security they are referring to a global issue - they do not want to provoke conflict over the grabbing of resources. It was pointed out that the price of coal was constant until China started to buy it all up. The point of view was offered that fusion and Hydrogen would of course be a risky investment, just like the Apollo Moon missions were, but what we need is big, brave thinking. ITER will be a multilateral project, but in the grand scheme of things it is still ‘peanuts’, a mere $10 billion, compared to the tens to hundreds of billions spent on gas R&D for example.

The issue of Intellectual Property Rights (IPR) was then raised. The UK wants to export its CCS technology to China and India, but also to maintain the IPR. With regards to investors and partners, if a country such as South Korea became involved in the fusion for Hydrogen fast track it would expect access to IPR. It was commented that from a business model perspective it mattered who came up with the technology first. One participant decided that if this were the case, then we’d just have to buy our fusion machine from whoever developed them. Another attendee contributed by saying we could be buying fusion from India or China just like fission technology is bought from France today.

Will this technology be deployable? If fusion is developed with aim of generating Hydrogen gas, then this is worrying, suggested one contributor. It was further added that in such a case coal plants might be required to maintain security of supply. The UK Government sees a liberalised energy market, driven by the private sector, where the approach will not be to give tax breaks, but rather to construct a policy framework – for instance, €40 per tonne of CO_2 emissions is needed to drive CCS, and the Government should work towards ensuring this. However, it was pointed out that different frameworks favour different technologies.

It was suggested that the business model should concern itself with establishing parameters within which to function. Agreeing with this statement, one participant added that a decision needs to be made as to whether the approach will be strategic, with many plants, or tactical, with perhaps a single plant. This situation was compared to the biofuels industry – if the Treasury refuses to buy the product, the UK can always sell it to the rest of Europe. But who will be driving this business?

The group’s attention was drawn to the third question, of the partners involved in any endeavour. In the end whose business would it be? Would it end up in the hands of the electricity-utilities majors? As the ideas involved are a hybrid of various technologies, it would probably be a consortium activity. Large consortiums are needed to drive even ‘simple’ industries such as coal. It was proposed that if the intellectual property rights were waived, perhaps the UN could drive this? The European Emissions Trading Scheme, which operated on a European-wide scale, was used to make the point that the UK could achieve little if it moved on its own.

The Stern Report was then discussed, and it was argued that the idea of ‘1% GDP now for a 10% GDP saving in the future’ offered a business framework within which to work. It was noted that **Sir Nicholas Stern** and **Professor Julia King** were currently working on a report in the same vein, in which ideas to solve the decarbonisation of transport would be put forth. There is a potential for a nuclear revival, and people are looking for guidance from the Government, and if not them, from a European framework.

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If ITER is successful then the likely outcome is that ambitious companies or consortiums will pick up the idea and build it. The first build will be more expensive so will require Government subsidies. A counter argument was made that if people want energy, then they are going to be reliant on fossil fuels for the rest of this century. It was surmised that in countries where there was more centralised control, there was a greater chance of things going ahead, so the business model may well evolve elsewhere. The consensus of the British members of group was that they would rather not change the UK's social constructs.

The markets already exist in a sense, but in order to look ahead 20 years requires a new type of thinking. Fusion for Hydrogen is more likely to take place in this country than in others. This sentiment was concurred, agreeing that due to the diffuse nature of the market in the UK, London is seen internationally 'the' place to raise capital, so Hydrogen and fuel cells have a good chance of taking off in this country. The concluding remark was made that in order to forecast for the next 30 years, it is necessary to consider the past 30 years – yet our liberal energy regime only came about 15 years ago – evidence that the markets and energy policy can change rapidly, and wildly.

1.15 Post-meeting Questions

Based on this meeting, what are the recommendations that would encourage a change in infrastructure? The 'intrepid' days leading up to the meeting were described, and the encouragement that one convenor had gained from the deep dialogue on the subject shared with such a diverse group of people. Another attendee added that the meeting had been a steep learning curve, enormously enlightening and that they hoped peoples' views had shifted. It was suggested that what is needed in the grand scheme of things is a mindshift on a larger scale. In conclusion, it was thought that there had been much communication between the various groups of people involved, and that tremendous encouraged was to be had from comments about the possibility of building DEMO soon. With regards to research challenges, this is one of the first times the commercialisation of fusion and Hydrogen have been discussed, and we are still in the domain of answering questions - the discussion is not yet finished.