Uranium Mining, Processing and Nuclear Energy Review Secretariat
c/- Department of the Prime Minister and Cabinet
3-5 National Circuit
Barton ACT 2601

Executive Summary

Dear Secretariat,

We make this submission as representatives of the Australian ITER Forum, a group of Australian scientists and engineers from seven Universities (the Australian National University, the Universities of Sydney, Canberra, Flinders, Newcastle, Wollongong, and Murdoch University), the Australian Nuclear Science and Technology Organisation (ANSTO), and the Australian Institute of Nuclear Science and Engineering (AINSE). The ITER Forum is seeking Australian participation in the next step international nuclear fusion project, ITER. We note that fusion has been named in the issues paper that supports the terms of reference of the Uranium Mining, Processing and Nuclear Energy Review.

Fusion energy, which has attracted relatively little media attention, is released when lower atomic weight elements join to form a new heavier element, in a reaction first discovered by the Australian Sir Mark Oliphant in 1934. It is the fundamental process that powers the Sun and the stars. Successfully harnessing nuclear fusion promises millions of years of clean, base-load sustainable power generation, virtually free of greenhouse emissions.

In the Sun, huge gravitational pressures are balanced by outward energy flux produced by nuclear fusion reactions. On Earth, strong magnetic fields are required to confine the nuclear fuel, which has to be heated to immense temperatures, 100 million ^{o}C, for fusion to occur. The most advanced magnetic confinement geometry is a toroidal, donut-shaped container known as a “tokamak”. The plasma particles are constrained to follow the toroidally closed lines of magnetic force. In essence, these act as a thermos flask, keeping the plasma hot.

Fusion is environmentally and politically friendly. The fusion process itself generates zero greenhouse gas emissions, acid rain or particulates. Almost all emissions are derived from the construction and processing of materials and fuel used in the reactor. Unlike fission, the direct products of fusion are not radioactive. Rather, radioactivity is generated indirectly, by neutron activation of the first wall and vessel structure. Employing present-day technology, the materials used in a fusion power plant which become radioactive could be completely recycled within 100 years of shutdown. Fusion is also intrinsically safe. There can be no chain reaction, explosions or meltdown. At worst, a loss of magnetic confinement will damage the first wall of the system. Magnetic confinement fusion cannot be used as a weapon, or in weapons development.

The next step in fusion development is the ITER project, an A$16bn international project undertaking to construct the next-step tokamak. Seven countries and groupings support ITER: the US, Russia, China, Japan, Korea, India and the EU. In addition to the scientific benefits resulting from solutions of cutting edge physics and technology problems, the industrial and technological spin-offs of ITER for the ITER partners will be immense. At this stage, most of the contributions of the ITER partners are in the form of industrial contracts to provide the machine components and structures.

ITER, which is a precursor to a demonstration power plant, will determine the viability of fusion power. For the first time ever, ITER will explore a continuous operation fusion regime, in which the heat of the confined products of reaction is greater than the external heating. In continuous operation, ITER will yield 5 times more power than is required to sustain the reaction, while in pulsed mode, the power gain could be as high as 30.

The ITER partners are not only committed to the implementation of the ITER project, but under the "ITER Broader Approach" have drawn up plans for the post-ITER development of fusion power with a demonstration reactor, DEMO. The possibility of Australian involvement in this R&D project is unlikely if it is does become formally involved in ITER.

Australian scientists and engineers are presently seeking to be involved in the ITER, through a federally funded workshop "Towards an Australian involvement in ITER", to be held over October 12-13, in Sydney. The workshop will bring ITER partner representatives together with science, government and industry communities, and discuss a possible role for Australia. The reasons for an Australian involvement are compelling:

- Australian involvement would increase our standing in international science and engineering and give us access to a wide range of technologies.
- There are potential short and long term contract opportunities for Australian engineering and component manufacturing industries in this project.
- Our nation possesses large reserves of materials with are strategically important to the development of fusion power. ITER involvement will allow these reserves to be exploited.
- As mankind tackles the problem of energy supply, our involvement in the ITER project will inspire a new generation of Australian students to choose a career in the sciences or engineering

By providing a research focus on fusion science, Australian engagement in ITER will foster strong collaboration between Australian efforts in plasma physics, collision physics and materials science, thereby sustaining a critical mass of research in these important areas. These collaborations could be supported by the establishment of a Centre for Fusion Science, which spans relevant expertise across university and government research organization sectors. With the support and recognition such a centre would bring, Australia could secure its hard-won capability in fusion science by attracting home outstanding graduates now working in international fusion programs. If not, as present expertise retires and new graduates necessarily move abroad, our capability will be irretrievably lost.

In closing, we also note that ITER is the world's largest science experiment, and is supported by governments representing over half the planets population. Under the ITER Broader Approach, the ITER partners have mapped out the next 40 years of research. The ITER partners intend to ratify the ITER implementing agreement in early 2007. Once ratified, the ITER legal entity will be established, contracts locked, and construction will commence. The window of opportunity to access industrial contracts is thus closing quickly. The next opportunity to engage ITER will be in the operational phase 10 years from now. However, at the present rate of attrition there will be no Australian scientists left in the field, and no basis for engagement. It is our conclusion that a failure to provide ongoing substantial support for Australian fusion science will have very long-term negative repercussions for the nation. Given the potential impact of fusion as a sustainable solution to the world's long-term energy needs, Australia needs to act now.

M.J. Hole

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Detailed Submission

Our submission is based on addressing the issues paper that supports the terms of reference, which span economic, environmental, and health and safety issues. Unlike fission however, fusion power is still a concept technology. As such, our submission does not conform the format of the issues paper, which is primarily orientated about fission exploitation. Where possible however, we have addressed the issues paper. To assist the Taskforce, we have identified at the beginning of each section pertinent questions raised in the issues paper.

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1. Fusion Power

1.1 The basis of fusion power

The nuclear force is the strongest of the four fundamental forces of nature: gravitational, weak-electromagnetic, strong-electromagnetic, and nuclear. Exothermic chemical reactions, such as the combustion of coal, access the strong electromagnetic force. The difference in internal energy between reactant and products is converted to heat. Accessing the nuclear force involves reactions of the nucleus of atoms. Nuclear reactions convert the binding energy of nuclei to kinetic energy.

Per reaction, nuclear reactions offer millions of times greater energy yield compared to chemical reactions. To illustrate, reaction (1) is the combustion of pure anthracite coal (dry mass). Reaction (2) is the fission of uranium into energetic products xenon and strontium, and a thermal neutron. Reactions (3) and (4) are the two easiest to initiate fusion reactions – involving the fusion of heavy isotopes of deuterium and tritium to form helium and an energetic neutron, and deuterium and light helium to form helium and an energetic proton.

$$C_6H_2 + 6.5\,O_2 \rightarrow 6\,CO_2 + H_20 + 30\,\mathrm{eV} \quad (1)$$
$$U^{235} + n \rightarrow Xe^{134} + Sr^{100} + n + 200\,\mathrm{MeV} \quad (2)$$
$$D^2 + T^3 \rightarrow He^4 + n^1 + 17.6\,\mathrm{MeV} \quad (3)$$
$$D^2 + He^3 \rightarrow He^4 + p + 18.3\,\mathrm{MeV} \quad (4)$$
$$D^2 + D^2 \rightarrow He^3 + n^1 + 3.27\,\mathrm{MeV} \quad (5)$$
$$D^2 + D^2 \rightarrow T^3 + H^1 + 4.03\,\mathrm{MeV} \quad (6)$$

The focus of this submission is into development of technology that exploits the easiest to initiate fusion reaction, the D-T cycle, given by reaction (3). Next generation cycles, based on the D-He (reaction (4)) and D-D (reactions (5) and (6)) reactions will be based on the same technology, but involve more extreme conditions.

Unlike the fission of U^{235}, which can be initiated by a neutron, the D-T and D-He cycles require the fuel nuclei to collide with sufficient kinetic energy (in the centre of mass frame) to overcome their electrostatic repulsion [1]. For a given collision, the probability of a fusion reaction σ is a function of the relative velocity *v* between the two reactant nuclei. The reaction rate (fusion reactions per volume per time) is σ*v* times the product of the reactant number densities. In a gas with a distribution of velocities, then the velocity average must be taken, <σ*v*>.

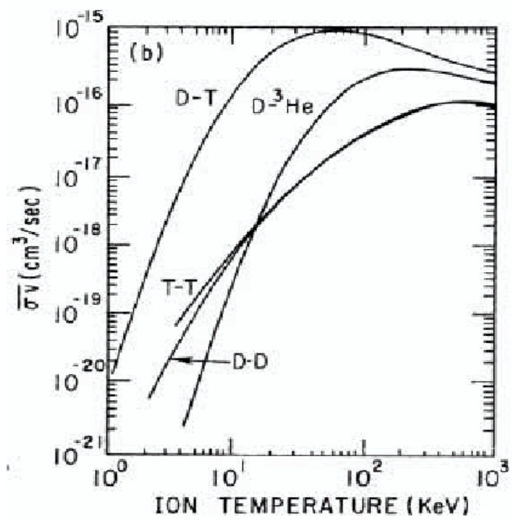


Figure 1 : Reaction rate as a function of ion temperature. 1 keV = 11 million °C

Figure 1 shows the reaction rate <σ*v*> as a function of ion temperature. Although the collision cross-section of D-T reaction is a maximum at around 60keV, the temperature need not be that high, because the required reactions occur in the very high energy tail of the velocity distribution function. The necessary temperature is around 10keV, or 100 million °C. At these extreme temperatures, which are 6-7 times hotter than the core of the Sun, the fuel exists as ions in the plasma state. That is, the fuel atoms are ruptured into their component electrons and nuclei.

To reach such high temperatures, a D-T plasma must be heated. To be useful, the heated plasma must be confined and controlled. From the power balance relationship in a confined plasma, a condition for plasma ignition (when the input heating power P_H approaches zero) can be obtained [1]. The confined thermonuclear power output per unit volume in a D-T plasma of equal part deuterium and tritium is given by

$$P_\alpha = \frac{1}{4} n^2 \langle \sigma v \rangle \varepsilon \tag{5}$$

with n the density of fuel ions and ε the kinetic energy of the confined He^4 ions (see reaction 3). The rate of energy loss is $P_L = W/\tau_E$, with W the stored energy and τ_E the energy confinement time. Conservation of energy yields the overall power balance relation,

$$P_H + P_\alpha = P_L \tag{6}$$

Finally, substituting expressions for P_α, P_L and $\langle\sigma v\rangle$ yields the important self-sustaining ignition condition or Lawson criterion,

$$nT\tau_E \geq 3 \times 10^{21}\,\mathrm{m^{-3}keVs} \tag{7}$$

The importance of the triple product $nT\tau_E$ is that it provides a figure of performance merit for fusion plasmas, and a reactor performance threshold. An example reactor relevant condition is n=10^{20} m^{-3}, T=10 keV, and τ_E = 3 s.

By treating the fusion plasma as a heat source, concept realization of fusion power as an energy source can be described independent of the details of the plasma. Figure 2 shows such a schematic of concept, showing the D-T plasma as a heat source, which is used (in this case) to generate electricity. As with fossil-fuel based large scale power systems, electricity is generated by the production of steam, which drives a turbine-generator combination. The plasma is a heat source, which could also be used for industrial processes such as desalination or hydrogen production (see Sec. 1.7).

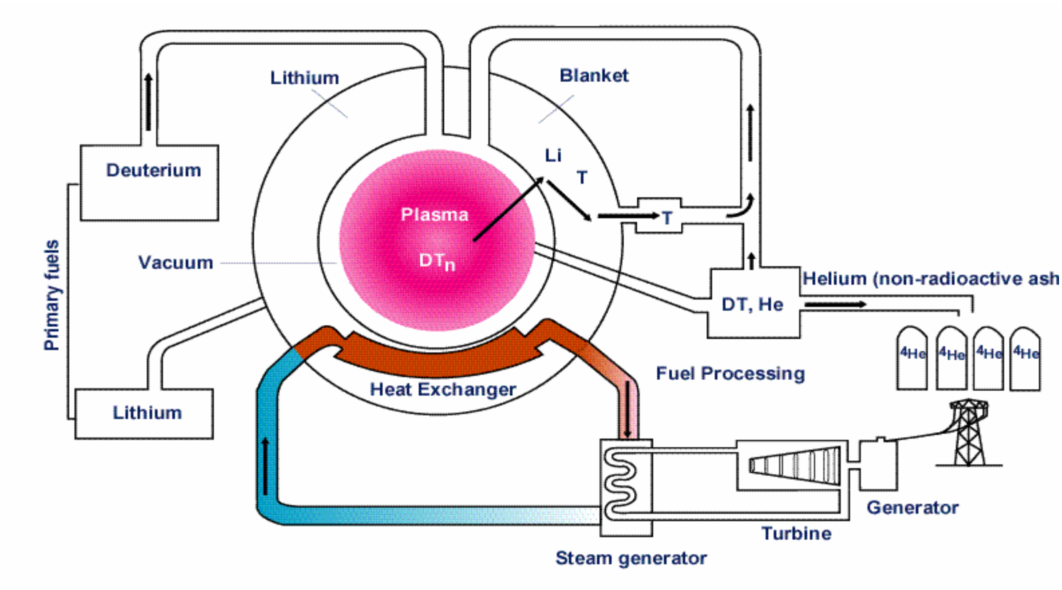


Figure 2: Fusion power plant schematic

A distinctive feature of D-T fusion is the fuel handling and processing cycle. One of the fuel ions, tritium, is radioactive with a half-life of 12.3 years – and so does not occur naturally. Instead, it needs to be manufactured, by neutron transmutation of lithium. The two processes are

$$n + {}^{7}\mathrm{Li} \rightarrow n + T + {}^{4}\mathrm{He} \ - 2.5\ \mathrm{MeV} \quad (8)$$

$$n + {}^{6}\mathrm{Li} \rightarrow n + T + {}^{4}\mathrm{He} \ + 4.8\ \mathrm{MeV} \quad (9)$$

In a working fusion power plant, tritium will mostly be generated in-situ, by neutron activation of lithium in a blanket surrounding the vessel walls. The D-T reaction releases a 14.1 MeV neutron, which carries 80% of the reaction kinetic energy out of the plasma. When the energetic neutron impacts lithium within the blanket, it generates tritium, via reactions (8) and (9). The blanket cannot be engineered so that all neutrons undergo such a reaction, and so a neutron multiplier such as beryllium or lead will be used. By processing the lithium, tritium can be separated, and used for injection into the plasma, whilst the helium gas can be removed as a waste product. Heat exchangers will remove the heat to produce steam for the turbine. To initiate the fusion cycle, some tritium will have to be manufactured separately.

1.2 Magnetic confinement fusion

The Lawson criterion prescribes the conditions of plasma density, temperature, and energy confinement time for net energy production in a hot, confined plasma. The leading technology to produce these conditions, and enable fusion power is magnetic confinement. The principle of magnetic confinement is the use of strong magnetic fields, which confine charged particles to gyrate about lines of magnetic force, as shown in Fig. 3. To prevent particles exiting the confinement chamber, the magnetic configuration is made toroidal – or donut-shaped, such that the field lines execute loops about the central axis.

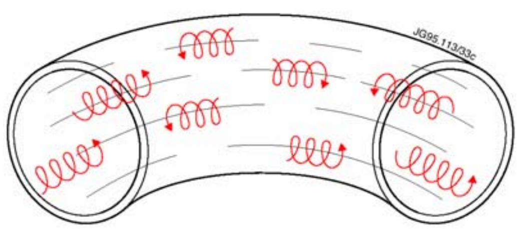


Figure 3 : Gyration of particles about field lines

At present, the most reactor-relevant toroidal magnetic confinement configuration is the tokamak, shown in Fig. 4. This is a donut-shaped (toroidal) plasma, with strong toroidal magnetic field produced by external field windings. An additional magnetic field is produced by a toroidal plasma current, which is partly induced by a transformer action due to the central solenoid (see primary transformer circuit in Fig. 4). Other advanced toroidal magnetic confinement concepts exist, which offer potential improvements in cost and steady-state operation. Research programs based around these concepts are important, both in terms of their ability to contribute to the programmatic development of fusion power (eg. ITER and the Broader Approach), and concept innovation and improvement. These are detailed in Sec. 2.1

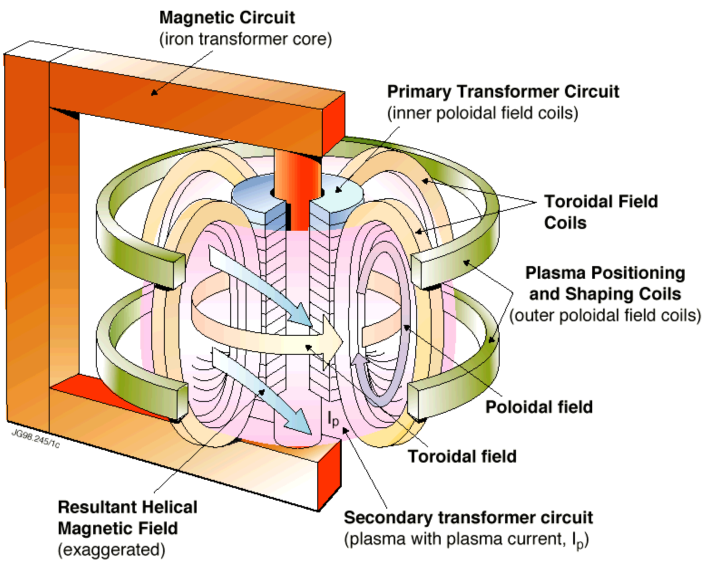


Figure 4 : Tokamak

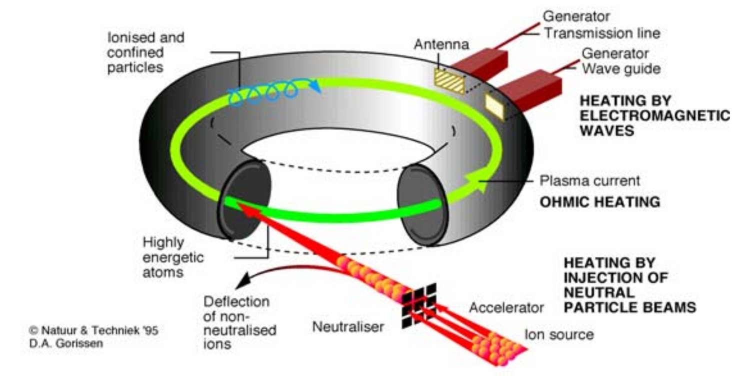


Figure 5 : Heating mechanisms

Three principle heating mechanisms are employed to heat fusion plasmas to reactor relevant temperatures. The simplest of these is resistive heating, which operates by the same principle as an electric household radiator. Plasmas can support large electrical currents. By inducing these in the plasma, normally by transformer action, the fuel ions can be heated via electron-ion collisions – a process also known as resistive (or Ohmic) heating. Another common technique for plasma heating is the use of electromagnetic waves, a process similar to cooking food in a microwave oven. In this case, antennas or waveguides couple radio-frequency waves directly to the plasma, and the plasma particles are heated by wave-particle resonant absorption. The final technique, which has yielded significant improvements in plasma performance is heating by injection of beams of energetic neutral particles. In this process, deuterium ions are accelerated electrostatically to high energy (eg. 1MeV for ITER), neutralized by charge exchange with a D_2 gas, and travel in a straight line into the plasma. Once inside the plasma, they undergo a second charge exchange event, producing an ionised deuterium ion, and a neutralized plasma particle. The high-energy ion is then confined by the magnetic field, whilst the low-energy neutral particle is lost to the chamber walls. Finally, via collisions, the high energy particle loses its energy to the bulk of the plasma, heating it. Figure 5 shows a schematic of these heating systems.

The use of these heating mechanisms, together with improvements in magnetic field configuration, access to improved stability and higher energy confinement regimes, and improved control and power handling, has enabled rapid advance in fusion performance. Figure 6 shows the increase in the fusion triple product (left vertical axis) with increasing central ion temperature. The right vertical axis indicates the approximate performance growth as a function of time. In 50 years of experimental research the triple product has increased five orders of magnitude (i.e. by a factor of 100,000). In the same period, the plasma temperature has increased from 1 million to over 100 million °C. Only two experiments, the Joint European Torus (JET) and the Tokamak Fusion Test Reactor (TFTR) have been capable of handling tritium. The highest performing discharge was in JET, with a demonstrated power gain

$$Q = \frac{P_{\text{fusion}}}{P_H}$$

of Q=0.65. In most plasma experiments however, tritium is not used. In these cases, the estimated power gain Q_{DT}, extrapolated from data assuming the plasma to be an equal mix of deuterium and tritium has exceeded break-even (Q_{DT}>1). Figure 6 also shows the ignition barrier, and the operating range of the next step fusion experiment, ITER, which is outlined in Sec. 2.1.

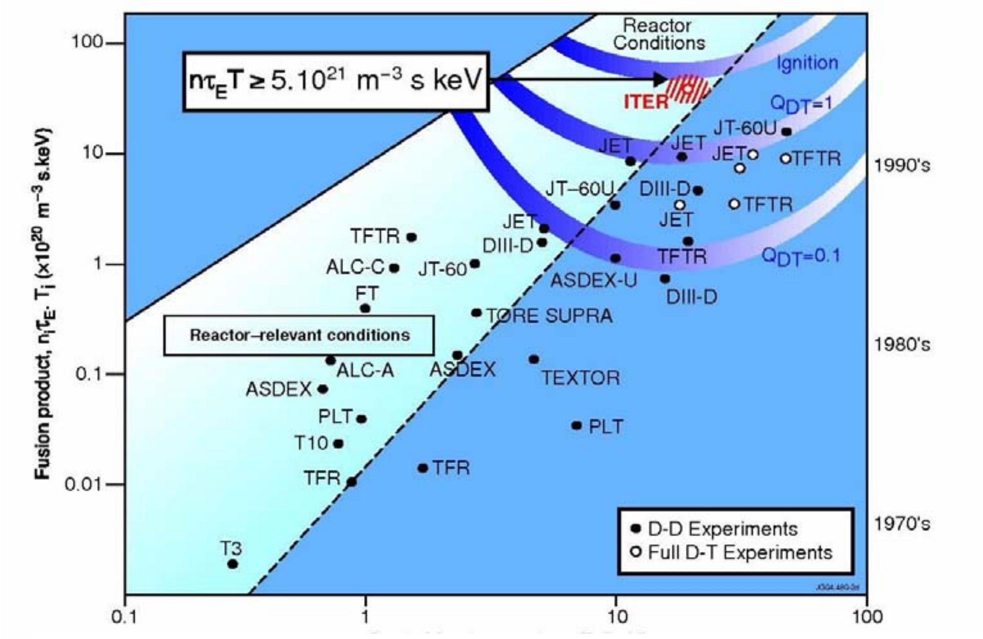


Figure 6 : Progress in the fusion triple product

1.3 Fusion fuels and materials

- *What are the global reserves for alternative nuclear fuels ?*
- *What are the Australian reserves for alternative nuclear fuels?*

Fusion fuels

The fuels for fusion are isotopes of hydrogen, the most abundant element in the universe. Of normal matter, hydrogen accounts for over 75% of all mass in the Universe. Normally, abundance of the elements is quoted with respect to hydrogen. For deuterium and lithium the abundance ratios are 1D:6500H (1 deuterium atom per 6500 hydrogen atoms) and 1Li:10^6 H (Earth), 1Li:1000 (Solar system).

Deuterium is chemically indistinguishable from hydrogen, and is found commonly in water. Enrichment of deuterated or heavy water (HDO) is usually accomplished by distillation, electrolysis, or isotopic exchange. Deuterium itself is extracted from heavy water by electrolysis. Any nation with access to water (sea or fresh) thus immediately has access to deuterium. The total mass of the hydrosphere is 1.4×10^{21} kilograms, giving an estimated terestial deuterium reserve of 23×10^{10} kilotonnes.

Excluding the oceans, lithium is found as both a mineral salt, and as a brine solution. Estimated economically demonstrated resources of lithium total 4.1 million tonnes [2], whilst the world's estimated reserves total 11 million tonnes [3]. Lithium may also be extracted from seawater (0.17g/m^3), yielding a further potential 230,000 million metric tonnes.

Like any resource, the duration D-T fuel can power civilization depends on the rate of use. Exploitation of the D-T cycle is limited only by the world's lithium reserves. Using a D-T fuel cycle, complete fusion burn of Earth's 11 million tonne lithium reserves would produce 3×10^{24} Joules. According to 2001 US DOE statistics, average world electricity consumption is 13.5TW. Even assuming a pessimistic efficiency of 30% of a fusion power plant efficiency, and total reliance on fusion power for all Earth's electricity needs, the burn duration of the D-T cycle is at least 2000 years. The burn duration is a lower estimate, as it assumes no improvement in efficiency of domestic power use, a pessimistic fusion efficiency calculation. The use of lithium in seawater pushes back this limit to several million years.

Exploitation of the D-D cycle offers millions, if not billions of years of energy.

Compared to coal and fission, fusion power offers very high energy density. A 1GW(electric) power station operating at 30% conversion efficiency will require 430 kg of Lithium, and 650 kg of deuterium in one year. In contrast, a coal power plant of the same size requires 2.5 million tonnes of coal, and a fission reactor requires 35 tonnes of uranium oxide, produced from 210 tonnes of uranium ore.

Table 1 shows Australian reserves of the fusion fuel lithium, as well as elements important in the construction of a fusion facility. As discussed, Australia reserves of lithium represent 4.1% of the world total. At present however, Australia supplies a disproportionate contribution to the world's lithium needs. The Sons of Gwalia mine in Western Australia is the world's second largest producer of lithium minerals, and the world's largest and highest-grade spodumene deposit [2].

Fusion Materials

Any form of energy production requires materials working at close to their physical limits to achieve optimum efficiency. In the case of fusion this means that different parts of the structure need to meet very stringent requirements, which differ, depending on the placement and role played. The relevant structures are:

- First Wall- high heat and radiation load, low hydrogen retention
- Diverters - extreme heat load, low hydrogen retention
- Vacuum Vessel - high radiation load, low hydrogen retention, vacuum integrity
- Lithium Blanket Module - efficient neutron capture and heat transfer
- Heat Exchange System - effective heat transfer using low neutron activation materials
- Electromagnetic Coils - superconducting material which can cope with high stress and potential neutron irradiation
- Structural materials - long term stability and rigidity in environment of moderate neutron dose and potential neutron activation.

The most extreme conditions are experienced by the first wall and diverters which are exposed to a heat load of 10-100 MW / m^2 and a continuous exposure to a high flux of 14MeV neutrons. At the same time the first wall material must be a good thermal conductor to allow heat transfer to the heat exchanger.

The first wall has to cope with:

- a heat load of 10-100 MW m^{-2},
- 14 MeV neutron irradiation,
- 10 keV D, T and He bombardment,
- tritium retention.

It also has to have the following characteristics:

- good thermal and electrical conductor,
- high melting point,
- not create long lived radioactive isotopes,
- ideally be composed of low atomic number species,

- not retain too much hydrogen,
- low sputtering yield,
- good thermomechanical properties,
- high resistance to thermal shocks,
- easy to machine.

Australia possesses significant quantities of the world's vanadium, tantalum, titanium and zirconium. These are all structurally important for a fusion power plant. Vanadium is a low activation metal, and has been suggested for use in the prototype power station, DEMO. Tantalum, titanium and zirconium are all transition metals, which offer promising characteristics in the MAX alloy class of steels (see Sec. 2.2.5). Many of these have low activation, and hence would be ideal candidates for the first wall of a fusion reactor. Finally, Australia also has significant reserves of niobium, which is required for the manufacture of superconducting field coils that will generate the strong magnetic field required both in ITER, and in power plants.

Table 1: Australian abundance of lithium and structurally important metals (kT = kilotonne)

	Mineral	**Australian EDR 1**	**Australian Total 2**
Fuel	Lithium	170 kT (4.1%)	257 kT
Structural	Vanadium	2586 kT (19.9 %)	5061 kT
	Tantalum	53 kT (94.6 %)	154.2 kT
	Titanium3	80.7 kT (21.5%)	158.7 kT
	Zirconium3	14.9 kT (40.5%)	40.9 kT
Superconductor	Niobium	194 kT (4.3%)	2147 kT

1 Economic Demonstrated Resource, 2. demonstrated plus inferred resources , 3. inferred from mineral sand deposits. **Source:** Australian Government, Geosciences Australia, 2005

1.4 Fusion power economics

- *What are the projected costs for nuclear power in Australia?*
- *How do projected costs for nuclear power in Australia compare with the costs for existing electricity generation technologies in this country?*
- *What are the likely developments in relation to future nuclear power plants (Gen. III and IV)?*
- *What are the cost implications of these developments in the medium to long term?*
- *What are the implications for Australia?*

Fusion power is not presently a commercial technology. Indeed, the research and development timeline (see Sec. 2.1) indicates it will not be a commercial technology until at least the second half of this century. As such, economic studies of fusion power are subject to enormous uncertainties. Nevertheless, comparative studies of fusion power economics do exist, at least for Europe and the US. A brief discussion of these reports provides insight into the commercial potential of fusion power, comparative to other technologies. To our knowledge, no such study exists for Australian conditions.

Our submission is based primarily on the work by Cook *et al* of the UKAEA "Prospects for economic fusion electricity" [4]. The primary findings of this report is that using modest physics optimisation, and anticipated near-term materials, the internal costs of electricity (which ignores environmental impact costs) would be 50% more expensive than fossil fuel based electricity, a figure roughly comparable to renewables. The use of advanced materials, technology and physics leads to an internal cost of electricity approaching fission and fossil fuels. Unlike renewables, fusion provides firm, uninterrupted, power.

Cook *et al* break down the costs of electricity into internal costs, which are the costs of constructing, fuelling, operating, and disposing of power stations, and external costs, which are the "estimated" impact costs to the environment, public and worker health. Internal costs have been calculated using the mathematical model PROCESS, which encapsulates the engineering, physics and costings of a commercial power station. Where possible, these have been independently verified against the projected costs for the next step fusion experiment ITER. As ITER is not a power station, the comparison is not complete. In cases where agreement was possible, agreement was within 10%. Based on these estimates, Cook *et al* predicted fusion electricity between 7-13 cents per kWhr, in 1996 Euro.

Fusion economic costs compare well to other energy technologies. Figure 7 shows the projected internal costs of electricity of coal, gas, fission, hydro, bio-mass, wind, solar photo-voltaic, tidal and fusion. Where necessary, storage costs of electricity have been included to make the electric power firm. For fusion, the internal costs of electricity are comparable to tidal power. The costs for solar photovoltaics and wind are larger than fusion, due to storage costs.

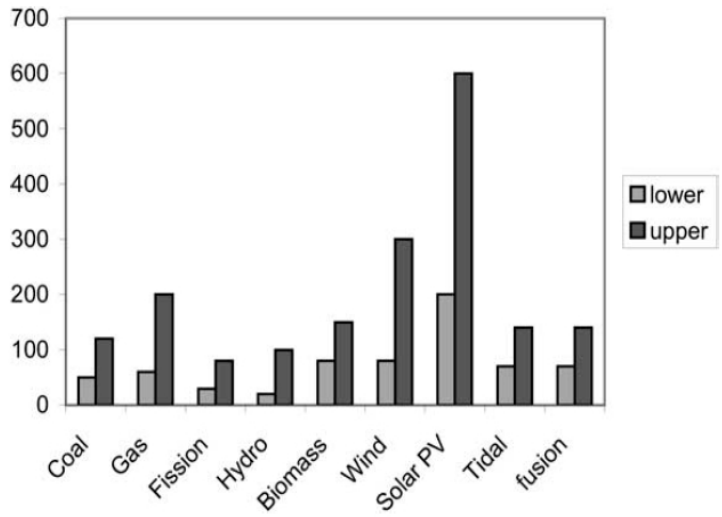


Figure 7 : Comparative internal costs of electricity production. The left axis is in units of 1996 USm$ (ie. $USD0.001) per kWhr. Reproduced from Cook *et al.* [4]

Cook *et al* evaluate the external costs of electricity production, which are those associated with environmental damage, or adverse effects on the environment, using the ExternE method. The ExternE method was developed to evaluate the external costs of a variety of non-fusion electricity sources, and assesses the entire life, fuel cycle and death of a power station. This includes materials manufacturing, construction, operation of the plant, dismantling, site restoration and disposal of waste. At each stage factors such as hazardous chemical or radioactive emissions, road accidents, occupational accidents, accidents at the plant exposing the public to risks and occupational exposure to hazards were considered. The adverse effects were quantified in monetary terms and summed to produce an estimate of the total external costs. The total external cost over the entire lifecycle of the power station was then divided by the total electrical output to produce the external costs per kilowatt-hour.

Figure 8 shows the calculated external costs, per kilowatt-hour of electricity generated, of electricity from coal, gas, fission, biomass, photovoltaics, wind and fusion [9]. All the numbers shown are subject to significant uncertainty. Fusion compares well to other technologies, with external costs comparable to wind. Compared to coal, the external costs of fusion electricity are 20 times lower.

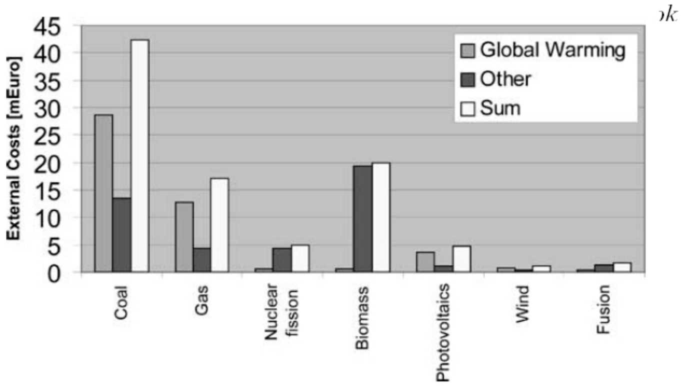


Figure 8: External costs of fusion power, using ExternE calculation. The left axis is in units of 2002 mEuro (ie 0.001Euro). Reproduced from Cook *et al.* [4]

1.5 Greenhouse emission implications of fusion power deployment

- *What are the current and projected greenhouse implications of nuclear power use globally?*
- *How are greenhouse emissions distributed over the nuclear fuel cycle?*
- *What non-greenhouse environmental implications are associated with nuclear power?*
- *What is their nature and scale?*
- *How do these effects compare to the environmental impacts of existing electricity generation technologies?*
- *What are the environmental implications for Australia of involvement in other stages of the nuclear fuel cycle, including mining, fuel enrichment, fabrication and reprocessing, power production, and waste management?*
- *What might be the potential impact on our greenhouse emissions, over time, of nuclear power use in Australia?*

Nuclear energy offers a high energy density power supply with low greenhouse emissions. The main greenhouse emissions associated with a fusion power plant are those associated with the construction and operation of the plant itself. As with fission, no CO_2 emissions are generated during reaction. Table 3, extracted from Meier and Kulinski [5] shows the estimated relative greenhouse emissions (in Tonne CO_2/ GWhr(electrical)). The fuel-related item is the CO_2 emission from mining, fuel processing, and transport. The processing of fuel for fusion is relatively simple, and the energy density high, hence the low CO_2 emissions per GWhr of electricity. The largest CO_2 emissions come from the operation of coal fired power plants. Overall, fusion is predicted to have over 100 times less CO_2 emissions than coal, and is the least CO_2 emitting technology assessed.

Table 2: Comparative CO_2 emissions from different energy technologies, in Tonnes / GWhr (electrical). Extracted from P. Meier and G. Kulinski [5]

Process	Coal	Natural Gas	Wind	Fission	Fusion (DT)
Fuel related	17	76	0	10	0.2
Plant Materials and construction	1	1	10.2	2	5.5
Operation and maintenance	956	386	4	2	3
Decommissioning	0.2	0.02	0.4	1	0.4
Total	**974**	**464**	**15**	**15**	**9**

1.6 Radioactive waste from fusion power

- *What is the current state of the technology for nuclear waste management?*
- *What is the state of play internationally and in Australia with regard to radioactive waste management (for low, medium and high level waste)?*
- *In which ways does radioactive waste management compare to, or differ from, the task required for the by-products of other power generation processes?*
- *What are forecast levels of radioactive waste from next generation reactors?*

The primary environmental difference between nuclear fission and nuclear fusion is that the 'ash' is non-radioactive helium. As described in reaction (3) however, D-T fusion also produces an energetic neutron, which will be preferably captured by the lithium blanket, thereby generating more tritium to fuel the plasma. Inevitably, a small fraction of neutrons will escape capture by the lithium blanket, and some of the vessel structure enclosing the plasma will be activated by neutron capture.

Compared to fission waste, the radioactive lifetime of the neutron activated structure is relatively short. Detailed studies of concept fusion power plant designs [6] have shown that the radiotoxicity (the biological hazard of activated materials) of fusion power plant materials decays by a factor of ten thousand after 100 years of shutdown. All of this material, after being kept in-situ for some decades, will be regarded as non-radioactive or recyclable. A small fraction (~10%) may require remote handling.

Figure 9 shows the projected material mass remaining after 100 years of shutdown of a concept fusion power plant [6]. The bulk of the power plant is either Non Active Waste (NAW), or is classified as Simple Recycle Material (recyclable with simple radioactive handling procedures). The remaining 7,740 tonnes of waste (10%) is also recyclable, but may require remote handling. The design is based on limited extrapolations in plasma physics performance, and a blanket design based on near term technology. More advanced concept designs exist, employing vanadium steel alloys and silicon carbide structures, which offer even further reduced activity.

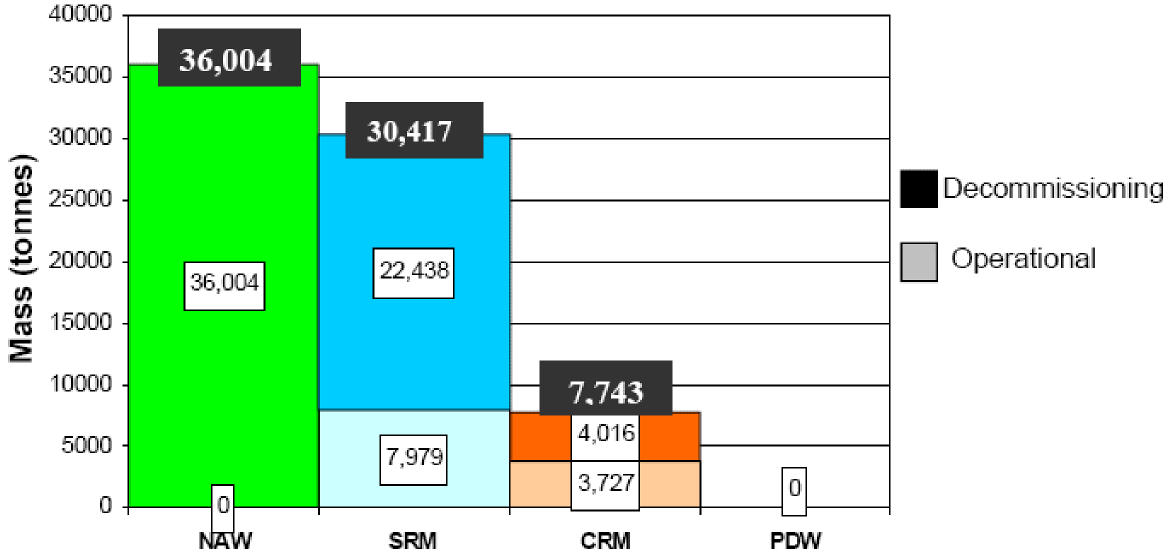


Figure 9 : Material masses after 100 years of shutdown of power plant conceptual study model B. Extracted from EFDA "A Conceptual Study of Commercial Fusion Power Plants", 2005 [6]. NAW is Non Active Waste, SRM is Simple Recycle Material, CRM is Complex Recycle Material, and PDW is Permanent Disposal Waste (non-recyclable).

1.7 Implications of fusion power

- *What is Australia's electricity supply and demand outlook?*
- *What other factors might drive the need for nuclear energy in Australia? For example, desalination or hydrogen production for transport uses might be such factors.*
- *What might the time frame be for such non electricity uses?*

Whilst fusion is a promising technology, it will not make a contribution to the world energy mix until at least 2050. In 2005, Australia's electricity generation capacity was 45GW. Due to physics constraints, fusion power plants are base-load generation systems, and most conceptual designs are based on 1GW(electric) systems. We thus envisage fusion power plants could play a significant role in future energy production, especially to provide power to major cities and electricity-intensive industrial activities (eg. aluminium smelting).

Nuclear fusion reactors are similar in operation to fission reactors in that energy is extracted initially as high temperature heat, and then converted into electricity via steam turbines. Consequently fusion reactors can be straightforwardly adapted to desalination and other applications of process heat.

Chemical Hydrogen Generation: Thermo-chemical hydrogen generation is more efficient than electrolysis, but requires high-grade heat, typically 850-950 °C. Of the many alternative chemical processes that have been proposed, some do not require temperatures quite as high, but most studies assume temperatures in the aforementioned range. Although initial demonstration reactor designs have blanket outlet temperatures in the range 600C-700 °C to simplify first wall and tritium breeding blanket design, technology development (dual cooling loops, improved structural alloys for the first wall) is underway to increase the output temperature sufficiently to more efficiently generate hydrogen.

1.8 Health and safety implications of fusion power

- *What are the health and safety implications (for all stages of the nuclear fuel cycle, including nuclear power stations)?*
- *What has been the overseas health and safety experience across the entire fuel cycle?*
- *What are the health and safety implications of next generation nuclear energy technologies?*
- *What are the comparative health risks associated with non-nuclear power production methods?*
- *Do we have sufficient trained health and safety professionals in nuclear disciplines? If not, how might demand for personnel be met?*

Health and safety modelling of fusion power is an active research topic. A series of EFDA studies, "Safety and Environmental Assessments of Fusion Power", has explored the safety and environmental impact of fusion power. Cook *et al* [7] summarise fusion as offering three areas of safety and environmental advantage : zero climate-changing emissions, low consequences of worst-case accidents, and no waste management burden on future generations. This study indicate that fusion has very good inherent safety qualities; with no chain reactions or production of actinides (radioactive elements with long half-lives). In addition, the radioactive fuel component tritium is both produced and consumed on-site, therefore there are no issues about transporting radioactive fuel.

Cook *et al* identified the following key aspects of fusion reactor safety: effluents and emissions from normal operation, including planned maintenance activities; occupational safety for workers at the facility; radioactive materials and wastes generated during operation and from later decommissioning; and potential incidents and accidents. We summarise each of these in turn:

- During normal operation, the total radioactive dosage to the most exposed member of the general public (a person located at the site boundary) would by less than 1μSv/year for gaseous leakage, and less than 0.2 μSv/year for liquid leakage. In contrast, the annual dosage to an Australian due to natural background radiation is 2000 μSv/year.

- Occupational radioactive exposure to workers is estimated to be comparable to the best performance of pressurised water fission reactors.

- The majority of the radioactive materials from operation and decommissioning can be released from regulatory control in reasonable timescales. It is estimated that 60% of the material would be below IAEA clearance levels after 30 years, growing to 80% after 100 years.

- In a worst-case accident, the total radioactive dosage to the most exposed member of the general public (a person located at the site boundary) would be comparable to the average annual natural background for a generic site. No single component failure will lead to very large consequences and no single event can simultaneously damage the multiple confinement barriers provided in fusion reactor design.

- Radioactive exposure to the general public due to a worst-case external event (eg. earthquake, terrorist attack) is limited by the vulnerable tritium inventory, which is 1kg. The release of one kilogram would result in a dosage to a member of the public in the plant area up to 4000 μSv – twice the yearly background radiation dose.

Work has continued Maisonnier *et al* [6] to extend this study into the design of four concept commercial fusion power plant designs. Maisonnier *et al* have also given consideration to improved containment concepts for the fusion reactor core, the production of activated materials during the lifetime of a fusion power plant and their possible reduction through recycling and material optimisation. Salient features of their designs include:

- Any power excursion will be self-limited to low levels by the inherent processes in the plasma. If a total loss of active cooling were to occur during the burn the plasma would switch off passively due to impurity influx deriving from temperature rises in the walls of the reaction chamber. Any further temperature increase in the structures cannot lead to melting.
- The power plant will be designed to withstand an earthquake with intensity equal to that of the most severe historical accident, increased by a safety margin.
- In case of fire, a maximum of a few grams of tritium could be released, by appropriate partitioning of the tritium inventory. At this level, evacuation would not be required.

1.9 Security and proliferation issues

- *What are the domestic and international security implications of any expanded role for Australia in one or more stages of the nuclear fuel cycle?*
- *What are the implications of nuclear power for energy security in Australia?*
- *What are the current global and Australian approaches to nuclear non-proliferation?*
- *What will be the impact of next generation nuclear energy technologies in this area?*

As energy supplies dwindle, the world economy becomes increasingly vulnerable to disruption and prices can escalate. Examples of such situations are provided by the Middle East conflicts, the Victorian gas explosion, and, most recently, the blocked oil pipeline in Alaska.

Although Australia has large supplies of natural gas, the economics of its use have become less attractive: since negotiation of the contract to supply China with gas from the North West shelf, prices have tripled. A new way to generate base load electricity is needed. Nuclear power offers a possible energy-secure, long-term solution.

Fission reactors can breed plutonium, and reactors originally built for electric power generation can readily be (and have been, as in the case of North Korea) reconfigured to produce plutonium for weapons purposes.

As proposed, fusion reactors will breed tritium for use as fuel. Tritium is useful in weapons only as an ingredient for hydrogen bombs, for which one must first have an atomic (fission) bomb, employing uranium or plutonium, as a trigger. Fusion neutrons can be used to breed plutonium, but this would involve rebuilding the reactor with uranium as the blanket, which would be complicated, costly and highly visible. The technical challenges involved in fusion make it extremely unlikely that a rogue state would elect to develop fusion reactors rather than modify fission power reactors to facilitate weapons production.

2. Research and Development

2.1 Magnetic confinement fusion research and development

- *What are the key areas of international nuclear energy R&D activity (fusion, fission across the full fuel cycle)?*

The field of fusion energy science is primarily advanced by integrated, international programmatic development. It is this programmatic development that has produced most of the innovations in fusion energy research, and driven the advance in the fusion triple-product. Uncoordinated and independent research efforts do still contribute to the science of fusion energy, but their contribution increasingly acts as more of a perturbation to programmatic development – they do not drive advances in performance.

The key area of international R&D activity in fusion energy is development of the next step fusion energy project, ITER. ITER will be the first experiment to explore the "burning plasma" regime, in which the heat of the confined products is greater than the external heating. In continuous operation, ITER will yield 5 times more power than is required to sustain the reaction, with total energy output of 500 MW. In pulsed mode, the power gain could be as high as 30. ITER, which is a precursor to a demonstration power plant, will determine the viability of fusion power. The international importance of this research is demonstrated by US. Dep. of Energy policy, which placed fusion energy and ITER as the highest priority for research funding across ***all*** the physical sciences.

The programmatic goal of ITER is "to demonstrate the scientific and technological feasibility of fusion power for peaceful purposes". The general goal is realized via a number of technical specific aims and performance requirements, details of which can be found in the ITER technical basis [8]. In summary, these aims are as follows:

- Produce and study inductively-driven, burning plasma at $Q \geq 10$ (400-500 MW) for an "extended" time, ~ 400 s (where Q is the power amplification P_{fusion}/P_{input} defined in Sec. 1.2)
- Aim at producing and studying "steady-state", burning plasma with non-inductive drive $Q \gtrsim 5$
- Demonstrate the availability and integration of essential existing fusion reactor technologies including superconducting magnets, components able to withstand high heat loads, and remote handling
- Test components for a future reactor including tritium breeding module concepts (neutron power load > 0.5 MW m^{-2}, fluence > 0.3 MW year m^{-2}).

Due to a blend of physics properties and engineering constraints, these aims force the ITER design to have the specifications listed in Table 3.

An engineering schematic is shown in Fig. 10, showing the major physical systems. For scale reference, a human is shown under the reactor core. The estimated cost of the ITER project is A$16 billion, composed of A$10 billion in construction and A$6 billion in operating funds for 20 years. In fiscal terms, ITER will hence be the world's largest science experiment, and the world's second largest science project, after the International Space Station (~A$100 billion). The ITER program is supported by over 30 of the world's most developed nations, representing more than half the planet's population.

Table 3: Key ITER operating parameters

Total Fusion power	500 MW
Steady-state non-inductive power gain	Q>5
Extended pulse length (~400 s) inductively-driven, burning plasma	Q>10
Minor radius / major radius	2.0 m / 6.0 m
I_P, plasma current	15MA
Toroidal field @6.2 m	5.3 T
Plasma Volume	837 m^3
Auxillary heating, current drive	73 MW
Central ion temperature	100 million °C

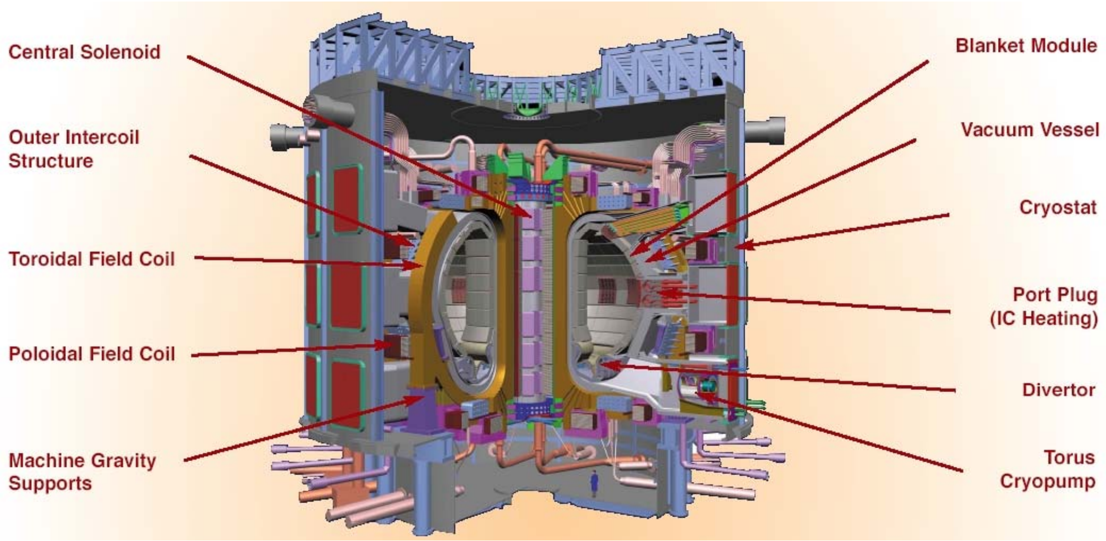


Figure 10 : Cross section cut-away of ITER, showing major systems. Note the human for scale under the reactor core.

As part of the "Broader Approach", the ITER partners are in the process of mapping out, and implementing, fusion development for the next 35 years. The following facilities and programs are being planned to accelerate fusion programmatic development:

- a remote experimental control centre as an alternate focus for interaction with ITER;
- a virtual plasma modelling laboratory, to bring together models for plasma behaviour on ITER and to make predictions, feeding back information subsequently from ITER operation;
- a "satellite" tokamak providing support (and the ability to rapidly evaluate new ideas) during ITER construction and operation;
- the prototype fusion power plant DEMO design team;
- a DEMO materials test/qualification facility (IFMIF).

It is proposed that each of these initiatives be composed under the auspices of the ITER project. A fast track development program for ITER, IFMIF, DEMO and commercial power production is shown in Fig. 11. This fast-track schedule, favoured by the UK government, would see commercial power production in operation by the middle of this century.

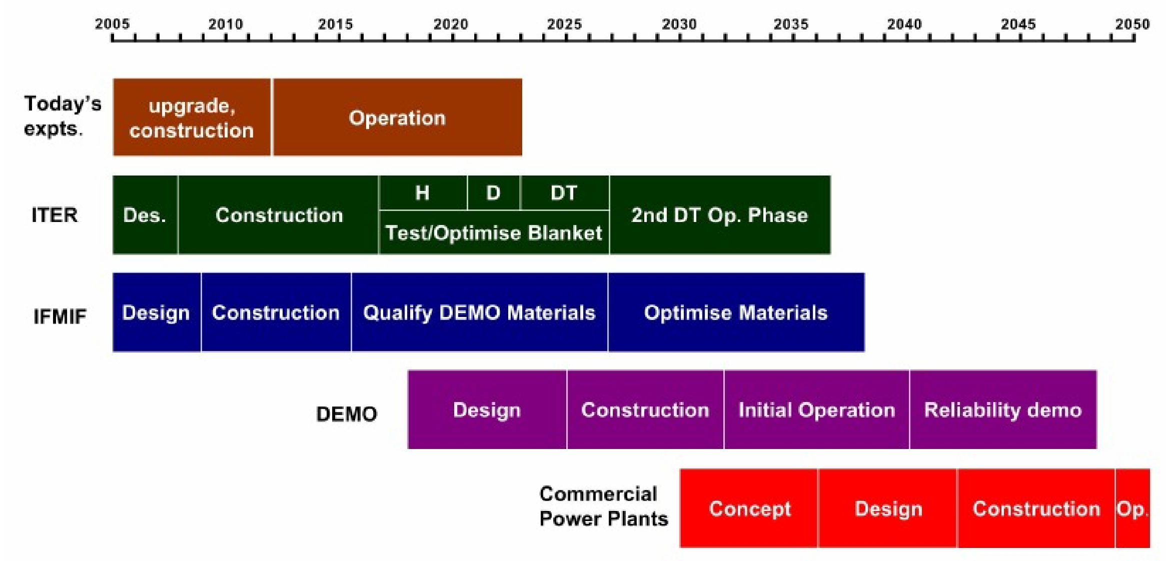


Figure 11 : "Fast-track" timeline for development of ITER, and fusion energy

2.2 Australian fusion research and development

- *What has been the history of nuclear energy in Australia?*

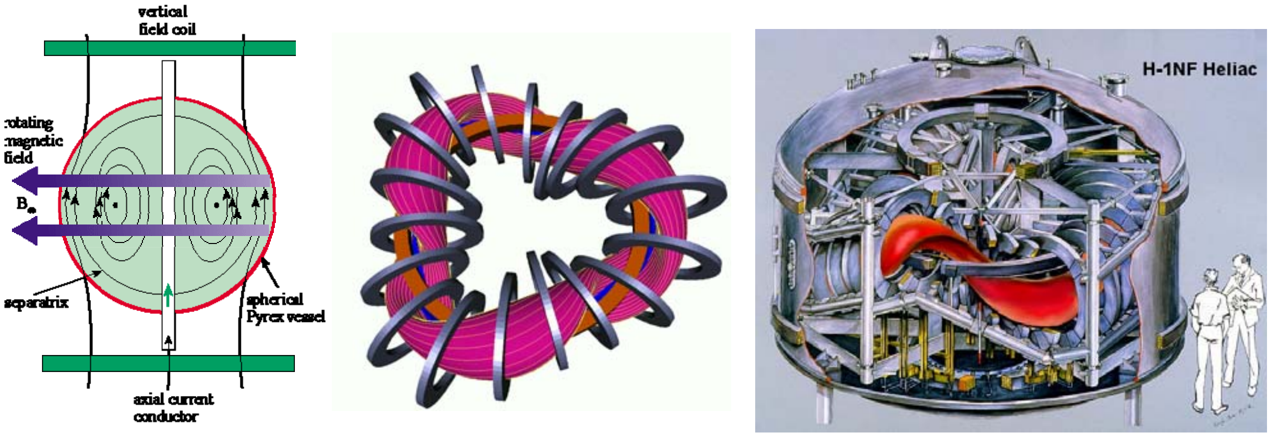
In 1933 [9], while investigating the interactions between positive ion beams and various solids at the Cavendish laboratory, Cambridge, Sir Mark Oliphant and Lord Rutherford discovered the heavy hydrogen isotope tritium, and the helium isotope He^3, by bombarding deuterated compounds with deuterons of energies up to 400kV. Energy balance analysis corroborated their postulate of a nuclear fusion process, and from stopping distances, the energies of the emitted neutron and He^3 ion were estimated at 2 and 0.7MeV respectively, within 20% of the presently accepted values. Oliphant was an early advocate of fusion energy [10].

In 1958, under Oliphant, Hilary Morton started research into plasma physics at the Australian National University. In 1963, Bruce Liley, a plasma theorist born in New Zealand, joined the group and began the construction of LT-1, which he described as a "slow toroidal theta-Z pinch". This turned out to be the first tokamak outside of Russia. Initially the most successful plasma confinement device, the "tokamak" was a doughnut-shaped ring of plasma confined by a toroidal magnetic field and a large current flowing in the torus. This current also heated the plasma, but was the source of serious "periodic disruptive" instabilities. The Russian inventors concentrated on stabilising these instabilities and stunned the international community by demonstrating a hot, well confined plasma in the T-3 tokamak in 1968.

The Australian group realised that they had a very interesting plasma device and focused on studying the instabilities in detail; they produced important insights into the phenomenon, for example, that a disruption rapidly redistributed the current throughout the plasma column [11].

Sizeable plasma research groups were founded at the University of Sydney by C.N. Watson-Munro and later (1964) at Flinders University by M. Brennan. The Sydney group established a strong tradition of research in Alfvén wave phenomena [12, 13] which continues in ongoing work on Alfvén instabilities (Sec. 2.2.3). The TORTUS tokamak, constructed in 1980 operated for around 15 years, making a significant contribution to the understanding of Alfven waves in toroidal confinement devices. At about this time, R.L. Dewar discovered modification to the

dispersion relation, caused by mode coupling, that produces some of the key features of these modes.
A continuing long-term theme at Sydney has been the development of diagnostic techniques particularly those involving spectroscopy and laser techniques, which help establish Australia's reputation in plasma diagnostics.



(a) (b) (c)

Figure 12 (a) The Rotamak spherical torus showing indicative magnetic field lines. (b) The H-1 heliac. The copper coloured circular conductor creates twist in the confining field lines. Only 18 of the 36 toroidal field coils are shown (grey) (c) Cutaway view of the complete heliac, the centrepiece of the H-1NF.

Ieuan Jones, at Flinders University invented and developed the "Rotamak" configuration (shown in Fig. 12a), a roughly spherical plasma configuration created by a rotating radiofrequency magnetic field in the sub-Megahertz range. This led to the world's first demonstration of a "spherical torus" configuration [14] in collaboration with the plasma group at the Australian Nuclear Science and Technology Organisation. This configuration is a compact form of the tokamak which is expected to be more efficient as a fusion reactor, with a larger plasma volume for a given device size. Along with the stellarator, this configuration is a contender for the experiment that will succeed ITER.

Conceived by an international team, the first heliac confinement device, "SHEILA" was built at the Australian National University in 1985 [15], followed in 1992 [16] by the H-1 heliac, the first heliac of sufficient size to approach "hot plasma" conditions (neutral particles are ionised before reaching the core, and charged particles sample the full extent of the magnetic geometry before experiencing a collision). The heliac is a toroidal confinement geometry defined by a magnetic field generated entirely by currents in external conductors. In particular, the twist of the magnetic field lines is generated by current in a central circular conductor instead of the current in the tokamak plasma. This avoids the instabilities inherent to the internal plasma current of the tokamak, and obviates the need for a transformer to drive this current. The heliac is distinguished from other stellarators by its helical plasma axis; both the magnetic field lines, and the plasma itself are highly twisted. This combination of twists increases the rotational transform (twist per turn) to 1 – 2, well above that attained in the tokamak (1/3 – 1/2), and provides stability at higher plasma pressure (β). Furthermore, H-1 is a "flexible heliac", by virtue of a helical control winding wrapped around the circular conductor, with the same helicity as the plasma. Relatively small currents (~10%) in this winding allow control of the plasma shape and vary the rotational transform from 0.6 to 1.5. Figure 12(b) and 12(c) shows the magnetic geometry and engineering cross-section of H-1.

Table 4 summarizes the institutional base of active research within the Australian ITER Forum at the time of writing. In the next five subsections, we detail Australia's existing fusion relevant research activity.

Table 4: Present fusion energy research mix of Australia

Institute	Physics
ANU	plasma physics (laboratory, magnetic confinement, space physics), surface science
Univ. of Sydney	plasma physics (laboratory, astrophysical and space theory) ,surface materials.
Univ. of Newcastle	High temperature materials
Univ. of Wollongong	Metallurgy, welding, surface engineering
ANSTO	Materials, surface engineering

2.2.1 Basic plasma physics

The ANU and University of Sydney have well established basic plasma physics research programs.

The Space Plasma Power and Propulsion Unit (SP^3) at the ANU has an extensive program on low pressure high density plasma physics. Basic research has devolved about nonlinear phenomena on plasma edges and in the plasma bulk, diffusion in high beta laboratory plasmas and space related research, computer simulation and modelling. The SP^3 unit has a broad collaborative program with a number of overseas laboratories: UC Berkeley, Bochum, Greifswald, Ecole Polytechnique Paris, West Virginia University, University of Madison. Bilateral collaboration is encouraged along with long term student exchange and co-tutelle programs.

At the present time the Sydney group is making a major contribution to the understanding of the operation of inertial electrostatic confinement devices as compact neutron sources [17]. It has an international reputation for its experimental computational and theoretical studies of plasmas containing particulates [18]. The potential important role of dust in future larger power loadings and longer operation times expected for new devices such as ITER is now recognized. In collaborations with parties directly involved in ITER current research is concentrated in several directions: the dynamics and transport of dust in the plasma sheath, near walls and in divertor areas, formation and properties of dust, and influence of dust on collective plasma processes. Analytical and numerical modelling efforts are complemented by mimic experiments in various kinds of laboratory discharges, enabling the study some particular properties of fusion plasmas [19, 20]. Sydney also has a significant program in surface modification using radiofrequency discharges and magnetically filtered vacuum arc plasmas, which has relevance to the edge regions and first wall interactions in magnetically confined plasmas.

One of these systems, a high-current multi-cathode pulsed arc system offers fine control of plasma composition and is used to create new alloys and nanostructured thin film coatings. It is a unique, highly flexible system capable of producing a wide range of plasma densities and temperatures for testing plasma diagnostics relevant to fusion devices. The group also has expertise in the use and development of ab-initio and empirical simulations of materials and uses such theoretical work to guide and interpret the materials synthesis. New ternary and quaternary alloys stable to temperatures in excess of 1500 °C have recently been developed using such a combined experiment - theory approach.

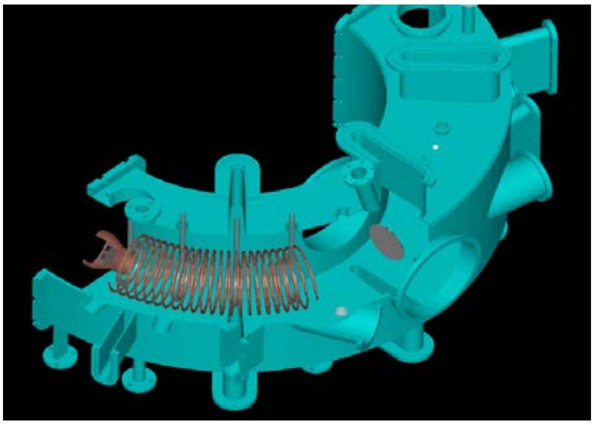


Figure 13 : Schematic of the pulsed cathodic arc at the University of Sydney. The cathode is on the far left, and the magnetic filter the spiral wound coil.

2.2.2 *H-1NF*

The present focus of Australian toroidal plasma confinement research is the H-1 National Plasma Fusion Research Facility, based on the H-1 Heliac device, which was upgraded in the first round of the Major National Research Facilities funding. Although not intended (and not large enough) to produce fusion, H-1NF allows basic research into advanced plasma shapes for the generation of devices following the ITER tokamak. The facility consists of the H-1 heliac, with average minor radius up to 0.2 m, and major radius of 1 m, in a 33 m^3 vacuum tank, containing 39 coils designed to produce magnetic fields up to 1 Tesla. Typical operation is in hydrogen, helium or deuterium plasmas at 0.5 Tesla, where the electron cyclotron second harmonic frequency matches the 28 Ghz, 200 kW microwave heating source; or at low fields in radio frequency heated (7 MHz, 100 kW) argon plasmas, where a higher pulse repetition rate is possible, and Langmuir probes may be used.

2.2.3 *Diagnostics*

Australia has been a leader in the development of sophisticated remote measurement systems for fusion plasma diagnostics and other applications. As a concrete example, coherence imaging (CI) systems developed on H-1NF in recent years represent an alternative approach to 2-D imaging of colour scenes via advanced spatial and temporal multiplex methods. High resolution CI cameras developed for plasma temperature and flow imaging have been sold or constructed for installation on the superconducting KSTAR tokamak in Korea, on the RFX reversed field pinch in Italy, at the W7-X superconducting stellarator in Germany and the JT-60U tokamak in Japan. It is likely that such systems and their variants will also be implemented on the ITER tokamak.

2.2.4 *Theory and modelling*

Fusion research poses many fundamental theoretical challenges, as a fusion plasma is a complex open system that is inherently far from thermal equilibrium due to the material and energetic fluxes to which it is exposed. This leads to the emergence of turbulence and other nonlinear phenomena.

The application of theoretical developments to interpretation of actual experiments, and the design and optimisation of new ones, requires an enormous amount of computational effort that requires access to supercomputers and the use of integrated modelling techniques.

The ANU theory group has an international reputation in both the development of new concepts using magnetohydrodynamics and dynamical systems theory, and the development of sophisticated computational approaches in full 3-D geometry. The group has graduated ten PhD students whose thesis work concerned fusion plasma theory, played an important role in obtaining Major National Research Facility funding for the H-1NF heliac, and contributes to the international profile of Australia in fusion science through international committees and conferences. It also contributes to Australian physics and mathematics generally, such as initiating the formation of the ARC Complex Open Systems Research Network (COSNet).

In order to accurately predict the behaviour of a plasma it is also vital to understand the interactions between all the species in the plasma. This is the field of atomic collision theory in which Australian scientists have excelled since the pioneering work by two Australian PhD students, Massey and Moore, while in Cambridge back in 1932.

The collisions of interest are governed by the laws of quantum mechanics with the long-ranged Coulomb potential, and are particularly difficult to formulate and solve. However, with the advance of supercomputers in the 1990s this field has been revolutionised and now the theory has matured to be of great assistance to fusion plasma modellers. The atomic collision group at Murdoch University has lead the field for over a decade and has developed computational theory for the interactions of electrons, atoms and ions of just the type likely to be found in fusion and astrophysical plasmas. For specific atomic and ionic species the theory is able to yield more accurate results than experiments can measure. For this reason they became consultants to the International Atomic Energy Agency in support of the fusion program, see for example de Heer *et al* [21]. This consultancy is still ongoing with regular workshops in Vienna where the current knowledge of atomic collision data is assessed and new data requirements are determined.

*2.2.5 **Materials science***

For ITER the materials have been chosen. In the most critical heat load locations the materials used will be tungsten, beryllium and carbon. These are not the best choices but the best compromises at this stage. More work is needed to develop better materials to meet these demanding situations.

Australia has a strong materials science community and there is a broad expertise base upon which meet these needs. In the broader structural area expertise in steels across a number of institutions can be called on. New steels need to be characterised and approved which contain only low neutron activation elements. This is important to ensure that any structure will not develop significant levels of radioactive emissions either during its working life or be an issue in the decommissioning phase.

For the most critical phase of the first wall, MAX alloys are a promising base from which to explore new low activation materials. Some have outstanding properties which can be best characterised as ceramics with the best properties of metals.

MAX alloys comprise (eg Ti_3SiC_2 and others in its class)

M = transition metal (Sc, Ti, V, Cr, Zr, Nb, Mo, Hf, Ta)
A = Al, Si, P, S, Ga, Ge, As, Cd, In, Sn, Tl, Pb
X = either C or N

Stochiometries of these can be in the ratio of 211, 312 or 413 which leads to over 600 potential alloys and more than half of these are comprised of low neutron activation materials. Australia is a major source of some of the elements required (eg vanadium, titanium, tantalum). There are currently research efforts at the University of Newcastle, the University of Sydney and Murdoch University in the synthesis and testing of MAX alloys.

Other key performance indicators of fusion materials include weldability, resistance to high heat flux and radiation, the embrittlement effects of hydrogen and helium transmutation elements and high thermomechanical loads that produce significant stresses and time-dependant strains. One key factor that has not received sufficient attention to date is the consideration of weld regions in fabricated components, as these are often more structurally heterogeneous and more likely to contain detrimental transformation products or structural defects. The University of Wollongong has an active materials science program able to address these issues, built upon 30 years experience.

2.3 International research centres, partnerships, and agreements

- *Where are the existing centres of research activity?*
- *What international partnerships exist?*
- *To what extent does our existing R&D link in with international efforts?*
- *Where are the existing centres of research activity?*
- *Are there areas where there is scope for greater international collaboration?*

Existing Agreements

Fusion research is a truly international enterprise that, since the unilateral de facto declassification by Kurchatov during the visit of Kruschev and Bulganin to the UK in 1956, followed by full declassification and the "Atoms for Peace" conference in 1958, has become a model for international cooperation. It was perhaps for this reason that Reagan and Gorbachev adopted the ITER project as a step towards thawing the cold war at their meeting in Reykjavik in 1986.

Since the fall of the Soviet Union, Russia cannot be said any longer to be a major power in fusion research, though it still contributes manpower to the ITER project. The major players are the US (Department of Energy), the EU (Euratom), Japan (Ministry of Education, Culture, Sports, Science and Technology), with China, Korea and India big players in the second rank—full ITER partners, with large superconducting tokamak experiments. A number of other countries, in particular Australia and Brazil, have a history of contributing to fusion research, both experimentally and theoretically. To aid in reading the content below, a list of abbreviations and acronyms is provided:

DoE	=	US Department of Energy
EU	=	European Union
MEXT	=	Ministry of Education, Culture, Sports, Science and Technology, Japan
STA	=	Minister of Science and Technology (obsolete), Japan
Monbusho	=	Ministry Education, Culture and Sports (obsolete), Japan
JAERI	=	Japan Atomic Energy Research Institute, Japan
NIFS	=	National Institute for Fusion Science, Japan
CRPP	=	Centre de Recherche en Physique des Plasmas, Switzerland
UKAEA	=	U.K. Atomic Energy Authority

In the following we sketch Australian involvements with some of these players:

Japan:
Until the merger of the Monbusho and STA ministries in 2001, Japan had two fusion programs, one based in the universities (under Monbusho) and one JAERI's Naka research establishment (under STA). Australian researchers have, over the last couple of decades, forged strong links with both arms of the Japanese fusion effort through a series of Australia-Japan workshops in diagnostics and theory and through exchange visits.

Since ANSTO left the field of fusion research in the late 1980's the Australian effort has been completely university-based, so it is natural that our links with the Monbusho program are stronger. These natural links are strengthened by similarities in research programs: H-1 is of the same concept class (stellarators, an alternative to the tokamak for a post-ITER fusion reactor design) as is the main focus of the Monbusho program.

The main Monbusho laboratory, the National Institute for Fusion Science (NIFS) was extremely supportive during the upgrade of H-1NF using the MNRF funding, with the Director-General of NIFS making a special trip to ANU to sign a memorandum of understanding, the provision of a gyrotron on indefinite loan, technical assistance and exchange visits.

USA:
A number of Australian researchers have graduate or postdoctoral experience in the US and there are ongoing exchange visits. Also, Australia trained a number of senior researchers now working in the US program. Links with the US can thus be classed as strong.

A memorandum of understanding has been signed with the Princeton University Plasma Physics Laboratory (a DoE-funded laboratory and the flagship of the US fusion effort). Recently, the Head of the ANU's Plasma Research Laboratory, Professor Jeffrey Harris, took indefinite leave from ANU to return to the US, based at Oak Ridge National Laboratory but liaising with the new stellarator project, NCSX, at Princeton. He forms a valuable link into the US program.

Another major DoE-funded laboratory with which there exist good links is General Atomics in La Jolla, California, and, on the theory side, there are ongoing collaborations with the DoE-funded Institute for Fusion Studies at the University of Texas at Austin, and at other universities.

EU:
Historically, antipodean expatriates in the UK (starting with Rutherford and Oliphant) made important contributions to fusion, and the return of Oliphant to Australia in1950 to found the Research School of Physical Sciences and Engineering at ANU led, ultimately, to H-1NF. Australians physicists have made important contributions to the Joint European Torus (JET) next to the UKAEA Culham Laboratory, and an Australian engineering firm did the project management when JET was built.

Currently there is a collaboration agreement between Sydney University/ANU and the UKAEA on research on the Culham MAST experiment. There are also potential collaborations with Warwick and York Universities as a result of the recent funding boost to the universities to train more students in fusion science so there will be a cadre ready to participate in ITER and other developments later this century.

One of Australia's significant European collaborations is with Germany as it has an advanced stellarator program in the Max Planck Institute for Plasma Physics at Garching and Greifswald. Theoretical and experimental collaborations are ongoing.

For the purposes of this discussion we classify Switzerland as part of the EU because it receives Euratom funding. It has had a long history of hosting Australian postdoctoral researchers at the Centre de Recherche en Physique des Plasmas (CRPP) in Lausanne, and also of exchange visits between researchers.

Other European links are with research laboratories in Austria, France, Italy, Spain and Sweden.

Korea
Australia has an existing collaborative project on design of a diagnostic for the superconducting tokamak KSTAR at Daejeon, and an Australian has been appointed to the KSTAR International Advisory Committee. The Koreans are keen to involve non-ITER partners from the Asia-Pacific region to collaborate as part of their ITER contribution.

International Agreements
In addition, Australia participates in international committees related to fusion, notably the International Energy Agency Implementing Agreement on the Stellarator Concept and the International Union on Pure and Applied Physics C16: Commission on Plasma Physics.

The Future

This submission calls for immersion into international programmatic research, via ITER and the "Broader Approach". Research engagement should be based on expanding and developing existing research strengths, as outlined in Sec. 2.2.

It is our recommendation that we bring together the Australian efforts in plasma physics, collision physics and materials science, to foster a research focus on fusion related activities and create a critical mass of research which will ensure a sustainable research effort into the future. This could be achieved by the establishment of a Centre for Fusion Science, spanning relevant expertise across university and government research organization sectors. The typical budget for such a centre would be $6M per annum. Depending on the nature of the funds, it is possible that up to 20% could come from the participating institutions. In the course of our research we would expect to attract substantial international revenues to expand the project through collaborations.

Outcomes over a five-year period would expect to exceed:

- Training over 25 research higher degree students
- Training 30 postdoctoral fellows in advanced research skills in this field.
- Bringing over 30 international experts to Australia to collaborate with the researchers
- Active involvement of over 20 of Australia's leading scientists in this field
- Participation in conferences leading to over 300 papers submitted
- Publication of in excess of 300 research papers
- Submission of at least 10 patents

2.4 Fusion spin-off technology

- *What other non-market factors might influence the demand for nuclear power in Australia? For example, non-market factors could include environmental benefits, energy security, and research spillovers.*

Australian plasma physics has generated a number of spin-off technologies. Coherence imaging systems are now being trialled at Bluescope steel mills in Port Kembla for optical thermography of the molten metal stream issuing from the blast furnaces. Potential applications for this new type of multi-spectral imaging can also be found in other areas of industry, defence and science. As another example, the helicon source, a technology for generation of high density plasma, was pioneered at ANU and is now widely used in the microelectronics fabrication industry. The helicon double-layer thruster, a derivative of the source technology, is now being tested by the European Space Agency as a possible source of thrust for future deep space missions. Research at the University of Sydney on plasma processing and modification of materials has produced commercial outcomes in relation to solar selective surfaces, industrial hard coatings, and biocompatible surfaces. The international program in fusion physics has, and will continue to generate spinoff technologies spanning medicine, pulsed power, power conversion, waste processing and materials processing [22].

An Australian focus on materials issues offers the opportunity for a number of leading edge spin off products. The extreme conditions faced by the first wall are similar to extreme environments currently faced or envisaged in future applications in aerospace applications and in other energy production applications:

- The continued growth of aerospace applications in aviation (passenger and military) and the greater demands applied to body parts and engines will need new materials to meet the heat load and corrosive environments.
- In energy production, there are several developments being investigated to improve the efficiency of coal fired power stations which require higher operating temperatures and more chemically aggressive environments.
- In solar thermal power conversion, the collector has to have the combined property of being a good energy absorber at the relevant wavelengths while also existing in a high temperature air environment.

All three areas share high temperature, chemically aggressive environments. Relevant spin-offs from the extreme materials research undertaken for the first wall of a fusion reactor will potentially benefit a much broader community.

2.5 Fusion research and development funding

- *What is the existing level of funding for nuclear R&D in Australia and overseas?*

Australia's fusion effort is funded through a combination of University block grants, curiosity-driven funding programs (eg. ARC Discovery Projects), and infrastructure funding such as the H-1 Major National Research Facility. Evaluation of the current level of funding is not a trivial exercise. By our calculation, which involves accounting personnel, applying a multiplying factor according to fraction of time invested, and summing over personnel and infrastructure, current Australian fusion research expenditure totals $1.3 million per annum. Almost none of this funding is strategically aligned. Representatives of the ITER Forum will be able to provide more detail if requested.

A complete quantification of the international fusion energy budget is beyond the scope of this submission. Rather, we present some case examples from the European Union, US and UK. In the case of the EU, the research budget across energy disciplines for the EU Framework Program 6 is used to illustrate the relative weighting applied to different energy technologies. This data is compared and contrasted to the mix of Australian research and development (R&D) investment. The EU commission research budget does not however include research expenditure of national governments. Instead, we have used US and UK R&D funding, as fraction of GDP, to provide a reference point for international fusion energy R&D expenditure. In turn, these estimates are applied to the Australia economy, to highlight the gap in existing research funding in this field.

The energy R&D mix

Table 5 shows the EU the 6th Framework research budget [23]. Energy research is divided into sustainable development, global change and ecosystems, and the nuclear energy orientated Euratom program. Fusion and sustainable energy research are funded at comparable levels, at €810 million, and €750 million respectively. Over 60% of Euratom funding is allocated to fusion energy research.

Australia's investment in energy research is summarized by the 2005 DITR commissioned report, "Energy R&D in Australia –A statistical profile of expenditure". Where data is available (from 1997), this report concludes that Australia's R&D profile is dominantly fossil fuel based. In 2003 US currency, Australia spent $US95 million on fossil fuels, and $US6.85 million of renewables. The total energy R&D budget was $131.9 million.

Fusion R&D Funding

In 2006, the US magnetic confinement fusion program budget increased to US$287 million, up by 7.7% from the 2005 budget [24]. The 2007 budget request is US$319 million. In 2005, the estimated GDP (purchasing power parity) was $US12.36 trillion, or $41,800 per person [25]. The US magnetic confinement program thus represents 0.0021% of US GDP, or US$0.89 per capita.

In 2003, the UK Engineering Physical Sciences Research Council took over responsibility for the UK's domestic fusion program. From April 2004, block funding of £48million was awarded for four years operation [26]. An additional £8.65 million was allocated to fusion work on JET and ITER over the life of the block grant. In 2005, the estimated GDP (purchasing power parity) was US$1.83 trillion. Converting to £56.65million to USD at August 2006 exchange rate gives US$107 million over four years. Over the four years, the UK fusion program represents 0.0015% of GDP, or US$0.44 per person. ITER contributions are in addition to this sum.

In 2005, Australia's estimated GDP (purchasing power parity) economy was US$640.1 billion. Based on UK and US estimates (0.0015% - 0.0021%), Australia's expenditure should be in the range $US9.6 million to $US13.4 million per annum. In Australian dollars at August 2006 exchange rates, this is between A$12.5 million and A$17.5 million, or between A$0.62 and A$0.86 per person. Australia's actual investment in fusion energy R&D is roughly 10 times smaller than the US and UK average, at AUD$1. 3 million, or between A$0.06 and A$0.08 per person. This level of support will not sustain the Australian R&D effort.

Table 5: European Union 6th Framework energy research budget

Area	Billion €
Sustainable development, global change and ecosystems	**2.12**
Global change and Ecosystems	0.7
Sustainable energy: renewables, energy storage and efficiency, alternative motor fuels, fuel cells, clean coal.	0.81
Sustainable (surface) transport	0.61
Euratom Research	**1.23**
Fusion energy research	0.75
Nuclear fission	0.48
Management of radioactive waste	0.09
Radiation protection	0.05
Other activities (nuclear technology & safety)	0.05
Euratom activities at the Joint Research Centre	0.29

2.6 Education and training

- *What are our current educational and training capabilities in the nuclear field?*
- *What are the education and training implications of an expanded Australian role in the nuclear fuel cycle?*

Physics majors from Australian universities have sufficient background to enter honours programs which allow an emphasis on plasma physics and fusion at the Australian National University, the University of Sydney and Flinders University. These three universities also have an emphasis on plasma physics in the last undergraduate year. With the ANU being the most significant, all three can offer relevant PhD programs in plasma physics/fusion. Australia has a long history of providing PhD graduates from these institutions who have taken up major positions in the International fusion research program.

Via the H-1 heliac and related programs, the ANU has the capacity to produce PhD graduates appropriately trained for participation in the ITER program at a rate of about 1-2 per year. Sydney and Flinders would have somewhat lesser capacity. Adelaide and Melbourne can produce PhD graduates appropriate to the nucleonics of fusion, while Newcastle and Wollongong can produce PhD graduates appropriate to the materials aspects of fusion. Australian involvement in ITER would provide an incentive for Physics honours and engineering graduates to enter these PhD programs.

As a flagship sustainable energy project, ITER engagement offers a spectacular pathway in which to attract students to science and engineering disciplines. Postgraduates trained in fusion science have highly transportable skills. This may address in part the looming national skills shortage, estimated to be as many as 75000 scientists by 2010.

2.7 Implications for expansion of fusion power research and development

- *What, if any, are the implications of a greater role for nuclear power in Australia for the research sector?*

Research in Generation IV reactors and fusion systems are so closely aligned that research in one benefits the other field: thus a greater role for nuclear power in Australia intrinsically boosts the potential of research in fusion.

It will particularly help build absorptive capacity in fusion research. Absorptive capacity is the ability of an organisation to identify, select, adapt and utilise innovations from elsewhere. A greater role for nuclear energy would encourage an increase in the number of skilled graduates and boost opportunities for companies providing advanced materials and consultancy services for nuclear energy businesses. The capabilities of these graduates and companies will be transferable from energy to fusion, thus increasing the nation's absorptive capacity in this area as well. However, without a formal outlet such as participation in ITER and a local centre of excellence in fusion, this absorptive capacity will be fruitless.

The flow will work in the opposite direction as well: participation in fusion research would increase absorptive capacity for nuclear energy, especially through the international linkages that will be established and sustained through the ITER project.

ITER will be the world's largest science experiment, and the world’s second largest science project after the International Space Station. The establishment recently of a working group of the Prime

Minister's Science, Engineering and Innovation Council indicates the strong importance that is being attached to engagement in international science and technology.

Finally, engagement in ITER, and the Broader Approach also offers access to ITER, the parallel IFMIF facility, satellite tokamak experiments, and a research center in Japan. ITER engagement will also enable access to the demonstration reactor program, DEMO. As demonstrated already by the work of the ITER Forum, which is bringing together materials science, plasma physics and atomic collision physics communities, ITER engagement will build cross-linkage across different disciplines.

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