Australian ITER Forum

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The Secretariat,
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South Australia

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Submission to the Nuclear Fuel Cycle Royal Commission

The Australian ITER Forum is a network of over 170 scientists, engineers, research administrators and policy specialists advocating sustainable Australian engagement in ITER, the experimental fusion reactor that is now being built in France. Fusion is process that powers the Sun and the stars. If realised on earth, fusion energy offers millions of years of baseload energy generation, with almost no greenhouse gas emissions and very little radioactive waste compared to nuclear fission energy and coal.

The Forum is pleased to have this opportunity to provide this submission to the Royal Commission. Realising the potential of nuclear fusion technology for energy production requires long term commitment to multilateral programs designed to carry out the necessary R,D&D. ITER is the only global collaborative program pursuing this objective.

The Forum, together with the Australian National University (ANU) and the Australian Nuclear Science and Technology Organisation (ANSTO) has a five-year $16.3m strategic plan for fusion research in Australia: *"Powering Ahead: A National Response to the Rise of the International Fusion Power Program"*. The plan, which was released on 10 July 2014, focuses on international collaboration, and features dedicated programmatic support for Australians to participate of the International Tokamak Physics Activity, which operates under the auspices of ITER, the development of Australian diagnostic on ITER, operational support for the Australian Plasma Fusion Research Facility, and a new capability for fusion materials studies involving the ANU, ANSTO and the University of Newcastle.

We would be willing to provide more detail to the Royal Commission and/or appear in person if required.

Yours Sincerely,

M.J. Hole

A/Prof. Matthew Hole, Chair, Australian ITER Forum
Dr Richard Garrett, Australian Nuclear Science and Technology Organisation
Prof. John O'Connor, Chair of the Board of the Australian Plasma Fusion Research Facility, Professor of Physics University of Newcastle, Australia.

Preamble:

Nuclear fusion is the process by which elements much lighter than iron bind together and release excess energy. This is what powers the Sun and the stars. If fusion power were harnessed directly on Earth, it could produce inexhaustible clean base-load power, with a component of sea-water as the primary source of fuel. The process is free of CO2 emissions and is intrinsically safe. Radioactive waste is very-low level and indirect, arising from neutron activation of the first wall. With current technology, the materials of a fusion power plant could be completely recycled within about 100 years of shutdown.

Today's nuclear power plants exploit nuclear fission to produce electricity. In nuclear fission elements much heavier than iron, such as uranium, thorium, and plutonium release energy by splitting into lighter daughter nuclei (or atoms). This process happens spontaneously in unstable elements, and can be amplified and controlled through a chain reaction involving neutrons.

In contrast, fusion power exploits the other side of the nuclear "valley" of binding energy per nucleon. Unlike fission, no nuclei spontaneously undergo fusion: nuclei are positively charged and must overcome, or quantum tunnel through, the electrostatic Coloumb barrier before the strong nuclear forces can bind nuclei together. In nature, the gravitational field of stars is strong enough that the stars core temperature, density and volume is sufficient to enable fusion through "quantum tunnelling". In the laboratory quantum tunnelling rates are far too low, and so the Coloumb barrier must be overcome by making the fuel nuclei sufficiently hot.

The easiest fusion reaction to initiate, which was first co-discovered by Australian Sir Marc Oliphant, is the combination of deuterium and tritium, isotopes of hydrogen, to form helium and an energetic neutron. The necessary temperature is around 10 keV, or 120 million degrees C. At these extreme temperatures, which are six to seven times hotter than the core of the sun, the fusion fuel exists as ions in the plasma state. That is, the fuel atoms are split into their component electrons and nuclei.

In the laboratory, confinement at such extremes can be accomplished through magnetic fields, where superconducting coils generate a powerful donut-shaped magnetic bottle. Today's experiments can confine plasmas at the required temperatures for net power gain, but the plasma density and energy confinement time (a measure of the cooling time of the plasma) are too low to self-heat the plasma to power plant operating conditions. Over a 40 year period of research, this fusion triple product of temperature, density and confinement time has increased by a factor of 1000.

The next step fusion experiment, ITER, under construction now in Cadarache in the south of France, will explore the "burning plasma regime", where the plasma heating from the confined products of fusion reaction exceeds the external heating power. The total power gain for ITER will be more than 5 in near continuous operation, and approach 10-30 for a short duration.

At a cost exceeding USD$ 20 billion dollar, and funded by a consortium of 7 nations and alliances, ITER is the largest science project on the planet. The scientific purpose of ITER is to demonstrate the scientific and technological feasibility of generating fusion power for peaceful purposes (principally electricity generation).

The engineering, physics and materials challenges are significant. ITER will have a field strength of ~5 T on axis and a device radius of 6 m, confining 840 cubic metres of plasma

(1/3 of an Olympic swimming pool). ITER will be a 23,000 ton device with 100,000 km of niobium tin superconducting strands. Niobium tin is superconducting at 4.5 K, and so the entire machine will be immersed in a liquid helium cooled cryostat.

ITER first plasmas are, at present, envisaged in 2020. Burning plasma experiments, planned from 2027, will be the first experiments to be dominantly heated by fusion-generated helium particles. . Accessing, maintaining and controlling this state, while avoiding performance-limiting instabilities such as large Edge Localised Modes (ELMs), is a grand science challenge. So called "Type I" ELMs have the capacity to deposit up to 10% of the stored energy of the plasma on the divertor. Unmitigated, they could melt the divertor target in as little as a single pulse. The materials challenge for successor power plants is to develop materials that can withstand very high heat flux (10-100 MW m^{-2}) and maintain resilience to a high flux of 14 MeV neutrons.

Information obtained from building and operating ITER will inform the design of successor power plants. The commercialisation path of fusion power envisages multiple prototype demonstration power plants, constructed in the 2030's. Concept designs are typically 1 GW electric, and 3 GW thermal. While first generation power plants will probably be the size and scale of ITER, it is hoped that improvement in magnetic confinement and turbulent control will lead to more compact later generation power plants. Likewise, power plants will be lower cost than ITER: long-term economic modelling (see Cook *et al.*[1]) forecasts the construction, fueling and operation costs of fusion power being similar to fission, and external costs to the environment comparable to wind.

In this submission we address Issue Paper 3: Electricity Generation from Nuclear Fuels.

A. NUCLEAR FUELS AND ELECTRICITY GENERATION

3.1 Are there suitable areas in South Australia for the establishment of a nuclear reactor for generating electricity? What is the basis for that assessment?

Fusion power plants, like any other large scale electricity generation scheme that relies on the steam cycle to drive a turbine (e.g. coal or nuclear fission) requires a reservoir of water in the form of a lake or the ocean. South Australia already has coal power plants, and so there are already available sites.

3.2 Are there commercial reactor technologies (or emerging technologies which may be commercially available in the next two decades) that can be installed and connected to the NEM? If so, what are those technologies, and what are the characteristics that make them technically suitable? What are the characteristics of the NEM that determine the suitability of a reactor for connection?

According to the present development time-line for fusion power a demonstration power plant will not be built until the mid 2030's. It is likely that this places fusion power strictly outside the timeline of deployment within the next two decades. Attractive characteristics of fusion power are: baseload, zero C02 emissions, no long-lived radioactive waste, no potential for catastrophic accidents, zero weapon potential, relatively simple and low cost decommissioning, and an almost inexhaustible supply of fuel. Most concept fusion power plants are 3 GW (thermal), 1 GW (electric) designs.

3.3 Are there commercial reactor technologies (or emerging technologies which may be commercially available in the next two decades) that can be installed and connected in an off-grid setting? If so, what are those technologies, and what are the characteristics that make them technically suitable? What are the characteristics of any particular off-grid setting that determine the suitability of a reactor for connection?

Although they are projected to produce significant electric power, fusion power plants have significant electrical start up power consumption requirements to cool the field conductors to superconducting temperatures, generate the confining magnetic field, and initiate and heat the plasma. This will not make it practical for off-grid settings.

B. VIABILITY OF ELECTRICITY GENERATION IN SOUTH AUSTRALIA

3.4 What factors affect the assessment of viability for installing any facility to generate electricity in the NEM? How might those factors be quantified and assessed? What are the factors in an off-grid setting exclusively? How might they be quantified and assessed?

A fusion power plant, like a nuclear fission power plant, will require a workforce skilled in large scale engineering, heavy manufacturing, and competent in nuclear licensing. There are a large number of high tech subsystems in the construction and subsequent operation of a fusion power plant, including cryogenics, superconducting fields and control systems. Some of these have overlap with the heavy manufacturing industry of Adelaide ports in the construction of Collin’s class submarines.

3.5 What are the conditions that would be necessary for new nuclear generation capacity to be viable in the NEM? Would there be a need, for example, for new infrastructure such as transmission lines to be constructed, or changes to how the generator is scheduled or paid? How do those conditions differ between the NEM and an off-grid setting, and why?

The transmission requirements are the same as existing large-scale electricity generation plants.

3.6 What are the specific models and case studies that demonstrate the best practice for the establishment and operation of new facilities for the generation of electricity from nuclear fuels? What are the less successful examples? Where have they been implemented in practice? What relevant lessons can be drawn from them if such facilities were established in South Australia?

Fusion is a technology still under development, and so there are no case studies of an operational power plant. The purpose of the ITER project, now under construction, is to demonstrate the scientific and technical feasibility of fusion power for electricity production. ITER will produce 500 MW of fusion power. The engineering requirements for the construction of a fusion power plant will be similar to ITER.

3.7 What place is there in the generation market, if any, for electricity generated from nuclear fuels to play in the medium or long term? Why? What is the basis for that prediction including the relevant demand scenarios?

It seems likely that there will always be a place for baseload power supply within the national electricity market. The existing array of storage solutions limits the contribution of intermittent sources such as renewable power to the national power grid.

The construction and operation of large scale supply solutions that are low or zero C02 emission are essential as part of a solution that addresses global warming. Large-scale electricity generation can also power energy intensive processes, such as desalination (an issue particularly important to South Australia) and aluminium smelting.

C ADVANTAGES AND DISADVANTAGES OFDIFFERENT TECHNOLOGIES AND FUEL SOURCES; RISKS AND OPPORTUNITIES

3.8 What issues should be considered in a comparative analysis of the advantages and disadvantages of the generation of electricity from nuclear fuels as opposed to other sources? What are the most important issues? Why? How should they be analysed?

Fusion power is not presently a commercial technology, and is unlikely to make a contribution to the world energy mix until at least 2040. 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.

Our analysis is based primarily on the work by Cook *et al* [1] of the UKAEA "Prospects for economic fusion electricity". The primary findings of this report is that by 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.

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, including CO2 emissions, and impact to 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 1 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.

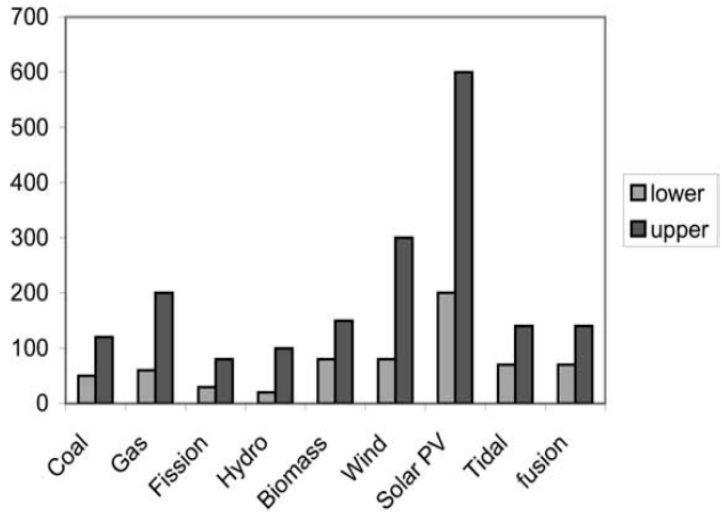

Figure 1 : Comparative internal costs of electricity production. The left axis is in units of 1996 USm$ (ie. $USD0.001) per kWhr. Reproduced from [1].

Cook *et al* also 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 2 shows the calculated external costs, per kilowatt-hour of electricity generated, of electricity from coal, gas, fission, biomass, photovoltaics, wind and fusion. 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.

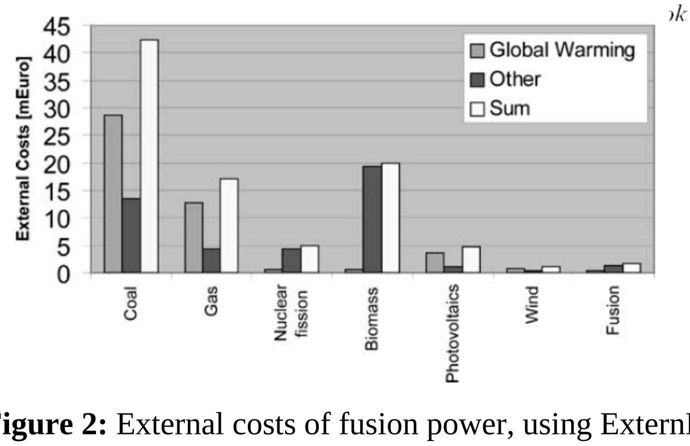

Figure 2: External costs of fusion power, using ExternE calculation. The left axis is in units of 2002 mEuro (ie 0.001Euro). Reproduced from [1]

3.9 What are the lessons to be learned from accidents, such as that at Fukushima, in relation to the possible establishment of any proposed nuclear facility to generate electricity in South Australia? Have those demonstrated risks and other known safety risks associated with the operation of nuclear plants been addressed? How and by what means? What are the processes that would need to be undertaken to build confidence in the community generally, or specific communities, in the design, establishment and operation of such facilities?

Fusion power plants are not capable of loss of coolant reactions like those at the Fukushima power plant. For fusion, a loss of power supply means the reaction ceases. In the worst case accident in which the inventory of tritium was released to the radioactivity would not exceed background levels at the site perimeter.

3.10 If a facility to generate electricity from nuclear fuels was established in South Australia, what regulatory regime to address safety would need to be established? What are the best examples of those regimes? What can be drawn from them?

See experiences from France in Cadarache, with the construction of ITER. ITER has already received its nuclear license and its construction and operation will be controlled by these conditions.

3.11 How might a comparison of the emission of greenhouse gases from generating electricity in South Australia from nuclear fuels as opposed to other sources be quantified, assessed or modelled? What information, including that drawn from relevant operational experience should be used in that comparative assessment? What general considerations are relevant in conducting those assessments or developing these models?

Projected greenhouse gas emissions per kWHr have been included in the ExternE calculations of Cook et al (see response to 3.8). They are projected to be similar to wind.

3.12 What are the wastes (other than greenhouse gases) produced in generating electricity from nuclear and other fuels and technologies? What is the evidence of the impacts of those wastes on the community and the environment? Is there any accepted means by which those impacts can be compared? Have such assessments making those comparisons been undertaken, and if so, what are the results? Can those results be adapted so as to be relevant to an analysis of the generation of electricity in South Australia?

The exhaust of D-T fusion reaction is Helium, an inert gas, and 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 by Maissonier [2] 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 3 shows the projected material mass remaining after 100 years of shutdown of a concept fusion power plant [2]. About 90% 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 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.

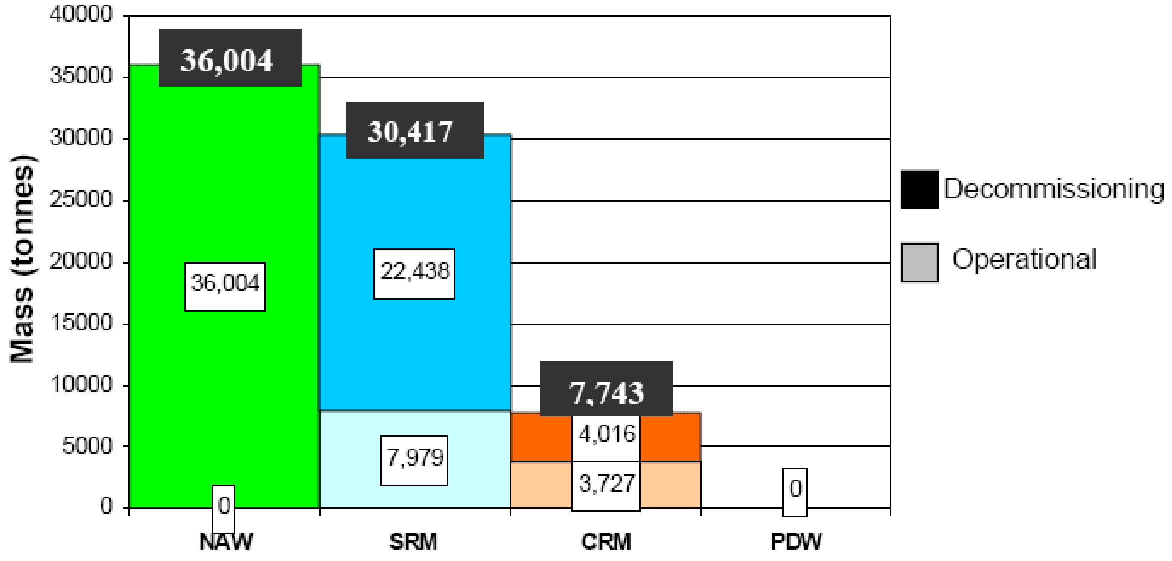

Figure 3 : Material masses after 100 years of shutdown of power plant conceptual study model B. Extracted from **[2]**. NAW is Non Active Waste, SRM is Simple Recycle Material, CRM is Complex Recycle Material, and PDW is Permanent Disposal Waste (non-recyclable).

3.13 What risks for health and safety would be created by establishing facilities for the generation of electricity from nuclear fuels? What needs to be done to ensure that risks do not exceed safe levels?

Cook, Marbach *et al*. [3] have explored the safety and environmental impact of fusion power. These authors 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* also 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 (e.g. 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.

Maisonnier [2] has continued to extend this study into the design of four concept commercial fusion power plant designs. Consideration is also given 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 these 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.

3.14 What safeguards issues are created by the establishment of a facility for the generation of electricity from nuclear fuels? Can those implications be addressed adequately? If so, by what means?

As proposed, fusion reactors will breed tritium for use as fuel. Tritium is used 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.

3.15 What impact might the establishment of a facility to generate electricity from nuclear fuels have on the electricity market and existing generation sources? What is the evidence from other existing markets internationally in which nuclear energy is generated? Would it complement other sources and in what circumstances? What sources might it be a substitute for, and in what circumstances?

Ideally fusion will provide a long-term replacement to coal. As mentioned in the Preamble, the fuel supply for fusion is virtually inexhaustible, with an almost unlimited supply of deuterium in sea water and the other component, tritium, being created by the working power plant.

3.16 How might a comparison of the unit costs in generating electricity in South Australia from nuclear fuels as opposed to other sources be quantified, assessed or modelled? What information, including that drawn from relevant operational experience, should be used in that comparative assessment? What general considerations should be borne in mind in conducting those assessments or models?

For fusion this is very speculative – however Cook *et al* [1] found that the internal costs of fusion (the costs of constructing, fuelling and operating a fusion power plant) were comparable to tidal power or Coal in the UK. The same study quantified that the External costs due to the environmental damage and adverse costs to the environment placed fusion as comparable to wind. There are no studies unique to South Australia.

3.17 Would the establishment of such facilities give rise to impacts on other sectors of the economy? How should they be estimated and using what information? Have such impacts been demonstrated in other economies similar to Australia?

The long-term introduction of fusion power in Australia would provide a significant boost to many sectors of the Australian activity, including heavy manufacturing, control and systems engineering, superconductivity.

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[1] Cook, I., Miller, R. L., and Ward, D. J. (2002). Prospects for economic fusion electricity. *Fusion Eng. Des.*, **63–64**, 25–33.

[2] Maisonnier, D. *A conceptual study of commerical fusion power plants.* European Fusion Development Agreement, 2005.

[3] Cook, I., G. Marbach, L. Di Pace, C. Girard, and N. P. Taylor. *Safety and Environmental Impact of Fusion.* European Fusion Development Agreement., 2001.