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NUCLEAR HYDROGEN PRODUCTION: RE-EXAMINING THE FUSION OPTION

Satyen Baindur

Ottawa Policy Research Associates, Inc. Ottawa ON K1P 1A1 Canada

Abstract

Nuclear Hydrogen Production (NHP) enables implementation of *two* major emission-free hydrogen production techniques - thermo-chemical and electrolytic - using *both* heat and electricity from nuclear reactors. A significant R&D effort is currently in progress to develop such technologies for *fission* reactor-based NHP. However, future fusion reactors also constitute a potential source of heat and electricity for this purpose. In addition to enabling all the processes that would be enabled by fission reactors, fusion reactors may also enable some fusion-unique processes. All the NHP schemes being considered for fission reactors today were originally worked out for *fusion* reactors. Now that construction work on the ITER fusion reactor is finally under way, researchers in the US, Europe and Asia are again seriously looking at the possibility of NHP from fusion, using *both* types of fusion reactors (magnetic and inertial confinement). Significant R&D challenges for fusion still remain, but some of these, especially the materials challenges, are also shared with next generation high-temperature *fission* reactors. Fusion-fission *hybrid* reactors have also been proposed, as have fusion concepts that produce only hydrogen (and not electricity). This paper outlines some of the technical proposals for fusion-based hydrogen production; and discusses related economic, safety and policy issues, as a contribution to technology foresight in non-fossil hydrogen production technology.

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1. Introduction

The possibility of using nuclear heat, nuclear-generated electricity and nuclear-generated steam for hydrogen production has aroused considerable interest in recent years as a non-fossil, emissions-free technology. A significant effort is now underway to develop the associated enabling technologies – in Canada as well as internationally. The recent focus on such technologies has been under the overall rubric of Generation-IV fission reactor concepts, where nuclear hydrogen production by electrolysis or thermochemical processes is a major goal for several of the proposed designs, especially the Very High Temperature Reactor (VHTR).

Fusion reactor technologies, however, were explicitly excluded from consideration within the Generation-IV Projects. They were in fact dubbed a 'Generation V' nuclear reactor technology, because, at the time the Generation IV reactor roadmap was being drafted (1999-2002) fusion seemed like a technology that would reach the commercialization stage significantly later than Generation IV technologies.

The United States, the major contributor to the Generation IV Roadmap, was not a part of the ITER fusion collaboration at the time the Generation IV Roadmap was being drawn up. The prospect for fusion was quite uncertain during this period. The ITER reactor design had not been finalized, and not even a site for the ITER reactor had been agreed upon. Commercial inertial confinement fusion also did not seem particularly near at hand at the time. Thus the Generation-IV Reactor Roadmap issued in December 2002, emphasized only *fission* reactors, and the nuclear hydrogen production schemes also visualized only fission reactors as sources of heat.

However, with the US rejoining the ITER collaboration in 2003, and with detailed project design on the ITER proceeding, it is worthwhile to re-examine the possibility of nuclear hydrogen production using fusion heat and/or electricity. These possibilities had actually been scoped in some detail during an earlier period (the 1970s and 80s) when fission and fusion had exchanged places in the imaginations of policy makers - the future of *fission* technologies looked less promising than *fusion*, both because of public concerns about fission following the TMI incident, and because of actual operational difficulties with various high-temperature gas-cooled fission reactors during the 1970s and 1980s that caused all of them to eventually be shut down.

The consensus view then moved to favour *fusion* as the heat source of choice for high-temperature applications by the 1970s and early 1980s. Later, with progress in fusion slowing and the ITER collaboration reaching an impasse in the 1990s, the consensus view shifted again to favour fission as the heat source for high temperature applications. Today, with fusion and fission programs *both* going ahead internationally, it makes sense to re-examine fusion as a source of energy in the context of nuclear hydrogen production.

This paper is also motivated by the prominence of "Generation IV" in the current nuclear technology and policy dialogue, and is also intended to provide, in part, a historical perspective on the evolution of nuclear hydrogen production technology. The rest of this paper is organized as follows. In **Section 2** we discuss the basic conceptual schemes for nuclear hydrogen production. In **Section 3**, we discuss the fusion *versus* fission arguments in the context of nuclear hydrogen production (NHP). In **Section 4**, possible fusion reactor configurations that produce only hydrogen are discussed, as well as the rationale why, if fusion is indeed commercialized in the future, this could be the preferred deployment route for fusion technology. In **Section 5**, we discuss economic and technology issues related to fusion and fission technologies, their possible mutual synergies, and possible future relationships to other energy sectors. Overall, this paper is intended as a contribution to policy analysis and techno-regulatory foresight in fusion technologies.

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2. Nuclear Hydrogen Production

Nuclear hydrogen production is proposed as a greenhouse-gas free technique of hydrogen production. Current transportation, domestic and industrial power and heating usage of hydrocarbons are exhausting both the earth's fossil fuel resources and contributing to its greenhouse warming. The transition from a hydrocarbon economy to a hydrogen economy would cleanly remove carbon from the energy equation, and thus also contribute to stabilizing carbon dioxide levels in the atmosphere. Hydrogen is an energy carrier, but because of its high reactivity, is not found on earth in its elemental form – instead one finds it in hydrides, hydrates, hydrocarbons and carbohydrates.

Current means of producing hydrogen involve separating it from hydrocarbons (such as by reforming methane) – but these processes also involve the emission of greenhouse gases, primarily carbon dioxide, just as the burning of the hydrocarbons does. With hydrogen production methods being used currently, the greenhouse gases come both from the heat source (methane burnt to generate steam in the reforming process) and the feedstock (methane reacting with steam to yield carbon monoxide/dioxide and hydrogen).

Great effort is therefore being expended on developing processes for hydrogen production that have a small (or zero) greenhouse footprint. This effort is designed to yield hydrogen both for the processing of heavy hydrocarbons and eventually to replace them altogether as the lightest hydrocarbon of all – hydrogen without the carbon. Since water is ubiquitous, even if not always abundant, and is a carbon-free source of hydrogen, the effort to develop greenhouse-emission free hydrogen production technologies has come to be focused on separating hydrogen from water, <u>also known as hydrolysis, powered by electricity or heat generated without using hydrocarbon fuels</u>.

Hydrolysis can occur either through thermochemical cycles, which work by trapping the hydrogen from water in a compound that can be thermally disassociated to yield gaseous molecular hydrogen. Figure 1 shows the S-I or sulphur-iodine cycle, a thermochemical cycle, now highly favoured for nuclear hydrogen production, which is among several dozen studied by General Atomics in the 1970s, and first proposed with a fusion heat source. Figure 2 depicts a general fusion-based NHP scheme.

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Thermochemical Cycles

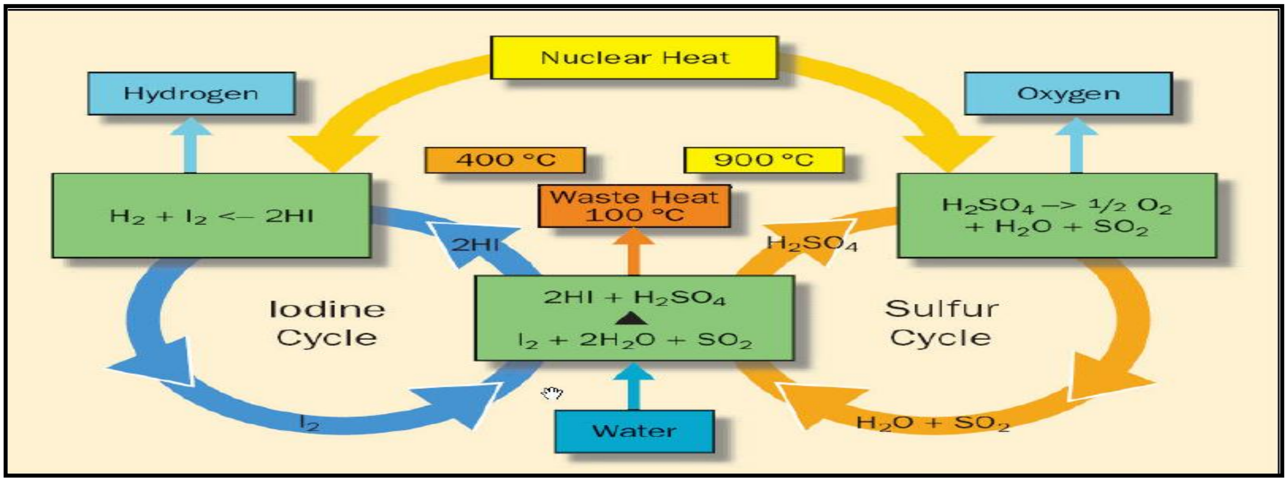

Figure 1: Concept of the sulphur-iodine S-I thermochemical cycle. Heat required can be supplied from either a fusion or a fission reactor.

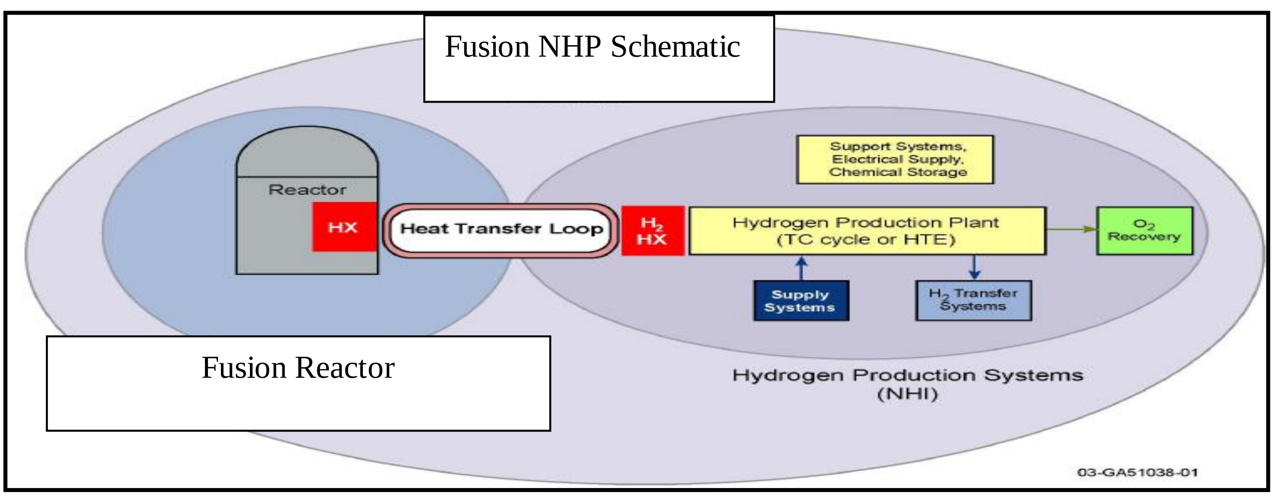

Figure 2: A nuclear hydrogen facility clearly showing the heat exchangers and heat transfer loops. At this conceptual level, the heat source is a Fusion reactor ("Generation V") but can also be a high-temperature Fission ("Generation IV") reactor. (Graphic adapted from Sherman 2006).

At a global level then, this scenario for the hydrogen economy is visualized as beginning with water, from which hydrogen is extracted. This costs energy, since water is a stably bound molecule. The energy needed to split water is supplied from a carbon-free source (here nuclear energy), and the separated hydrogen leaves behind oxygen, which is released to the environment. Then, the separated hydrogen is combusted - either chemically or electrochemically, releasing energy either as heat or electricity - powering transport, and the entire range of human technological applications. This hydrogen combustion uses oxygen and thus re-creates water, which was the original 'feedstock'.

So long as no intervening step involves the use of hydrocarbons, the net *carbon impact* of a hydrogen economy in these terms is expected to be very nearly zero. However, the net *environmental* impact will involve materials other than carbon, and will certainly need to be fully assessed, both at global and at local levels.

A variety of energy sources are being considered for hydrolysis, these include solar energy and geothermal energy. The primary benefit of nuclear energy however, is the fact that the high temperatures needed for hydrolysis can be reached easily and the heat generated can be transferred safely. Thermal solar may also be able to produce such high temperatures fairly easily, but only where insolation intensity is high and intermittency is low – which severely restricts the geographic range of applicability of such a solution.

Nuclear fission energy does not suffer from this type of geographic restriction or intermittency, but on the other hand, running a large nuclear plant in a load-following mode in a power grid – varying power *output* when the *demand* varies – can be a significant challenge. Also, while most nuclear plants have high capacity utilization rates, they can suffer from occasional shutdowns due to operational maintenance, routine refuelling, and sometimes to meet regulatory mandates from safety considerations. The earliest fusion plants, when they come on line, are unlikely to have the highest capacity utilization factors and reliabilities now seen in the best fission plants simply because any complex novel technology will need some time to standardize responses to routine operational occurrences.

In this connection, therefore, nuclear hydrogen production could use the surplus power in a nuclear fission reactor at times of low demand. For fusion plants, the same rationale may also apply when they become as reliable as fission plants currently are. But during their initial deployment phase, their reliabilities and capacity factors are likely to be lower (Nuttall 2006). Therefore, utilities supplying business and consumer demand might initially find fusion plants less attractive, and hydrogen production could be the fusion 'first adopter'.

Another rationale in favour of nuclear is that much investment in deployment concepts development has already occurred, and fully scoped versions, not only of nuclear power production and hydrolysis, but also nuclear desalination, process heat, and district heat has already been made. As a result, it is possible to visualize that economies of both scope and size may be realized in nuclear technology.

For all of these reasons, nuclear hydrogen production has become a favoured technology for future fossil-free hydrogen production. In the next section we consider how the two nuclear technologies, fusion and fission, stack up relative to each other, both in the context of nuclear hydrogen production and more generally.

3. Fusion, Fission and Nuclear Hydrogen Production

Figure 2 shows a conceptual nuclear hydrogen production plant drawing heat and electricity from a future fusion power plan. However, at a conceptual level, either a fusion rector or a fission reactor could supply the heat and electricity needed in the two hydrogen production technologies depicted (thermochemical and electrochemical). Indeed, the figure is adapted from Sherman (2006) where a high-temperature fission reactor (the gas-cooled VHTR) is considered.

3.1 Hydrogen has a dual role

In considering the possibility of hydrogen production using **fusion** technologies, an interesting duality with regard to hydrogen comes to light – the main fusion schemes that are conceptualized to provide power for the hydrogen production themselves fuse atomic hydrogen isotopes. Although many different fusion schemes have been studied – the one currently in favour both for magnetic and inertial fusion involves the fusion of deuterium (D) and tritium (T), the two heavier isotopes of hydrogen. (Others involve fusing deuterium with itself [i.e., again two hydrogen isotopes] and deuterium with helium-3, helium-3 with itself, and boron with protium [the simplest hydrogen isotope]).

Hydrogen is thus in a dual role – as both fuel and output – in a fusion-based hydrogen production scheme. The nuclear *fusion* of two hydrogen isotopes in an *ionic* plasma generates the neutrons and then either the heat or the electricity that thermo- or electro-chemically hydrolyse water, to produce *molecular* hydrogen.

3.2 Fusion breeds own fuel, but Fission can breed Fusion s*tarter* fuel

In the classic D-T fusion reaction, an alpha particle (${}_2He^4$) and neutrons (${}_0n^1$) carrying 14.1 MeV of energy are produced. Other fusion reactions such as the ones mentioned above have their peak cross sections at much higher energies and are thus even more difficult to achieve than D-T fusion. In tokamaks like ITER, the tritium fuel can be bred in a 'blanket' of lithium (that surrounds the plasma vessel and absorbs the neutrons), but this can only occur once a sustained fusion reaction has been achieved. A preliminary supply of tritium is also needed to start the initial reaction. In the most likely scenario, ITER will use the tritium generated as a side-product in CANDU heavy water *fission* reactors. Fusion and fission, both sources of nuclear energy – emerge in this perspective as *complementary* technologies that must co-exist, rather than compete with each other as substitutes. Heavy water power reactors, which generate substantially larger inventories of tritium than light water reactors, emerge in this perspective as *enablers of fusion*. Outside this context, the large tritium inventories in HWRs are often viewed with concern.

3.3 Fusion and Fission have each had Setbacks

In contrasting fusion and fission, however, the argument that fusion is a technology that has always been 'thirty years out in the future', is often brought up. While this is undeniable as a literal truth, it is also true that significant progress *has* been made in developing fusion technology in the past half century, and that some of the delay has actually been due to policy inaction, giving the 'truth' an element of self-fulfilling prophecy. It is worth recalling that fusion was discovered and understood – as the source of energy in stars – before fission.

However, the effort to realize fusion has been challenging, and can still be usefully framed in terms of an attempt to bring a star to earth to emphasize the challenge. Fission, on the other hand, was able become a source of power in just over a decade after its discovery. However, there is an interesting twist to this: the first (experimental) nuclear fission reactor to produce electric power was actually a breeder reactor rather than the once-through fuel cycle reactor that subsequently became commercial. Subsequent attempts to build large scale power breeder reactors encountered considerable operational difficulties, and fission power reactors moved along a different path. In this sense, the difficulties faced by fusion do have something of a fission analogue.

3.4 Fusion-based NHP is the Ultimate Hydrogen Economy

An interesting way to see a fusion plant designed to produce molecular hydrogen is as the *ultimate hydrogen economy*, in that it both uses and breeds *isotopes* of atomic hydrogen, and also creates *molecular* hydrogen for use elsewhere in the economy as a fuel. Further variants on this basic concept involve the use of hydrogen as a cryogenic liquid cooling the superconducting magnets for the tokamak, and also as the fuel burnt by fuel cells supplying the electricity for the fusion plant (Nuttall, et al. 2006). This intriguing set of conceptual proposals, however, has no fission analogue.

3.5 Fission reactors can also breed own fuel

Even without a molecular hydrogen production facility, however, a fusion reactor is an attractive proposition because it can be designed to *breed* a major component of its own fuel – the tritium isotope of hydrogen. In this respect, however, there is again a fission analogue – fission reactors *can* be designed to breed fissile uranium and plutonium from fertile isotopes.

3.6 Fusion can breed fission fuel

While fission reactors could supply the fusion starter fuel as outlined above, an even more intriguing suggestion is that the two may exchange places and that **fusion** reactors could help breed *fission* fuel, as well as transmute the actinide content of the used fission fuel to short-lived radioactive elements. Several versions of this idea have been explored in the literature, and the resulting reactor concept, often called a <u>fusion-fission hybrid</u>, was strongly advocated by Bethe [2], though it has a pedigree almost as old as fusion itself [e.g, Titchmarsh et al 1979, and Ragheb et al 1979].

In this version of fusion technology, the hybrid serves as a fission fuel breeder reactor. What is also interesting is that in this scenario, the 'fusion half'of the hybrid need not be producing more power than it consumes (Q can be less than 1), because its role is to provide neutrons for fission fuel breeding, while the fission reactors it fuels provide the actual commercially usable power. A figure of merit for such a hybrid then becomes the number of fission reactors it can sustainably fuel, rather than its own Q, which, for a stand-alone fusion reactor must be much larger than 1. In this sense, fusion, even if not fully developed as a power source, could function as a neutron source for *fission* fuel breeding.

3.7 Fusion and Fission are Complements, possibly Symbionts

Fusion and fission thus emerge from this discussion as *complementary* nuclear technologies, and while fission is more developed at the present time, the nuclear future could certainly include both technologies interacting in interesting ways. Indeed, a future hydrogen economy is one way they could come together. A Fusion-Fission hybrid, in addition to a role in breeding fission fuel, could also have a role in spent fission fuel management – in supplying neutrons that can transmute highly radioactive long-lived actinide isotopes to shorter-lived ones with lower radioactivity. If a version of the fusion-fission hybrid were to be realized, then fusion and fission could be seen as actually *symbiotic* instead of merely complementary.

3.8 Fusion and Fission release the Same Kind of Energy

It is not out of place to mention that both fusion and fission result in the release of nuclear energy of the *same* type, and that in each case it is carried by neutrons. This basic realization is often missing not only from everyday conversations, but also from technical discussions, which often regard the two energy sources as fundamentally different. Fusion-driven processes in the universe are much more common than fission-driven, and the lighter elements are more abundant across the universe, hydrogen being the most abundant of all. The heavier elements were formed from fusion of the lighter ones.

3.9 Fusion-unique NHP Processes might exist, but present challenges

With regard to nuclear hydrogen production, however, the question still remains as to whether fusion might confer advantages in hydrogen production that fission cannot match. The answer, unfortunately, is not quite as clear cut as one might wish. Fusion proponents have argued that fusion-*unique* hydrogen production processes do exist, i.e., hydrogen production processes exist which can only be achieved with neutrons and/or heat generated by fusion, and not fission.

Two of these 'fusion-unique' hydrogen production processes are notably mentioned – radiolytic hydrogen enabled by fusion neutrons, and hydrogen produced by non-equilibrium chemical reactions enabled by localized thermal spikes created by fusion neutrons. Inertial fusion concepts involving laser fusion have been especially studied in the context of radiolytic hydrogen production (Vagelatos, 1978). Neutrons generated by fusion, it is proposed, can be used to radiolyze water - by design - to yield hydrogen.

3.9.1 Thermal Spike Chemistry

Thermal spike chemistry that enables non-equilibrium hydrogen producing reactions is said to be enabled by fusion neutrons, but it may well also be enabled by fission neutrons. However, since the two neutron sources have different energy distributions and peaks, it is conceivable that the thermal spikes needed for producing hydrogen from some set of reacting species might favour fusion neutrons. But if true, this will clearly be chemical species-dependent – some non-equilibrium reactions could favour fusion neutrons over fission and vice-versa. This still needs to be conclusively established by experimental studies.

Thermal spike chemistry is an example of non-equilibrium **molecular** level interactions being *directly* furthered by a **nuclear** constituent – the neutron. Thermochemical hydrogen production on the other hand, uses neutrons *indirectly*, through the heat produced in a thermalhydraulic loop. So it is possible that, if thermal spike chemistry were commercially feasible, that it might have an advantage in energy efficiency over thermochemical hydrogen production. However, thermal spike chemistry as a fusion-unique hydrogen production process will likely have to overcome, among other problems, low hydrogen yields, and tritium contamination in the produced hydrogen.

3.10 A-neutronic Fusion Schemes also exist

While the preceding discussion has focused on possibilities from fusion *neutrons*, it must not be assumed that *all* fusion schemes result in neutrons. A-neutronic *fusion* – fusion schemes that do not generate neutrons are also possible, and have their own advantages. For example, the fusion of a proton by a Boron nucleus can result in 3 energetic alpha particles and no neutrons. (A-neutronic *fission* may also be theoretically possible - if a nucleus was to fission, for example, into symmetric fragments - but since most heavy fissile nuclei are neutron rich, fragment nuclei will tend to restore the neutron-proton balance by neutron emission. This makes it likely that, even if no prompt neutrons are produced in a given fission reaction, that some delayed neutrons would eventually be produced.) Whether a-neutronic fusion schemes could still catalyse thermal spike chemistry is conjectural, but unlikely since alpha particles would be unable to generate localized thermal spikes as well as neutrons.

The specific difficulty in the H-B *a*neutronic fusion scheme is that the cross-section peaks at much higher energies than it does for the classic D-T reaction (thus much higher temperatures are required for the reaction to occur), and there are also difficult problems in controlling the reaction plasma (over and above those already experienced in D-T plasmas). However, if realized, the advantage of aneutronic fusion is that neutron activation of plant materials ceases to be an issue, since there are no neutrons generated (Movig, 2006).

Another advantage of an *a*neutronic fusion process is that the resulting fusion plant becomes proliferation-proof, since the neutrons needed to breed fissile materials are then not available. This is relevant since the original motivation for much research into fusion reactors had been to find a means of reliably breeding fissile material. Therefore, ensuring that any fusion technology that eventually becomes commercialized be proliferation-proof remains a key goal, analogous to the situation with fission technology. (Santarius et al, 2003).

3.11 Both Fusion and Fission have Safety Issues

Fusion proponents have also argued that it is inherently safer than fission, and that the fusion fuel supply is virtually inexhaustible. Since nuclear hydrogen production raises safety issues in its own right, it is claimed that fusion as the enabling technology will lower the joint risk from the thermo-electrochemical-nuclear plants. Only a comparative and comprehensive quantitative risk analysis can settle that question. This has not yet been conclusively done.

Fusion skeptics on the other hand, argue that the safety advantages claimed for fusion do not stand up to close scrutiny. While it is true, they argue, that an uncontrolled meltdown of the type modelled in 'severe accident' scenarios in fission reactors cannot occur in fusion reactors, *other* types of severe accidents *could* occur in a fusion reactor. Since tritium is used as a fuel in fusion reactors, for example, its possible escape into the environment is an important safety issue in fusion reactors (this is a concern also with fission reactors, where it is produced in neutron activation of heavy water).

The risk probability of environmental tritium contamination from a fusion reactor also depends also on which coolant is used – water cooled fusion plants, for example, would likely generate a higher tritium inventory than would helium cooled fusion plants. Also, since magnetic fusion plants are designed to *breed* tritium as a fuel, possible leakage from either the fuel inventory or the breeding blanket must be properly considered in the overall risk assessment of a fusion plant.

3.12 Fission and Fusion Each Have Plentiful Fuel Sources

In answering the claim advanced by fusion proponents that fusion fuel is almost inexhaustible, (pointing out that sea water is an abundant source of deuterium; and lithium, which can be used to breed tritium is also geologically abundant in rocks and minerals), fission proponents counter-argue that fission fuel is also almost inexhaustible, pointing out that sea water is also a source of natural uranium, while fission breeder reactors can breed even more fissile fuel from fertile isotopes. More than this, we have argued that both fission and fusion technologies are potentially able to breed each other's fuels.

The overall takeaway message in this fusion *versus* fission discussion thus seems to be that, while the question of whether fusion-unique processes do indeed exist (and can be commercially realized) for nuclear hydrogen production is not conclusively settled, one can agree that fusion will likely have *some* role in the mix of future nuclear technologies. This paper has also argued that fusion and fission technologies could well be future technological *complements*, or even *symbionts*, rather than being *competitors* or *substitutes*.

With the major industrialized and emerging economies now committed to joint development of magnetic fusion through the ITER collaboration (while also separately working on inertial fusion) it becomes worthwhile to scope out how fusion *may* develop in a national techno-economic context. The next sections are devoted to examining this set of issues.

4. Hydrogen-only Fusion Schemes: The Nuttall-Glowacki-Clarke Fusion Island

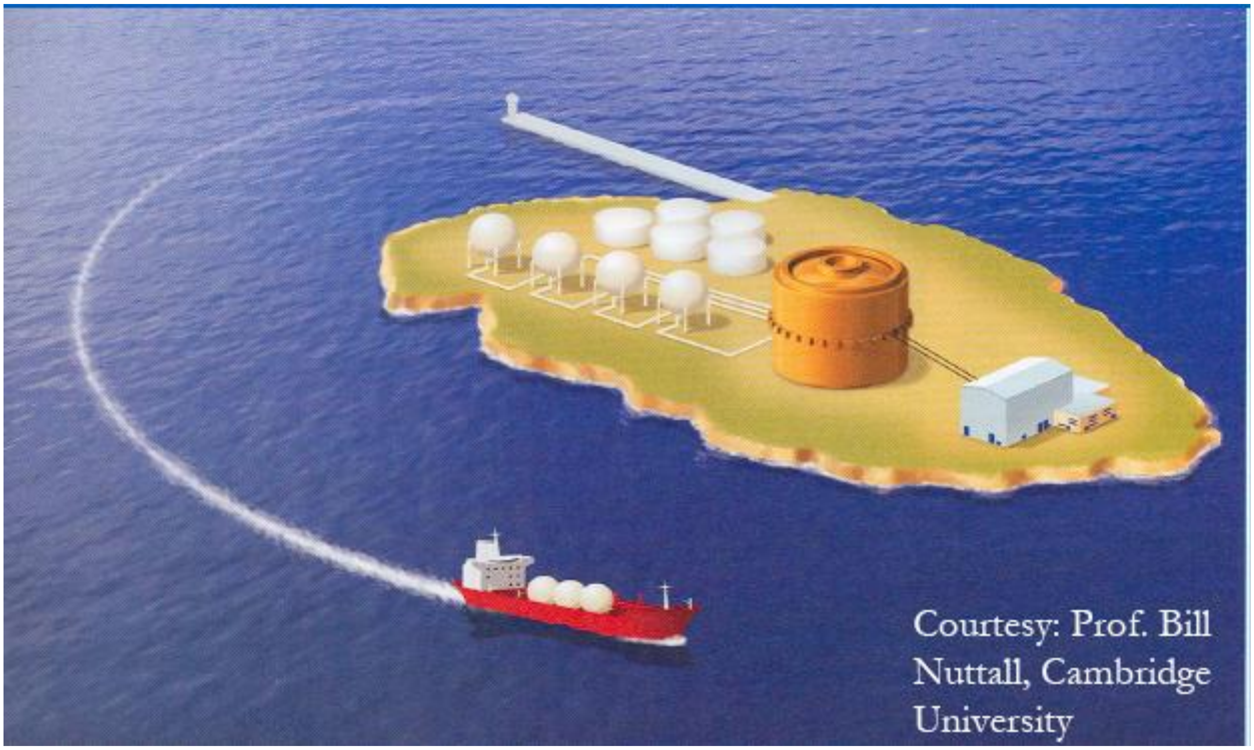

Figure 3: An artist's simplistic portrayal of the The Fusion Island concept, scoped by Nuttall, Glowacki, and Clarke (2006). Figure Courtesy: Dr. Bill Nuttall, Cambridge University.

We discussed in **Section 2** that the earliest fusion plants, when they come on line a few decades from now, will suffer a deployment obstacle in the form of risk-averse utilities unwilling to invest in technology that will quite likely experience some unreliable initial operation. Utilities having to guarantee a quality of service to their customers or suffer a financial penalty would be particularly unlikely to invest in a fusion power plant (Nuttall, 2006). And when this happens, it will not be unique to fusion; the earliest fission nuclear plants also faced this issue. This was overcome in the fission context with governments either directly absorbing the costs of running the first commercial nuclear plants or indirectly achieving the same end through subsidies.

Therefore, if power production were the only thing that a future fusion plant would be capable of, then the deployment obstacle would be unsurmountable in the absence of some early adopter application. Fusion would then be all set and ready but have nowhere to go.

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Nuclear hydrogen production could be the early adopter application for fusion technology and thus catalyse its widespread adoption. By the time, around 2050 or later, that fusion technology will have developed to the point that it can move into commercial applications, fossil fuel resources will have become significantly more expensive and scarcer than they are today. It can be expected also that the enabling technologies and infrastructure needed for a successful hydrogen economy in the transportation sector will have by then been developed. Thus there will be an incentive for fossil fuel suppliers who currently supply fossil fuel to the transportation sector to become suppliers of hydrogen to the same sector in the future.

Such 'oil majors' are also likely to be the only private sector participants with the capacity and investor appetite to invest in fusion technology development, right now and in the future. This is the setting for Fusion Island, a complete hydrogen economy, first suggested by Nuttall, Glowacki and Clarke (2006). The Fusion Island concept, shown in caricature in Figure 3 (courtesy Dr Bill Nuttall), involves a D-T fusion magnetic confinement reactor cooled by liquid hydrogen, with heat exchange coupling to both the thermochemical and the power production units. The thermochemical process generates gaseous molecular hydrogen which a hydrogen-gas fuelled cryogenic plant turns into solid hydrogen (the electrochemical process is not suggested as being less efficient.)

Thus on Fusion Island, hydrogen is:

1. The fuel in the reactor – D-T plasma
2. The coolant in the reactor – liquid Hydrogen
3. The fuel for the gas-turbine cryogenic plant – gaseous Hydrogen
4. The fuel for hydrogen fuel cells that provide a 'blackstart' capability
5. The product shipped – the output of the cryogenic plant - solid hydrogen

In this way, the Fusion Island concept shows how the nuclear, chemical and electrochemical energy in hydrogen may each be utilized, with hydrogen itself occurring in all its forms – plasma, solid, liquid and gas. The concept cleanly and clearly links nuclear fusion energy to the hydrogen economy (which heretofore has largely been seen in terms of modalities for using hydrogen's chemical and electrochemical energy).

The Fusion Island concept also clearly identifies both a possible early adopter for fusion technology and a sector that has the resources, appetite and motivation to invest in the development of fusion technology now and into the future. In this way it points to a lucid and plausible development and deployment timeline for fusion. As with all technologies, this is a necessary condition for its practitioners to change their own mental construct and begin to consider the technology as something that can be achieved in a foreseeable and finite timeframe.

Many of the practitioners of fusion technology have in the past seen it not as an achievable objective but rather as an R&D project, almost coming to themselves believe in the myth that fusion will always be thirty years away. Fusion Island is now a plausible vision that they and the general public can keep in mind as they navigate toward a fusion and hydrogen powered future.

A compelling question that then arises is whether and how a Fusion Island could come to exist in Canada in the future. First, consider the fact that the oil industry, and the tar sands in particular, is a growing user of hydrogen, and their final product is consumed in the transportation sector. Second, consider the fact that the final product of Fusion Island is hydrogen. Thus the tar sand industry is a possible consumer for the output of a future Fusion Island, and potentially also an investor in the required R&D.

Fusion Island could thus anchor a post-fossil fuel economy. Other industries that will also be impacted by a possible future Fusion Island are the Automotive, Nuclear and Chemical sectors, the existing Hydrogen industry, and the Heavy Engineering industry. Geographically - the hydrogen, chemical and oil sectors have a significant concentration in the BC-Alberta region; while the automotive, hydrogen and heavy engineering have concentrations in the Ontario and Quebec areas. Thus if universities and industries in these areas were to prepare themselves by investing in fusion R&D, they would be in a position to contribute to and benefit from possible Fusion Island-like power-and-industrial park clusters that could flourish in those regions decades hence.

5. Policy and Foresight on Fusion Technology

If fusion is thus not merely a future *component* of the future suite of nuclear technologies, but also a possible *complement* to fission, then a separate-silo view of fusion at the policy level is not justifiable. In the past, fusion and fission have each suffered in the policy discourse from having been seen as two separate entities. Over the years, constituencies within both the fusion and fission communities have developed with an unfortunate tendency to see the other as a competitor for resources and influence.

The policy dialogue on nuclear technology development can gain from a new, unified perspective on fusion and fission in several ways. For example, many of the R&D issues that (i) next generation fission and (ii) fusion face have much in common, especially in regard to materials challenges (Baindur, 2007). Both fusion and next generation fission reactors will subject reactor materials to higher radiative fluxes and corrosive coolants. Coolant concepts for both fusion and fission reactors include helium and supercritical water, which will impact reactor materials in similar ways in both fusion and fission reactors. Both fusion and fission could be a potential energy source for nuclear hydrogen production (NHP), and plant-level conceptual analyses regarding heat transfer fluids or thermo-electrochemical units are identical, whether a fusion or a fission reactor is used for heat. Supercritical carbon dioxide, which is used as a surrogate thermal fluid in thermalhydraulic studies for fission reactors in place of the more expensive supercritical water, has been suggested as the actual coolant in fusion reactors. These are just a few examples, the similarities run quite deep.

Fusion plant *economics* may, however, initially be different from fission plants. While fission plants started small – very small, and then grew bigger (and are becoming smaller again as SMRs), the earliest fusion plants could start at the much larger scale of 3GWth which would be about 1GWe, (but since they are likely to be exclusive hydrogen producers, mentioning the electrical power equivalent is a bit superfluous). The large size is indicated because the plasma instabilities that will inevitably arise will need a larger plasma mass and volume to become stabilized. A fusion reactor thermal power of 3GWth could result in large hydrogen production capacities indeed. Second generation fusion reactors might be smaller, and indeed, may also utilize fusion schemes other than the magnetic or inertial confinement that are the focus of current development work – for example, magneto-acoustic fusion, or bubble fusion, or sonoluminiscence, or muon-catalysed fusion, all of which have different size/energy tradeoffs.

Since this paper is about technology foresight, it is relevant also to mention that during the Generation IV roadmap exercise in 1998-2002, some fission concepts that had been presented by proponents were judged to be too early-stage to warrant a full-scale R&D program within the 'Generation IV' research agenda. These concepts were lightly scoped out at the time the Generation IV reactor roadmap was being drawn up, but were judged too preliminary to be included in it. While fusion as a whole has been dubbed a 'Generation V' technology, there are thus also 'Generation V' *fission* reactor possibilities. In some of these Generation V fission concepts, gaseous reactor cores and magnetic confinement have been proposed for fission reactions. These ideas are very similar to those currently being developed for fusion, thus R&D in current generation fusion technology could benefit not only future Generation IV fission reactors but also future Generation V fission reactors.

In ending, we comment on the Canadian situation. Canada has had a mixed history with fusion. During the 1980s and early 1990s, it had a National Fusion Program, but that was cancelled in 1997. Today it is not in the ITER collaboration, though it had bid to host ITER, dropping out in 2003. This makes it the only G-8 country today not to either be in ITER or have a National Fusion Program.

Though ITER is an international collaboration, the intellectual property (IP) generated in building the ITER reactor remains the property only of the collaborating countries. Thus Canada runs a high upside risk in this situation. If important new insights were to emerge regarding fusion from ITER, Canada risks losing knowhow in a technology that could be a great future fit for several of its major industries – hydrogen, nuclear, oil, auto chemical. A future hydrogen economy may well be powered by fusion, and fusion-manufactured hydrogen in this economy could be the equivalent of today's refined crude oil.

It would seem prudent, therefore, for Canada to develop options for participation in international fusion collaborations, as well as to encourage development of domestic research capacity in related knowledge areas such as plasma physics, laser and magnetic technologies. The policy perspective will also gain by seeing fusion as an essential component in the suite of future nuclear technologies.

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