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REDACTED: Technical Reference Document: Fusion Energy: Current State of Affairs in Canada and on the World Stage in 2021

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Disclaimer:

This reference document was prepared using mostly *publicly available information.* The majority of the information contained in the document was updated prior to May 1, 2021. The global fusion energy industry is growing and changing as time progresses, and so any new and important developments in fusion science and technology that have occurred after May 1, 2021 are not included in this document.

This comprehensive reference document provides a *"snapshot in time"* on the state of fusion science and technology within the international community, and within Canada.

This document has been prepared as an "UNRESTRICTED" document, to be registered as a CNL document and it is intended for distribution outside of CNL.

This document contains a number of useful figures and images that have been obtained from previous presentations, reports, papers, publications, and from public websites. However, many of these figures and images may be subject to special copyright issues, and have been removed/redacted, by necessity. The reader is encouraged to look up the reference citations to see the original images and figures.

EXECUTIVE SUMMARY

Fusion Energy: The Challenge of Duplicating the Sun on Earth

Nuclear energy can be generated in two ways: by splitting heavy elements into two or more particles, or by fusing light elements together into a larger one. The former is referred to as nuclear *fission* and is the method used by nuclear power plants operating today. The latter is called nuclear *fusion* and it is the basic process that powers the Sun and all stars in the universe. Replicating such a process at a small-scale on Earth requires creating and maintaining conditions that are hotter and denser than those found in stars.

Generating power from controlled nuclear fusion requires developing technologies and the supporting scientific understanding that meet three basic requirements: (1) heating fusion fuels to temperatures of over 100 million degrees Celsius, (2) compressing fusion fuels to very high densities, and (3) confining the high-temperature, high-density fusion fuel long enough to ensure that a sufficient number of fusion reactions occur, which will result in a net energy gain.

Magnetic confinement fusion (MCF) is one of the two mainstream approaches to achieving nuclear fusion energy that is under development. It consists of trapping and confining the fusion fuel (in a plasma state) using extremely powerful electromagnetic fields. The other mainstream fusion approach is *laser-based inertial confinement fusion (ICF)* and it consists of compressing the fusion fuel with high-powered lasers to extreme densities and pressures. In both cases, the goal is to create the necessary conditions to allow for fusion reactions to occur.

The scientific and technological challenges of fusion energy have kept the scientific community busy since the 1950s, as old challenges have been solved and new ones have been discovered. However, after more than 60 years of research and development by the international community, it appears that a number of working prototype demonstration fusion reactors are within reach. Given recent scientific and technological innovations, demonstrating fusion energy with net electrical power generation could happen within the next 10 to 30 years, depending on the level of investment by both government and the private sector.

Breakthroughs in Fusion Innovation Could Unlock an Abundant New Source of Clean Energy

Today, the world faces a dual challenge: providing the energy to enable continued growth and to improve the quality of life for all of humanity, while minimizing the pollution and environmental impact caused by energy usage. If realized, nuclear fusion technologies could represent an abundant and non-emitting energy solution, allowing humanity to meet these challenges.

Fusion energy has significant potential advantages relative to other energy sources as well as potential near-term challenges:

- *<u>Abundant Fuel Supply:</u>* The preferred fusion process requires deuterium and tritium (both heavier isotopes of hydrogen), which are fusion fuels. Lithium, which is used to breed tritium, is also required. Deuterium is naturally occurring and relatively abundant: it is found in water. Technologies for extracting deuterium from water have been proven and are well developed, particularly in Canada since deuterium in the form of heavy water (D_2O) is used as a moderator and as a coolant for CANDU (CANada Deuterium Uranium) pressure tube heavy water reactors (PT-HWRs). Tritium, a heavier, radioactive isotope of hydrogen, however, does not occur naturally. Tritium must be produced, usually from lithium. It is foreseen that tritium will be bred continuously as part of the normal operation of a fusion reactor through fusion neutron interactions with lithium. Lithium supply requirements for fusion reactors are expected to be much less compared to other industries (such as those manufacturing electric storage batteries). Thus, it is expected that the fusion fuel cycle will improve energy sustainability and be will be self-sufficient. It is also recognized that Canada has the world's largest civilian stockpile of tritium, which is a normal by-product from the operation of CANDU reactors.

- *Safety and Security:* The fusion process is inherently safe. The fundamental differences in the physics, technology, and fuel used in fusion reactors in comparison to conventional nuclear fission reactors make a meltdown of fusion fuel non-existent, or a power pulse due to a *"runaway"* nuclear fusion reaction impossible. If there is any perturbation in the fusion process, the fusion reaction ceases immediately, with no decay heat from reaction-products, since they are stable elements. Even in the unlikely event of a total loss of the cooling function, meltdown of nuclear fuel is impossible (or meaningless), since the fuel is already in the form of high-energy plasma. In contrast to nuclear fission reactors, fusion reactors produce no long-lived, high activity radioactive fission by-products. Thus, there is no need for high-level waste (HLW) storage and long-term disposal. The by-product from fusion is only helium, although neutrons produced from fusion will cause activation of various structural components and materials in a fusion reactor, making them slightly radioactive. However, it is expected that the radio-isotopes in these irradiated materials will be relatively short-lived, and will decay naturally to stable, non-radioactive isotopes such that the materials could be recycled within 100 years or less. Thus, only short-term, low-level radioactive waste storage methods would be required for fusion reactor components. There are no fissile or fertile nuclear materials, such as uranium or plutonium in a fusion reactor. Thus, the risk of nuclear proliferation for fusion reactors is zero. The use of tritium fuel, which is only present in small amount (a few grams at any given moment) will not create any additional significant proliferation risks. Tritium is already used today for a number of commercial applications.

- *Clean and Reliable Energy:* Fusion could be among the most environmentally friendly sources of energy. Given its high energy density, one kilogram of fusion fuel could provide the same amount of energy as approximately 10 million kilograms of fossil fuel. There are also no air pollutants, no carbon dioxide, nor any other greenhouse gases (GHGs) produced directly from operating a fusion power plant. Fusion power plants are expected to require significantly less land than various renewable energy technologies and some fusion reactor designs could be small enough in size to be built close to the sources of energy demand, reducing the need for long transmission lines. Finally, fusion power plants can be designed to produce a secure, reliable, continuous, on-demand supply of electricity, independent of weather, season, or time of day. This capability is in stark contrast to intermittent renewable energy resources, such as wind or solar/photovoltaics, which require significant investment in energy storage infrastructure to ensure a reliable supply

- *Near Term Challenges:* While much progress has been made over the last 60 plus years, fusion energy still faces several scientific and technological challenges, and some of these challenges may be orders of magnitude larger than those faced by other energy technologies. The scientific and technological challenges are also accompanied by economic and public policy hurdles that that must be overcome. The pathway to fusion energy commercialization requires large and long-term financing, which until recently has come primarily from a dozen or more national governments funding small and modest domestic programs at national research laboratories and universities, along with a number of collaborative international programs. Historically, the research and develop (R&D) sector for fusion energy has struggled to obtain secure, long-term funding to support fusion research facilities. While the limits placed on investment in fusion R&D have constrained it to a slower rate of progress, fusion as a commercial energy source is expected to arrive sometime in the 2050s. A wave of recent and significant private investments in fusion R&D may very well shorten the time to commercialization, with the construction of prototype demonstration power plants potentially occurring as soon as mid-2020s to early 2030s.

Globally, Fusion Is a Fast-Emerging Sector Supported By both Public and Private Investments

Originally limited to government and university laboratories, fusion R&D is now being undertaken by an increasing number of private companies. Throughout the world, there are 97 different fusion reactor experiments currently in operation and more than 27 fusion projects are in the design or construction phase.

Over the last decade, several of these fusion R&D projects have attracted significant private investments. In fact, over $2 billion CAD in financing has been deployed to private fusion energy companies. In many developed countries, government spending has significantly grown as well. As of 2021, the combined expenditures by governments in the United States, the United Kingdom, and the European Union exceeds $1.7 billion CAD annually. A substantial portion of that expenditure is from the collaborative efforts of 35 nations (USA, UK, Europe, Japan, Russia, China, South Korea, India, and others) that are working currently and collaboratively on the construction of the world's largest fusion experiment known as ITER (International Thermonuclear Experimental Reactor), which has an estimated price tag of $32 billion CAD. The ITER fusion experiment is expected to be a pre-cursor to the first demonstration/prototype commercial fusion power plants (DEMO). Member nations of ITER are providing both in-kind and direct monetary contributions. In return, they will share expertise, experimental results and intellectual property (IP) rights from the ITER project, which by themselves represent additional long-term economic benefits. Currently, Canada is not a member of ITER.

In addition to harnessing fusion energy for electric power generation, research scientists, governments and now private investors around the world are also motivated to develop fusion energy for other value-added applications. Fusion reactors could be adapted and used to provide process heat for a number of industrial processes (such as production of hydrogen, petrochemical processing, steel-making, steam-assisted resource extraction) as well as district heating, and desalination of sea-water. As a source of neutrons, fusion reactors could also be adapted to produce medical and industrial radioisotopes, which would be a value-added activity.

The global fusion industry is fast emerging and R&D initiatives are proceeding worldwide. Driven by growing energy demands and the quest to achieve decarbonized and sustainable economies, fusion energy has the potential to become a catalyst for economic wealth generation and job creation.

Canada’s Expertise in Tritium-Related Technologies is a Potential Competitive Advantage

Building on two decades of small-scale academic and government laboratory research, Canada established a National Fusion Program (NFP) in 1978 through the National Research Council of Canada (NRCC). Oversight of the NFP was later transferred to Atomic Energy of Canada Limited (AECL) in 1987. The Canadian NFP maintained a diversity of fusion-related projects that leveraged Canadian expertise, particularly in the areas of breeding and handling tritium, while also supporting university fusion research activities. For various reasons but mainly dealing with efforts to drastically reduce government expenditures to avoid a national debt crisis, the Canadian NFP was terminated in 1997. Of the G7 nations, Canada provides the least government support for the nuclear fusion industry. All of the other G7 members either have dedicated national fusion programs with committed annual funding or are hosting several significant fusion projects.

Despite the lack of a national funding program, the Canadian fusion sector has remained active at a small-scale level, driven by the ingenuity and creativity of scientists and entrepreneurs. There is a diversity of Canadian fusion stakeholders at work in academia, industry, and government laboratories, with expertise that could be leveraged to contribute to both domestic and international initiatives in fusion energy development. The University of Alberta and the University of Saskatchewan have established fusion R&D programs and have internationally recognized fusion scientists. Canadian Nuclear Laboratories (CNL) has maintained several capabilities that could be advantageous in making advances in fusion technology, particularly in the area of tritium production and handling. Founded in 2002, General Fusion is a private-sector Canadian company that is among the leading private ventures in the world pursuing an alternative fusion reactor concept that promises to be more compact and economical than conventional mainstream approaches to fusion. The provincial electrical utility, Ontario Power Generation (OPG), has decades of experience and expertise in handling tritium, which is a by-product from the operation of CANDU reactors. OPG safely manages the world’s largest civilian stockpile of tritium, and will continue to produce tritium from its CANDU reactors until at least the year 2050, when the current fleet of CANDU reactors are expected to reach the end of their operational life.

In October 2020, a Nuclear Cooperation Agreement (NCA) was signed between Canada and the ITER Organization. The NCA was ratified by Parliament in May 2021. While Canada is not a current member of the ITER consortium, the NCA enables Canadian entities to provide goods and services to ITER in line with Canada's nuclear non-proliferation policy. Of particular significance, supplying tritium to ITER and other fusion experiments around the world could open a new revenue stream for Canada, which is estimated at over $660 million CAD over the next decade.

Going Forward with Fusion: Canada's Role

Historically, the quest for fusion energy has been considered a high-risk, high-reward endeavor. However, given the current state of research, the rising number of players in the field, and the increasing funding levels in both the public and private sectors, fusion as a viable energy source appears to be within reach within the next 10 to 20 years.

Given that the potential environmental, economic, and social advantages of fusion power are very compelling, the international community will continue develop fusion energy, with or without Canada's participation and assistance. Should the necessary investments be made to pursue fusion energy domestically, Canada could act as both a developer and supplier of both fusion fuels and technologies.

Strategically, fusion could also complement ongoing efforts to decarbonize the economy and help Canada slow or mitigate the effects of climate change. While many challenges still exist, the risks appear to be slowly fading. It remains to be seen what role Canada will play in a future that includes fusion energy.

1. Introduction

1.1 What Is Fusion Energy?

Fusion is the nuclear reaction that powers the Sun at the center of the solar system. Without it, there would be no life on Earth. In contrast to the process of nuclear fission, where the nucleus of a large, heavy element (such as uranium) is split into 2 or more lighter atoms along with additional particles, such as neutrons, and releasing energy in the form of heat, the process of nuclear fusion involves combining two light-weight atoms (such as different isotopes of hydrogen) to form one or more heavier atoms (such as helium), along with additional particles such as protons or neutrons.

Very light-weight elements, such as hydrogen and their isotopes, are much easier to fuse, while very heavy elements and their isotopes, such as thorium, uranium, and plutonium are more fissionable. Fusion of very light-weight nuclei is an exothermic reaction that releases energy (due to lighter elements having a lower binding energy per nucleon). Similarly, fission of heavy-weight nuclei is also an exothermic reaction (due to very heavy elements having a lower binding energy per nucleon). The elements with the highest binding energy per nucleon have an atomic mass in the range of 50 to 80, and include elements such as iron and nickel. When accelerated to very high speeds (~1,000 km/s, or higher) and allowed to collide with each other, very light nuclei will have enough kinetic energy and momentum to overcome repulsive electrostatic forces caused by the positively charged nuclei. This process will allow the colliding nuclei to get close enough such that short-range strong nuclear forces can become very large and allow the colliding light nuclei to undergo fusion.

1.2 The Challenge of Producing Net Fusion Energy

Why is nuclear fusion so challenging? Nuclear fusion for power production is a challenge that the world's scientific community has been pursuing since the late 1950s.

In the Sun, which is more than 1.39 million km in diameter (109 times the diameter of the Earth), the large gravitational forces confine hydrogen atoms in its core at high-enough densities (up to 160 g/cm^3 (160 times the density of water)), pressures (up to 250 billion atmospheres) and temperatures (close to 15 million °C) for a long enough period of time to undergo fusion. Fusion of hydrogen in the core of the Sun is a multi-step process involving several nuclear reactions, with the net result being helium atoms and energy (4 hydrogen atoms + 2 electrons$\rightarrow$ 1 helium atom + energy). Although the probability of fusion of hydrogen atoms to produce helium is extremely low, even at 15 million °C, the Sun (like other stars) is large enough to be a self-sustaining fusion reactor, as long as the supply of hydrogen fuel lasts (for another 5 billion years). However, it would be impractical, or perhaps even impossible, to use the Sun's very same hydrogen-based fusion fuel cycle on a much smaller scale on Earth.

The reason why thermonuclear fusion reactions like those that occur in a star are hard to replicate on Earth is due to two very important factors. The first is that *extremely high temperatures* (often in the order of millions of degrees Celsius) must be achieved and maintained within the reactor in order for "burning" of the hydrogen isotopes (fuel) to occur and for the fuel to sustain ionization as plasma. The second factor is *sufficient plasma confinement time*. These two metrics: sufficient confinement time (as given by the product of plasma pressure (or density) and time – the Lawson Criterion); and extremely high temperatures to achieve a sufficient energy production rate, are critical to achieving net energy production. The Lawson Criterion is a quantity or metric used in nuclear fusion research that compares the rate of energy being generated by nuclear fusion reactions to the rate of energy losses to the environment through either radiation or conduction. The Lawson Criterion are the conditions required for what is called *fusion ignition:* when a nuclear fusion reaction becomes self-sustaining. The reaction is self-sustaining when the energy being given off by the reaction (the energetic helium ions, or alpha particles produced from fusion) balances the energy losses and plasma cooling. The Lawson Criterion and the ability for a fusion reactor to achieve fusion ignition should not be confused with the *fusion energy gain factor* (often more commonly expressed as the “Q-value”) of the fusion reactor. The Q-value is the ratio of fusion power produced by the fusion power reactor to the power required to maintain and confine the plasma. The key difference between fusion ignition and the fusion energy gain factor achieving “breakeven” (Q = 1.0) is that the Q-value ignores energy losses to the environment whereas fusion ignition is more of a measure of how self-sustainable a reaction is. A fusion system at Q = 1.0 will cool down without external heating because not all of the heat generated from the reaction will be captured and absorbed within the plasma (there are energy losses).

Although duplicating the fusion fuel cycle from the Sun at a small scale on Earth is practically impossible, fortunately, there are alternative fusion reactions that are far easier to initiate to achieve the Lawson Criteria, and to achieve ignition. The easiest fusion reaction that can be replicated on earth with current fusion experiments is the reaction between two different isotopes of hydrogen: deuterium (D) and tritium (T). The fusion of deuterium and tritium produces a heavier element, helium, and one neutron ($D + T \rightarrow He\text{-}4 + n + \text{energy}$). With the DT reaction, and possibly other fusion fuel combinations, it is possible to create and control a small-scale “Sun” on Earth.

1.3 The Large Benefits of Fusion Energy

The potential benefits of net fusion energy production to the world are immense. Fusion has the potential to transform the world’s energy supply. Nuclear fusion energy and fusion reactors represent an alternative zero-carbon energy resource and technology, which could augment, complement or potentially replace other existing zero-carbon and low-carbon energy resources and technologies. These existing zero or low-carbon energy resources in Canada include conventional nuclear fission energy, hydro-electric power, variable renewable energy (VRE) resources such as wind turbines and photovoltaic solar panels, biomass energy resources, and others. As a clean, safe and abundant source of energy, fusion presents an opportunity to stop, slow, or mitigate the effects of climate change while still meeting the world’s growing energy needs. Fusion has the highest energy payback ratio (EPR) of all clean energy sources (including solar, wind, and fission). The output or “exhaust” of a fusion reaction is helium, which is a safe and inert gas; there are no air pollutants, carbon dioxide or other GHG output from the fusion reaction. It is expected that there will be relatively little high-level radioactive waste produced from the operation of fusion reactors due to neutron activation. It is anticipated that the radioactive waste that is produced will decay to relatively insignificant levels within decades or less, rather than hundreds to thousands of years for radioactive waste from nuclear fission reactors.

In addition, nuclear fusion uses no special nuclear materials (SNM), such as uranium or plutonium, and so there is no risk of proliferation. Because there are no fissile fuels, or fission products, there is no risk of a reactor "meltdown" due to decay heat from irradiated nuclear fuel. The fusion reaction produces no radioactive fission products. Although tritium, which is bred in the surrounding lithium-based blanket of a fusion reactor, is radioactive, the heat generation rate from its decay is relatively insignificant and does not pose a risk for causing meltdown. However, it is recognized and understood that existing protocols and practices for proliferation protection that are applied to existing facilities handling tritium (such as the Darlington Tritium Removal Facility, DTRF) would need to be applied to fusion power plants.

Since it is difficult to reach and maintain the conditions necessary for fusion, if any disturbance in the fusion plasma occurs, the plasma will cool within seconds and the reaction will stop, with zero decay heat generation. The quantity of fusion fuel present in the fusion confinement chamber at any instant is only just enough for a few seconds of power generation without refuelling, and there is no risk of a chain reaction and an associated power pulse, as might occur, albeit unlikely, in a conventional nuclear fission reactor under a highly unusual accident scenario. Nuclear fusion reactions occurring in current fusion reactor experiments are inherently safer than fission reactions occurring in conventional nuclear power reactors.

There are also economic benefits to nuclear fusion, such as the fact that fusion reactor experiments and future fusion power plants will employ many workers in the STEM (Science Technology Engineering and Mathematics) and construction fields. Most of the current activity in nuclear fusion around the world is at the stage of scientific proof-of-principle in large-scale projects. However, there is also a growing emphasis on investigating engineering and technical issues which need to be addressed in the implementation of future fusion reactors. Once research and development has advanced and progressed sufficiently, it is expected that future generations of fusion power plants will be economically competitive with existing zero-carbon sources of energy.

1.4 A Brief Summary of Fusion in Canada – Past and Present

Starting in the late 1970s, and lasting during the 1980s, until the mid-1990s, Canada had an established National Fusion Program (NFP) [1], [2], [3]. For various reasons, but largely influenced by efforts of the Federal Government of Canada to reduce government spending and eliminate budget deficits, support for Canada's NFP was withdrawn in the late 1990s.

Despite the lack of a national fusion program and the associated federal funding support since 1997, the Canadian fusion sector has continued to be active at a small-scale level due to the efforts and passion by scientists, entrepreneurs, enthusiasts, and grass-roots supporters in Canadian academia and industry. There is a diversity of Canadian stakeholders at work in academia, industry, and government laboratories with a significant amount of expertise in fusion. The University of Saskatchewan and the University of Alberta are well known for their fusion R&D programs in magnetic and inertial confinement respectively, including their international collaborations. Canadian Nuclear Laboratories (CNL) have been able to maintain several capabilities that could be leveraged in supporting progress in fusion technology. The provincial electrical utility, Ontario Power Generation (OPG), has significant expertise in handling tritium, and it also manages the largest civilian stockpile of tritium of all nuclear nations, given that CANDU heavy water reactors produce tritium as a by-product.

Within the private sector, General Fusion is a Canadian company (founded in 2002) that is among the leading private ventures pursuing fusion energy and has secured more than $192 million CAD in funding, some of which was obtained from the federal government and leveraged to attract private sector investment.

Within the realm of grass-roots supporters and advocacy for fusion, the Canadian Nuclear Society established its Fusion Energy Science and Technology Division in 2009. In 2016, the Alberta/Canada Fusion Technology Alliance (ACFTA) was established as a fusion advocacy organization, and it evolved to become the “Fusion Energy Council of Canada” (FECC) in 2020 [353].

In October of 2020, a Nuclear Cooperation Agreement (NCA) was signed between the Government of Canada and the ITER Organization [352]. While Canada is not a member of the ITER consortium, the NCA enables Canadian entities to provide goods and services to this fusion experiment in line with Canadian nuclear non-proliferation policy.

1.5 Objectives of this Fusion Technical Reference Document

There is a very large investment in research and development by many nations around the world to further develop and understand different fusion reactors and associated supporting technologies, and to develop more practical and cost-effective approaches to fusion. The purpose of this comprehensive reference document is to highlight these efforts and to provide an outlook into the current nuclear fusion energy landscape of the world. This document highlights most of the key fusion technologies under development, and provides a review of Canada’s involvement in fusion research over time. This document also highlights most of the significant fusion projects underway around the world, and summarizes how governments of different nations are supporting fusion research and development.

The goal is to inform the reader of the current state of affairs in nuclear fusion energy around the world. This comprehensive reference document could be used to provide input to a future *“Canadian Fusion Roadmap*”, which could help guide future fusion energy development in Canada. It some ways, the development of a Canadian Fusion Roadmap could parallel recent efforts to develop a Canadian Roadmap for Small Modular Reactors (SMRs) [4], [5]. It is expected that such a Canadian Fusion Roadmap document would leverage and expand upon earlier efforts within Canada’s existing grassroots fusion community in 2016 to develop a fusion roadmap document [6], [7].

2. The State of Fusion Technology

This section provides an overview of the state of fusion technology, including the types of fusion technologies, and applications. Much of the information in this section can be found in a previous document, *"Fusion 2030: A Roadmap for Canada",* published in 2016 [6], [7], which provides an excellent overview. More comprehensive details and context can be found in the Appendices, in Sections A.1 and A.2. A number of ideas and concepts discussed in this section overlap with those introduced previously in Section 1.1 and 1.2.

2.1 Overview of Different Fusion Technologies

The following sections provide an overview of the requirements for net fusion power, and different fusion technologies.

2.1.1 Requirements for Net Fusion Power (Breakeven and Beyond)

Two metrics are critical to achieving net energy production in a fusion reactor: sufficient confinement time (as given by the product of pressure and time (Lawson Criterion); and appropriate temperatures to achieve a sufficient energy production rate. These metrics are shown as the two axes in the plot below in Figure 1**.** The Burning Plasma region (light blue) where net energy production can be achieved is shown in the upper right region of the curve. More information and details on the requirements for fusion breakeven are found in the Appendices, in Section A.1.1.

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* The vertical axis (y-axis) is fusion fuel plasma pressure × confinement time. The horizontal axis (x-axis) is fusion fuel plasma temperature in units of kilo-electron-Volts (1 keV corresponds to approximately 10,000,000°Celsius).

Figure 1: Metrics of Performance to Date for Magnetic and Inertial Fusion Approaches [6].

2.1.2 Magnetic Confinement Fusion Energy

Magnetic Confinement Fusion research aims to develop a fusion power plant where a fusion plasma is confined in a "magnetic bottle"; using powerful, steady-state magnetic fields generated from external coils, along with steady-state and time-dependent dynamic magnetic fields generated by electrical currents in the plasma. These systems, including Tokamaks, stellarators, reversed field pinches (RFPs), and other devices, are toroidal in shape, with the Tokamak configuration being the most widely studied. These devices are designed to confine a high-temperature deuterium-tritium plasma, resembling a giant pink plasma "donut", inside a large vacuum chamber.

Construction of the world's largest Tokamak is underway at the ITER (International Thermonuclear Experimental Reactor) project (see Figure 2) [19] in Cadarache, southern

France. The ITER project is a collaboration of many countries (the EU, China, India, Japan, Korea, Russia, and the USA), with first operation expected in the very near future, 2025. The mission of the ITER project is to demonstrate the feasibility to "ignite" a deuterium-tritium fusion fuel plasma in a fusion reactor with a net energy gain. A key goal of ITER is to achieve a fusion energy output that is more than ten times the heating energy input ($Q \geq 10$). If this goal is achievable, then the Tokamak could be adapted and scaled to a commercial fusion power plant.

IMAGE REMOVED / REDACTED	**IMAGE REMOVED / REDACTED**
(a) CAD Drawing of ITER	(b) ITER Site at Cadarache in Southern France

Figure 2: Three-Dimensional (3D) Computer Aided Design (CAD) Image of the ITER Tokamak Fusion Experimental Device [26].

Significant progress has been made towards Tokamak reactors. The Joint European Torus (JET) machine has set the world record of Q=0.6 in 1996 [27]. Extrapolating from deuterium plasma performance in the JT-60 Tokamak, the device achieved an equivalent of Q=1.25, indicating that break-even conditions would have been surpassed had a deuterium-tritium fuel mix been utilized [28]. In China, the EAST Tokamak experiment recently set records for high temperature (70 million degrees), with a long-pulse operation. In Japan, scientists and engineers are constructing a new superconducting Tokamak, JT-60SA, and in Europe, the JET Tokamak (the world record holder for fusion power) is to begin new tests with deuterium-tritium fuel in mid-2021 [29].

The progress in the development of Tokamak-based Magnetic Fusion is shown in Figure 3**,** showing exponential improvements in performance over four decades to 2005, that are comparable or better than that in the semiconductor industry, a benchmark referred to as *"Moore's Law"*.

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Figure 3: Progress in Tokamak-based Magnetic Fusion compared to Moore's law for Semiconductor Improvements [6].

In recent years there have been major scientific and technological advances and improvements in other magnetic fusion configurations. In Germany, the Wendelstein 7-X stellarator [30], [31] recently began scientific operations (see Figure 4), and quickly demonstrated record performance for this type of system, re-igniting interest in stellarators as fusion power plants. Another major stellarator is Large Helical Device (LHD) in Japan [32].

The Spherical Tokamak (see Figure 5) [33] is a type of Tokamak with low aspect ratio (a “fat torus”). Active research has been carried out in the Mega-Ampere Spherical Torus (MAST) in the UK [34] and the National Spherical Torus Experiment (NSTX-U) at the Princeton Plasma Physics Laboratory in the United States [35]. Key anticipated advantages of spherical Tokamaks include improved plasma stability and higher power density, with the potential to build compact fusion reactors with lower capital investment. The advent of high temperature superconductors (HTS) is a key game-changing, enabling technology that permits much higher currents and magnetic fields to be generated by the external field coils in a spherical Tokamak fusion device.

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(a) Simplified View of Field Coils and Plasma	(b) Image of Device and Plasma

Figure 4: Illustrations of the Wendelstein 7-X Experimental Stellarator Fusion Device [31].

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Figure 5: Image of plasma in the MAST Spherical Tokamak Experiment at the Culham Laboratory in the U.K [36].

At the same time, a new wave of innovation in high temperature superconductors is leading to concepts at MIT, Princeton, and in the UK that would make for smaller, lower cost fusion power plants, and the potential for an accelerated commercialization program. More information and details on magnetic confinement systems for fusion can be found in References [19] to [55], and also in the Appendices, in Section A.1.2.

2.1.3 Laser-Based Inertial Confinement Fusion Energy (L-ICF / IFE)

The main approach to inertial confinement fusion (ICF) energy relies on using very high-power laser pulses to compress and heat the deuterium-tritium fusion fuel target to the point of ignition and burn in a single pulse and micro-explosion of energy. This process is somewhat analogous to what happens in a diesel engine, except that the peak fuel densities and temperatures are millions of times higher.

As shown in Figure 6**,** there are number of configurations currently being explored, from the traditional indirect drive and direct drive approaches, to more advanced and innovative schemes, such as using a separate laser pulse to produce the actual ignition of the fusion reactions (like a match lighting fuel, or using a spark plug in a gasoline engine). Once ignited, the fuel will burn extremely rapidly, in a fraction of a nanosecond (1 ns = 1 billionth of a second).

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* Note: Images provided courtesy of Professor Robert Fedosejevs, University of Alberta

Figure 6: Various approaches to laser fusion energy, from left to right: Indirect Drive, Direct Drive, Fast Ignition and Shock Ignition (from Reference [8]).

The *indirect drive* approach [56] has to date been the most developed. With the construction of the largest laser system in the world, producing 1.8 MJ pulsed energy, the multi-billion dollar National Ignition Facility (NIF) [57] at the Lawrence Livermore National Laboratory (LLNL) in California is a test platform for this concept. This approach, which converts laser light into a burst of X-rays inside a small canister which then irradiates and compresses the fuel capsule, has the advantage of being very robust and has been pursued as the mainline approach by the USA and France to date.

The next most investigated approach is the *direct drive* approach [58] using the laser beams to directly irradiate the fuel pellet. This approach is energetically more efficient, should lead to ignition at lower overall laser system energies, and achieve higher gains for a given laser energy. The largest laser system in the world pursuing this approach is at the Laboratory for Laser Energetics (LLE) in Rochester [59] with a peak laser pulse energy of 40 kJ.

The most advanced ICF approaches currently proposed would use a two-stage approach for compression and ignition (somewhat analogous to a gasoline internal combustion engine). An initial laser pulse is used for the initial compression stage. A second, separate laser pulse is then used to create an ignition spark. This two-stage laser approach would reduce the requirements of the primary laser pulse which only needs to compress the fuel to a high density ready to burn. There are a variety of such approaches, including Fast Ignition with electrons [60], [61], Fast Ignition with protons [62], and Shock Ignition [63]. These approaches have the advantage of being more efficient, yet would lead to much higher gain at significantly lower overall laser energies than the single pulse approaches. The variety of approaches is illustrated in Figure 6 and the scaling of net energy gain versus overall laser pulse energy is shown in Figure 7.

IMAGE REMOVED / REDACTED

* Note: “KrF” is Krypton Fluoride

* Note: Image provided courtesy of Professor Robert Fedosejevs, University of Alberta

Figure 7: Calculations of Net Energy Gain, Defined as Fusion Energy Produced Divided by Laser Energy Used for Various Approaches to Laser Fusion Energy as a Function of Total Laser Energy in Mega-Joules (MJ) [8].

At present, a number of the largest nations of the world have built or are building large laser systems to explore indirect drive fusion with the option to convert to direct drive if, in the end, the direct drive approach looks more promising. These facilities include the 1.8-MJ NIF facility in the United States **(**Figure 8**),** the 2-MJ LMJ facility in France, the 600-kJ Shenguang IV facility in Mianyang China, and a Megajoule-class facility in Russia.

In addition, there are smaller laser facilities investigating various aspects related to laser fusion including direct drive and advanced ignition. These include the 40-kJ laser facility at the Laboratory for Laser Energetics (LLE) in Rochester, NY, United States; the 12-kJ laser facility at the Institute of Laser Engineering (ILE) in Osaka, Japan; the 6-kJ laser facility (Orion) in Culham, England; the 2-kJ Central Laser Facility at Rutherford Appleton Laboratories (CLF RAL) in England; the 1-kJ class laser facilities in Paris, France (LULI), Shanghai China (Shenguang II), and the United States (JLF at LLNL, and NRL in Washington, DC).

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Figure 8: Photo of 1.8-MegaJoule Laser Bay of the National Ignition Facility at Lawrence Livermore National Laboratory (from References [8], [57]).

The best result achieved to date has been at LLNL using the indirect drive approach with the production of net energy gain of 17 kJ fusion energy production from 10 kJ energy invested in the ignition hot spot of a laser fusion pellet [64]. This value is within a factor of 2 of ignition at which point the fuel would ignite and start to burn releasing MegaJoules of energy (thousands of times larger).

Current experiments at LLE for the direct drive approach if scaled to the 1.8-MJ laser driver energy indicate that this approach would yield 120 kJ of fusion energy [65] and thus are very similar in status to the indirect drive approach. Current experiments still have a number of technical issues which can be improved including the uniformity of the implosion and further shielding of the target fuel from preheat before compression. These are the subject of investigations funded by the Department of Energy (DOE) in the USA with the goal of reporting in 2020 [66] on the understanding of all technical issues related to achieving laser fusion ignition, and a recommendation of a route forward for achieving ignition.

At the same time, many of the smaller government and university research laboratories are studying the technical issues related to implementing advanced ignition techniques. The study and implementation of these advanced ignition techniques is envisaged in a number of the large laser facilities currently under construction including LMJ in France and Shenguang IV in China. Two planning studies for Engineering Scale Demo systems have already been prepared: the LIFE system for Indirect Drive Fusion [67] at LLNL and the HiPER system [68] using advanced ignition techniques in Europe. These proposals for building demonstration ICF fusion power plants will be put forward once ignition and fuel burn has been demonstrated at one of the current facilities.

More information and details on laser-based inertial confinement systems for fusion can be found in References [56] to [91], and also in the Appendices, in Section A.1.3.

2.1.4 Magneto-Inertial Confinement Fusion / Magnetized Target Fusion

Many innovative new approaches lie in a branch of fusion research called Magneto-Inertial Confinement Fusion (MICF) or Magnetized Target Fusion (MTF) [92]. Magnetic Fusion (MF) systems are typically envisioned as low density, long-confinement time, steady-state systems (or long-pulse electromagnetic devices), where the cost of confining large, low-density fusion plasmas dominates. In laser-based inertial confinement fusion systems (L-ICF/IFE), the actual plasma volume in the target is extremely small, but also extremely high-density. However, the complexities and costs of an L-ICF system are dominated by the cost of the very high power driver systems (such as lasers). The good and encouraging news is that for both systems and approaches, recent scientific and technology advances and innovations are helping to significantly reduce such costs.

The MICF/MTF approach spans the intermediate regime between MF and IFE, using small to intermediate-sized plasmas confined by self-generated magnetic fields, followed by rapid compression and heating to fusion conditions using an electrically-conducting external liner, which is insulated from the plasma by the magnetic fields generated by high electrical currents within the plasma. The aim with the MICF/MTF approach is to avoid the large costs associated with the large field magnets and larger laser drivers in the MFE and L-ICF systems respectively. The goal of the MICF/MTF approach is to create an intermediate system where the simultaneous complexities and costs of the compression driver (for achieving high plasma densities and temperatures) and confinement component (for achieving a sufficiently long fusion fuel plasma confinement time) can both simultaneously be made significantly lower, as illustrated in Figure 9 [93].

MTF concepts trace back to research first undertaken in the 1970s, however the science in this regime remains less explored than MF or IFE. Recent efforts in the United States are aiming to close this gap [94], [95], [96], and [97]. In Canada, the private company General Fusion is undertaking pioneering research to explore the behaviour of compressed magnetized plasmas [98], [99] (see Figure 10). In 2015, the Department of Energy's Advanced Research Projects Agency for Energy (ARPA-E) in the United States launched their ALPHA program, funding nine different groups pursuing variations of MTF and supporting science. ARPA-E grant recipients included private companies such as Helion Energy in Seattle, national laboratories such as Los Alamos National Laboratory, and universities such as Swarthmore College and the University of California. Sandia National Laboratory, also a recipient of ARPA-E funding, is researching another approach to magneto-inertial fusion using an extremely large pulsed magnetic field to compress the fuel, called Magnetic Liner Inertial Fusion (MagLIF) [100]. Research efforts on these concepts are also underway in China.

More information and details on MICF/MTF systems for fusion can be found in References [92] to [102], and also in the Appendices, in Section A.1.4.

IMAGE REMOVED / REDACTED

Figure 9: Magnetized Target Fusion compared to Inertial and Magnetic Fusion (from References [98], [99]).

IMAGE REMOVED / REDACTED

Figure 10: General Fusion's Experiment for Acoustically-Driven Magnetized Target Fusion (from References [98], [99]).

2.1.5 Alternative Fusion Concepts

Alternative concepts for fusion energy have been proposed periodically over several decades, but have generally received much less financial support for development in comparison to Tokamak and L-ICF approaches [104]-[108]. In some cases, attention and support for alternative fusion concepts have been distracted, diverted, and hampered by proposals for highly unorthodox ideas for fusion reactor concepts, with very little, very weak, or flawed scientific foundations. However, within the last 20 years, a more diverse range of highly credible alternative fusion concepts with a very strong scientific foundation have emerged and have attracted meaningful investment in both the private and public sector [109], [110], and [111].

These alternative fusion reactor concepts share a common theme of accepting risk from the application or exploration of new science and technology, with the goal of developing a commercially-viable fusion power plant in the near future. Examples of such private fusion companies include Tri Alpha Energy (TAE) in Irvine, California, studying a unique Field-Reversed Configuration (FRC) (see Figure 11), Lockheed Martin's Skunkworks Division (in the USA) developing a magnetic fusion configuration based on a combination of the FRC, magnetic mirror and magnetic cusp approaches, EMC2 (USA), developing a multi-cusp, magneto-electrostatic fusion concept known as the “Polywell”, and others. Even within Canada, a number of small-scale private fusion companies (such as Hope Innovations, Fuse Energy Technologies, and Norax Atomics) have started up in recent years, hoping to further develop alternative fusion reactor concepts that may have some practical and operational advantages relative to conventional approaches to fusion.

More information and details on alternative fusion reactor concepts and technologies can be found in References [104] to [187], and also in the Appendices, in Section A.1.5.

IMAGE REMOVED / REDACTED	**IMAGE REMOVED / REDACTED**
(a) TAE Field-Reversed Configuration	(b) TAE Experimental Facility

Figure 11: Images of Tri-Alpha Energy (TAE) Fusion Device (from References [170], [171]).

2.1.6 Hybrid Fusion-Fission Reactors (HFFRs)

A unique alternative application for fusion reactors is that they can be used as an efficient neutron source to drive a sub-critical nuclear fission reactor. Such a system is known as a hybrid fusion fission reactor (HFFR). A HFFR can be used for generating power, and/or breeding fissile nuclear fuel for conventional nuclear fission reactors, such as Canadian-designed CANDU reactors, and various types of small modular reactors (SMRs).

A conceptual illustration of an HFFR is shown in Figure 12. High-energy fusion neutrons are generated in the central fusion plasma. These neutrons escape, and bombard the “blanket” surrounding the central fusion region. This blanket is a sub-critical fission reactor, and it contains various fissile (such as U-233 and Pu-239) and fertile nuclear fuels (such as thorium, and/or depleted uranium). When neutrons bombard the blanket, they cause fission of the fissile isotopes, and they also cause breeding of new fissile fuel from the fertile fuel.

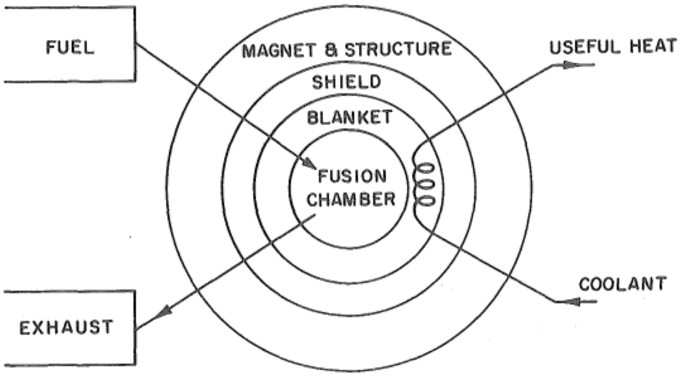

Figure 12: Conceptual Illustration of a Hybrid Fusion-Fission Reactor [197].

The one key advantage of a HFFR over a conventional pure fusion reactor, is that it does not require a high-performance fusion reactor. A HFFR could be designed to operate successfully (generate more power than it consumes) using a low-performance fusion reactor ($Q \leq 1.0$), since most of the power is coming from fission instead of fusion. In principle, it should be possible to build a HFFR today, using current technology. No new breakthroughs are required. As mentioned previously, various types of experimental Tokamak fusion reactors have already achieved Q~1.0, such as the Joint European Torus (JET) in the UK [29].

Although some advocates may suggest that the HFFR is a short-term “bridging technology” to a pure fusion system, the HFFR is valuable in its own right, since it can be an alternative source of zero-carbon power. More importantly, the HFFR can serve as a fissile fuel breeder, to support a larger fleet of conventional fission reactors (such as the Canadian CANDU reactor).

Various HFFR concepts have been under study for several decades, nearly as long as fusion reactors. Prominent scientists and Nobel Prize winners, such as **Andrei Sakharov** (who was a co-inventor of the Tokamak fusion reactor concept) [218] and **Hans Bethe** [193] were early and strong advocates for the development of HFFRs. During the 1970s and 1980s, many groups around the world were closely investigating HFFRs, including scientists at AECL Chalk River Laboratories [196], [197], [198], and [199]. In more recent years, especially since 2010, there has been renewed interest in HFFRs, particularly in China [203], [204], and [213], and Russia [209], [210].

More information and details on hybrid fusion fission reactors can be found in References [188] to [221], and also in the Appendices, in Section A.1.6.

2.1.6.1 Fusion Energy R&D: Timeline of Key Initiatives/Milestones

Various studies by the International Atomic Energy Agency (IAEA), European Union, and USA (References [8] to [12]) have outlined roadmaps to fusion power plant systems. At the current rate of progress, it appears very likely that scientific demonstration of the conditions required for net electrical energy production ($Q \geq 3$) by fusion energy will be reached fairly soon, possibly within the next 10 to 20 years (2030 to 2040) for ITER, NIF, and LMJ. Depending on the success of ITER and other prototypes to demonstrate scientific and engineering feasibility, and stimulation by private sector competition, the first demonstration commercial fusion power plants could begin operation in 20 to 40 years (2040 to 2060). Similar roadmaps of project timelines and expected progress for different fusion technologies are summarized in Figure 13 (for L-ICF, [8]), Figure 14 (for Magnetic Fusion [9]), Figure 15 (for ITER and DEMO [11], [12]) and Figure 16 (for all systems [6]).

IMAGE REMOVED / REDACTED

* Note: In 2013, NIF achieved "partial ignition" with 14 kJ of fusion power output, from 10 kJ of direct heating to the compressed D-T fuel target.

* Note: Image provided courtesy of Professor Robert Fedosejevs, University of Alberta

Figure 13: European Inertial Fusion Energy Roadmap (from Reference [8]).

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Figure 14: Timelines for International Magnetic Fusion Roadmaps (from Reference [9]).

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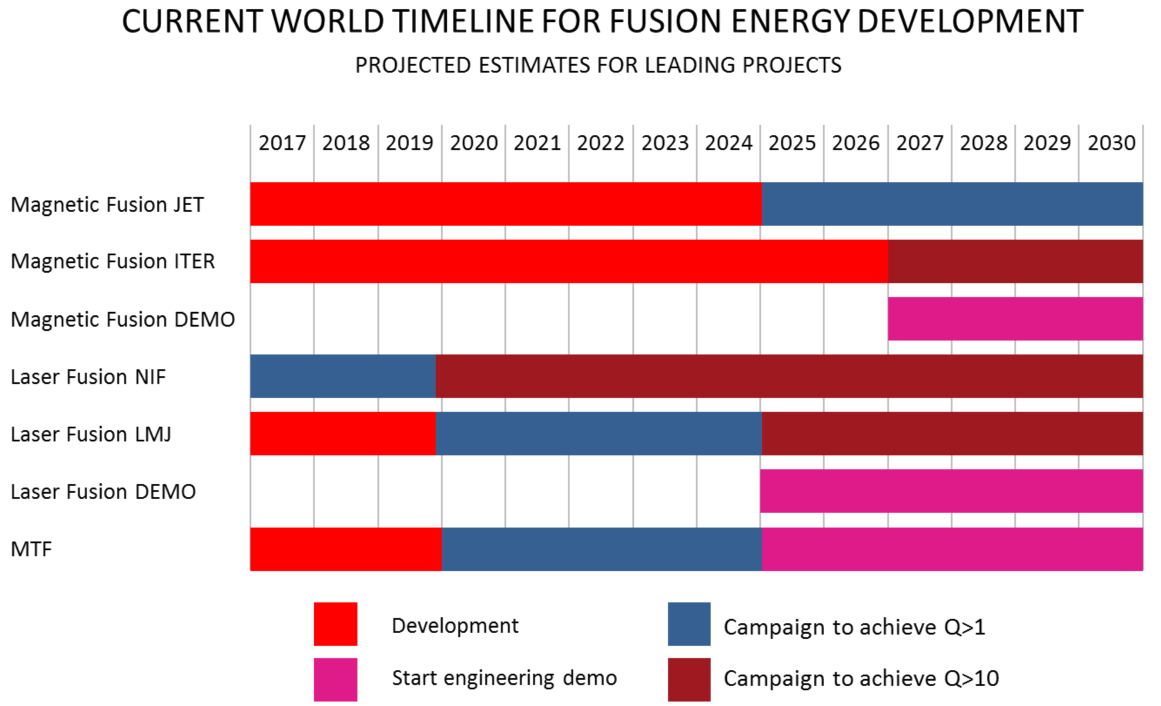
Figure 4: Diagram depicting how information from ITER, during its four-phase assembly/operation phase, flows into the DEMO Conceptual and Engineering Design Activities. CDR=Concept Design Review. The dates are indicative.

Figure 15: EUROFUSION's Anticipated Timelines for the Different Phases of Development for ITER and DEMO (from References [11] and [12]).



* Note: LMJ = Laser Mega Joule Facility in France. DEMO is the anticipated commercial fusion demonstration project, to follow ITER.

Figure 16: International Progress and Estimated Timelines of Major Fusion Programs till 2030 (from Reference [6]).

2.2 Potential Applications of Fusion Energy

Fusion energy and fusion reactors are an alternative source of energy and power, that could be used to complement, or possibly replace the use of fossil fuels and other low-carbon or zero-carbon sources of energy, including nuclear fission reactors, hydro-electric dams, variable renewable energy resources (such as wind and photovoltaic solar), and biomass.

Fusion reactors have several direct and indirect applications, including the following:

- Base-load electric power generation.
- Production of hydrogen as energy carrier/fuel, and as a chemical feedstock for making plastics/polymers, ammonia (for fertilizer and other uses), as a replacement for coal for steel-making and other large-volume products.
- High-temperature process heat and steam for manufacturing chemical compounds, special materials, smelting metals, petrochemical processes, refineries, upgrading fossil fuels, cement manufacturing, and others.
- Production of synthetic, practical, low-carbon transportation fuels (such as methanol, ethanol, and dimethyl ether) to replace gasoline, diesel and kerosene/jet fuel.
- Desalination of sea-water, to produce pure, distilled, fresh water.

- Direct air capture and removal of carbon dioxide from the atmosphere.
- Production of medical and industrial radio-isotopes.
- Production/breeding of fissile nuclear fuels (such as U-233 and Pu-239) from fertile nuclear fuels (such as thorium (Th-232) and U-238 (in the form of depleted or natural uranium)).
- Transmutation/destruction of radioactive waste.
- Fusion-based neutron sources for different applications (detectors, interrogation, neutron activation)

For more information about the applications of fusion energy, see References [222] to [245] and the further discussion in the Appendices, in Section A.2.

2.3 Overview of Fusion Technology Readiness Levels

To review, the following are the European definitions for different technological readiness levels [13] applied to technology development:

- TRL 1 – Basic principles observed
- TRL 2 – Technology concept formulated
- TRL 3 – Experimental proof of concept
    - Different fusion technologies are expected to reach or exceed this state in the period of 2020 to 2030. In many aspects, the component technologies for Tokamak, Stellarator, and L-ICF devices are already at this level.
- TRL 4 – Technology validated in lab
    - Different fusion technologies are expected to reach this state in the period of 2020 to 2030.
- TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
    - Different fusion technologies are expected to reach this state in the period of 2030 to 2040, with the operation of ITER, and other concepts.
- TRL 7 – System prototype demonstration in operational environment
- TRL 8 – System complete and qualified
- TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)
    - Different fusion technologies are expected to reach this state in the period of 2040 to 2060, with the operation of DEMO, and other commercial prototypes.

Based on progress made over the last 30 years in different mainstream and alternative fusion reactor technologies and concepts, the technological readiness level (TRL) for a fusion power plant is expected to range between 3 to 4 up to the year 2030, as discussed in publications by Tillack [14], Kembleton [15], Sagara [16], and Chapman [17], and Prinja [18]. Once the next generation of large-scale experiments get underway, such as ITER, the TRL will jump to levels 5 and 6 over the period of 2030 to 2040. With the advent and implementation of high-temperature superconductors, more compact spherical tokamak devices, and alternative fusion devices relying upon the use of external field magnets could potentially reach the same TRL levels in a shorter time frame with accelerated effort, depending on the level of government and private sector investment.

2.4 Fusion Energy and Fusion Reactor Economics

A Simple View

From a simplistic and qualitative perspective, and looking at the history of energy technology development, it may be natural to expect that the first generation of fusion reactors are going to have relatively higher capital costs, and a higher levelized cost of electricity (LCOE) in comparison to existing, operational technologies. As experience is gained with the construction and operation of fusion power reactors, and as new improved designs and technologies are introduced into the fusion power plant fleet, then one might expect that the capital costs and LCOE costs will come down, possibly to levels that are comparable and competitive.

Guidance from Historical Example

Historically, the first generation of nuclear fission power reactor prototypes built during the late 1950s and early 1960s were relatively more expensive than the contemporary oil-fired and coal-fired power plants. Starting in the late 1960s, with the development of larger-scale nuclear power plants, evolutionary design improvements in fuels, materials science, chemistry, and improvements in maintenance and operations, nuclear power plants were becoming comparable or lower in cost with competing energy technologies [247], [248]. This trend was expected to continue.

It is recognized that from the period of the late 1970s to the late 1990s, the costs associated with nuclear power in Canada and the United States began to rise significantly, due in part to added financing costs (and interest on debt) as there were added design requirements, and construction and operation delays associated with addressing public, political, and regulatory concerns regarding perceived and potential safety issues. However, in certain jurisdictions, nuclear power still remained competitive as the only viable zero-carbon source of baseload electricity [247], [248].

The more recent interest in small modular reactors (SMRs) [4], [5] has developed as a means to supply smaller-sized markets, and to achieve cost savings through the economies-of-scale associated with assembly-line, factory-fabrication of reactors, and reduced financing costs (the cost of borrowing money) with shorter construction time periods, and smaller capital outlay.

If pollution and carbon taxes, or the costs of pollution and greenhouse gas mitigation technologies (such as carbon capture and storage) are further imposed on the use of fossil fuels (such as coal, oil, and natural gas), or conversely, if zero-carbon credits are applied to nuclear energy, then modern nuclear power plants become even more economically competitive as reliable and robust baseload power plants [247].

In an analogous way, it might be expected that fusion power plants will become more cost competitive with existing conventional sources of energy, as improvements in technology are developed, and as experience in operations is gained. Like conventional nuclear fission energy, fusion has the distinct advantage of being a zero-carbon energy technology, with the expected ability to operate with high capacity factors (≥80%) in baseload power plants.

Estimates for Overnight Capital Costs and LCOE for Fusion Power Plants

In 2014, researchers at Canadian Nuclear Laboratories carried out a literature survey to obtain estimates of expected costs for fusion power plants in the future, including both overnight capital costs and levelized costs of electricity (LCOE). Data and information were obtained from various sources [249]-[258]. Preliminary estimates are shown below in Figure 17 and Table 1. This survey indicated that there is broad range of values with high uncertainties.

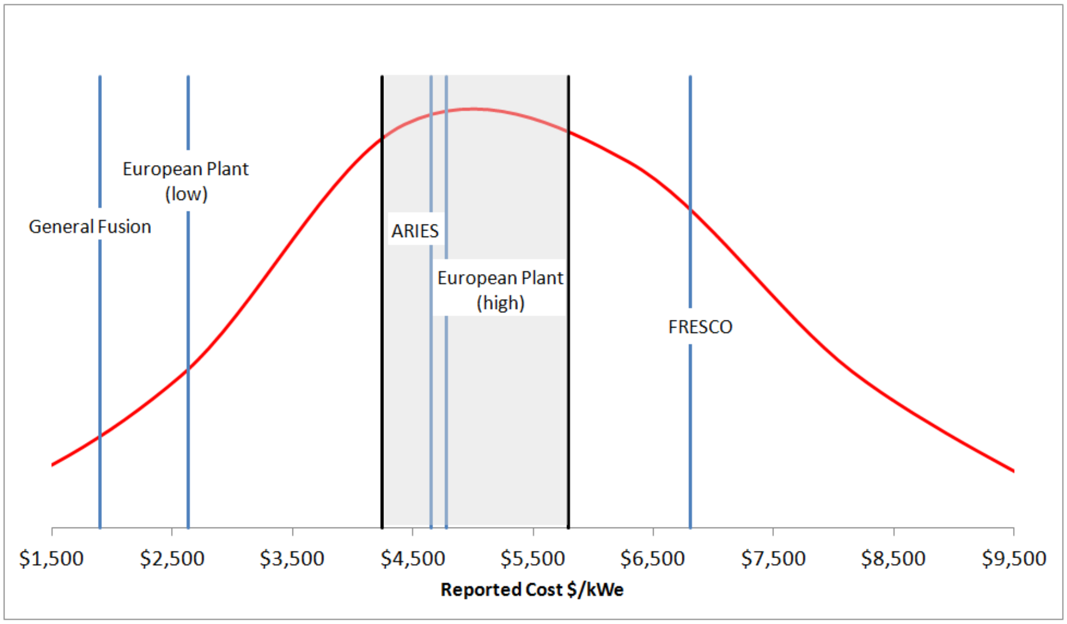
For overnight capital costs, fusion power plants were estimated to range approximately between 2000 and 8000 $USD/kWe-installed (in 2014 $USD), as shown in Figure 17. For comparison, in the same survey, large-scale nuclear fission reactors were estimated to range between 4000 and 6000 $USD/kWe-installed.

Revised fusion reactor capital cost estimates were developed in another study by Han and Ward in 2009 [259], [260]. Taking into account anticipated technological improvements when the DEMO is to be built in the 2050 to 2080 time frame, Han and Ward estimated that the overnight capital costs could range from 2200 to 4,000 $USD/kWe-installed (in 2000 $USD), with the lowest cost expected for the most advanced and mature systems. Assuming a 2.3%/year inflation rate, these estimates by Han and Ward scale to 3000 to 5500 $USD/kWe-installed in 2014, and 3500 to 6300 $USD/kWe-installed in 2020.

For the levelized cost of electricity, the cost for fusion was estimated to range between the lower and upper extremes of 30 and 390 $USD/MWe-hr, as shown Table 1**,** depending on the technology and the level of progress. For more advanced, mature fusion power systems, the LCOE is 60 $USD/MWe-hr, assuming a 3% discount rate. Large-scale wind power systems (> 100 MWe) are expected to have an LCOE between 28 and 113 $USD/MWe-hr.

However, it should be noted that wind power systems will likely have a significantly lower capacity factor (≤40%). If the costs for using a lithium-ion battery energy storage system are grossly lumped with wind, to ensure a capacity factor comparable to either fission or fusion (≥80%), then the LCOE of a combined wind-plus-storage system could range between 76 and 311 $USD/MWe-hr. In this regard, it would appear that a modern fusion power plant could be economically advantageous relative to the use of variable renewable energy combined with storage capacity.

Thus, it is possible that future fusion systems could be very comparable in cost to other existing zero-carbon energy sources. Development of new technologies (such as compact fusion reactors using high magnetic fields and high-temperature superconductors), and additional applications could further reduce the LCOE and capital costs [262], [263].



* Note: Costs are adjusted with inflation to 2014 $USD.
Blue bars are individual fusion reactor technologies. Grey area represents expectations for fission reactors.
Red curve is the normal distribution for fusion reactors. Data is from 2014 survey study by CNL scientists.

Figure 17: Distribution of Estimated Overnight Capital Costs ($USD/kWe-installed, Year 2014) for Fusion Power Reactors and Compared with Conventional Nuclear Fission Reactors.

Table 1: Levelized Cost of Electricity (LCOE) from Various Studies (from CNL Survey in 2014).

Study [Reference]	LCOE Estimate ($/MWe-hr)	Year / Currency	LCOE Equivalent Value in 2020 $USD/MWe-hr*
Survey of published projections [250]	70 - 130	1996 $USD	120 to 224
New ARIES System [251]	47.12	1992 $USD	89
ARIES-RT Reference [251]	47.53	1992 $USD	91
Tokamak Estimates [251]	67	2008 $USD	85
Hypothetical Fusion Reactor [252]	46.8	1977 $USD	187
FRESCO Code [253]	76	2000 $USD	119
PROCESS Code [253]	80	2000 $USD	126
FRESCO Code [254]	192.61	1990 $USD	389
PROCESS Code [254]	212.73	1990 $USD	429
Monte-Carlo Estimate [254]	90 - 270	2014	103 to 309
Fusion with 50% Learnings [255]	8.11 (1)	Euro 2000	138
Fusion with 65% Learnings [255]	9.6 (2)	Euro 2000	163
Early Generation [255]	50 - 100	Euro 2000	85 to 171
Mature Technology [255]	30 - 60	Euro 2000	50 to 102
Mature Fusion Technology [256]	3 – 7 (2)	Euro 2005	33 to 105
ARIES-RS [257]	82	1995 $USD	146
SPPS-MHH [257]	80	1995 $USD	141
TITAN [257]	53	1995 $USD	94
IFE HYLIE-II [257]	56	1995 $USD	99
Alternative Zero-Carbon Energy Technologies			
Conventional Large-Scale Nuclear Fission Reactors [261] *** (3)	40 to 60 (3)	2020 $USD	40 to 60 (3)
Large-Scale Wind Turbines (5) [261]	28 to 113	2020 $USD	28 to 113
Energy Storage (4) [261]	48 to 200	2020 $USD	48 to 200
Wind + Energy Storage (4), (5)	76 to 313	2020 $USD	76 to 311

(1) Assuming an average inflation rate of 2.3% per year

(2) EURO-Cents (0.01 Euros)/kWe-hr. Note: 50 $USD/MWe-hr is the same as 5 cents/kWe-hr

(3) Large-scale nuclear fission reactors have power levels typically in the range of 700 MWe to 1,700 MWe. Note: LCOE Estimate for nuclear includes a 3% discount rate. Note: capital costs (overnight) for new large-scale nuclear reactor are typically in the range of 2,200 $USD/kWe-installed to 4,300 $USD/kWe-installed [261].

(4) Overnight cost for energy storage with Lithium-Ion Batteries ranges between 450 and 2000 $USD/kWe-installed. Note: LCOS (Levelized Cost of Storage) can be treated as LCOE, when it is combined with a variable, low-capacity factor energy resource, such as wind turbines.

(5) Overnight cost for onshore wind turbines in Canada and the USA ranges between 1300 and 2,300 $USD/kWe-installed. Note: LCOE estimate for large-scale wind turbines is value typical for U.S.A., with a 3% discount rate. A capacity factor of ~40% is typically assumed. Average LCOE is ~48 $USD/MWe-hr.

3. Fusion Energy: Canadian Landscape

3.1 Key Current Canadian Players in Fusion Technology R&D

Across Canada, there are several small groups at different laboratories, academic institutions and private companies carrying out fusion-related research, or promoting knowledge and understanding of fusion energy science and technology. These institutions are listed below in Table 2 and Table 3. Advocacy groups and professional societies promoting fusion include the Fusion Energy Council of Canada (FECC) and the Canadian Nuclear Society (CNS). Government laboratories and universities involved with fusion-related research include Canadian Nuclear Laboratories (CNL), University of Saskatchewan, University of Alberta, University of Toronto Institute for Aerospace Studies (UTIAS), Ontario Tech University, and Queen's University. The small-scale work at each of these institutions has usually involved efforts of 1 to 5 academic or research staff, and have contributed directly or indirectly to international efforts over the last 40 years, many through collaborative work, or through research contracts.

Within Canada's nuclear industry, the provincial utility Ontario Power Generation (OPG) has expressed recently an interest in becoming more involved with fusion energy development, largely due to its accumulated reserves of the fusion fuel tritium, which is a by-product from the operation of the CANDU heavy water power reactors in Ontario. Historically, OPG's predecessor, Ontario Hydro, in cooperation with AECL, was actively involved in Canada's previous National Fusion Program through the Canadian Fusion Fuels Technology Project (CFFTP) during the period of 1987-1997 [264], [268].

In cooperation with OPG, the Organization of Canadian Nuclear Industries (OCNI) has led a recent initiative to engage with representatives of the ITER project in Europe to establish a political and business framework through which Canadian companies with expertise supporting the Canadian nuclear industry could provide technical services to the ITER project through sub-contracts with companies of ITER member nations.

Small-scale, start-up companies involved with fusion or applied plasma physics research include Plasmionique in Varennes, QC, Fuse Energy Technologies in Napierville, QC, and Norax Canada in Levis QC, and Hope Innovations in Mississauga, ON.

One private company of special distinction is General Fusion, based in Burnaby, British Columbia. General Fusion is a start-up fusion company founded in 2002 with the primary goal of developing a fusion power reactor prototype based on the concept of acoustically-driven magnetized target fusion. Since its founding, General Fusion has grown to over 75 employees, and has been successful in attracting both public sector and private sector investment. Effectively, General Fusion has become the largest group of fusion specialists in Canada, and a major player within the international community, leading work in the area of magnetized target fusion. General Fusion also has the distinction of being one of the larger private companies dedicated solely to developing fusion technology.

See Section A.3 for more information and details on the experience and expertise of the different key players in fusion in Canada.

Table 2: Canadian Players in Fusion Energy Science and Technology.

Region	Company/Institution/Organization	Key Information
Canada	Fusion Energy Council of Canada (FECC) (since 2019) https://fusionenergycanada.ca/	Fusion Advocacy Organization, evolved from the Alberta-Canada Fusion Technology Alliance (AFTCA).
Canada	Canadian Nuclear Society – Fusion Energy and Accelerator Science and Technology Division (CNS-FEASTD) (since 2009) https://www.cns-snc.ca/CNS/fusion/	Grassroots, not-for-profit professional society. Objective is to promote technical communication and cooperation in Canada among fusion energy experts and enthusiasts. Organizes technical sessions and panel discussions and workshops at conferences. Communicates periodically with its membership to provide updates on fusion news in the international community.
BC	General Fusion – Burnaby (since 2002) www.generalfusion.com	Acoustically-driven Magnetized Target Fusion (MTF). A variant of LINUS Concept from the 1970s.
AB	University of Alberta – Department of Electrical Engineering, Photonics and Plasma Research Group (since 1970s) https://www.ualberta.ca/electrical-computer-engineering/research/photonics-and-plasmas	Focus on Laser-Based Inertial Confinement Fusion S&T.
SK	University of Saskatchewan (since 1960s) Department of Physics & Engineering Physics Plasma Physics Laboratory http://plasma.usask.ca/	Focus on Tokamak-based Magnetic Confinement Fusion S&T. Only experimental Tokamak in Canada – STOR-M. Minor effort on alternative concepts, such as the Dense Plasma Focus (DPF).
ON	Canadian Nuclear Laboratories (CNL) (formerly AECL – Chalk River Laboratories) (since 1970s) www.cnl.ca https://www.cnl.ca/en/home/facilities-and-expertise/all-facilities/tritium.aspx	Mainly work in tritium production / handling. Some work in physics analysis of hybrid fusion fission reactors. Prior work at AECL, Chalk River Laboratories in support of the Canadian Fusion Fuels Technology Project (CFFTP), in period of ~1982 to 1997.
ON	University of Toronto Institute of Aerospace Studies (UTIAS) (since 1970s) https://www.utias.utoronto.ca/ https://www.utias.utoronto.ca/research/fusion-energy-plasma-materials-interactions/	Experimental/computational modeling of plasma-wall interactions. Materials research. Mostly work in support of Tokamak research and ITER. Many international collaborations.
ON	Queen's University, Kingston, Department of Physics (since 2003) https://www.queensu.ca/physics/home https://www.physics.queensu.ca/~morelli/jm/	Small scale experimental and computational plasma physics and electromagnetics research.

Table 3: Canadian Players in Fusion Energy Science and Technology – Continued.

Region	Company/Institution/Organization	Key Information
ON	Ontario Tech University, Oshawa Faculty of Energy Systems and Nuclear Science. https://faculty.ontariotechu.ca/gaber/	Small scale plasma physics research. Advanced Plasma Engineering Laboratory (APEL). Studies being carried out on Z-Pinch and Dense Plasma Focus fusion devices.
ON	Ontario Power Generation (OPG) – Darlington & Pickering Nuclear Generating Stations https://www.opg.com/powering-ontario/our-generation/nuclear/darlington-nuclear/	Interest in selling stockpiles of tritium (and decayed Helium-3) to ITER and other fusion projects in the international community. Initially led efforts in 2019 to develop "Canadian Fusion Office" (CFO) to help facilitate and coordinate cooperation between Canadian nuclear industry and the ITER project in Europe as a sub-contractor.
ON	Organization of Canadian Nuclear Industries (OCNI) https://ocni.ca/	Interest in marketing capabilities of its member companies to international community (such as the ITER Project) for fusion energy engineering, science and technology development. Co-lead initial effort with OPG to develop "Canadian Fusion Office" (CFO) in 2019.
ON	Hope Innovations, Mississauga, Ontario (since 2011) http://www.hopeinnovations.ca/	A small start-up fusion research company. Working on an alternative concept related to Z-Pinch and X-Pinch Devices.
QC	Plasmionique (since 1999) Varennes, QC https://www.plasmionique.com/	An R&D company created after the demise of Tokamak de Varennes (TdeV) fusion project and its associated team of technical and scientific staff at the University of Quebec at Montreal (UQAM). Company develops and sells plasma processing technology, and does supporting R&D.
QC	F-Energy / Fuse Energy Technologies (since 2018), Napierville, QC https://www.f.energy/	A small start-up fusion R&D company in Quebec. Working on developing a variant of a fusion Z-Pinch; looking to develop alternative applications and to find near-term customers and partners for their work.
QC	Norax Canada / Norax Induction / Norax Atomics (since 1995) Levis, QC http://noraxcanada.com/index.php	Norax develops pulsed and RF power supplies for radio-frequency (RF) induction heating systems, some which could be employed in fusion energy research. CEO and some key staff members have an interest in fusion and are working confidentially on developing an alternative fusion concept; information is being kept proprietary.
Other Provinces	There does not appear to be any fusion players in MB, NB, NS, PEI, NL, or the Yukon, Northwest, or Nunavut Territories.	

3.2 Status of R&D Fusion Initiatives in Canada

The following sub-sections provide summaries of the status of fusion research and development activities and initiatives in Canada in different sectors by key players. More information and details can be found in the appendices, in Section A.3.

3.2.1 Canadian Academia

Within Canadian academic institutions involved with fusion-related research, the following is a brief summary of the current status of activities:

- **University of Saskatchewan (USask), Saskatoon, SK**
    - Within the Department of Physics, University of Saskatchewan has been involved in plasma physics and fusion-related research since the late 1950s, focusing on the experimental and theoretical/computational studies of magnetic confinement of fusion plasmas. There are four professors at USask carrying out fusion and plasma-physics-related work.
    - The Plasma Physics Laboratory at the University of Saskatchewan (USask-PPL) currently operates a small-scale experimental Tokamak magnetic fusion device (STOR-M), and has been carrying out experiments investigating the use of compact toroid injection (CTI) as an improved method for refuelling Tokamak fusion reactors, and the use of alternating current (AC) drive for operating a Tokamak in a near-steady-state conditions. See Section A.3.2 for more information about USask-PPL.
- **University of Alberta (UAB), Edmonton, AB**
    - Within the Departments of Electrical Engineering and Physics, the University of Alberta has been involved with fusion research since the 1970s, focusing on computational modeling and experimental studies of laser-based inertial confinement fusion (L-ICF). There are up to six professors at UAB carrying out fusion and plasma-physics related work.
    - Current fusion-related work at UAB includes theoretical modeling and large scale numerical simulations, as well as most aspects of laser-based fusion. Professors at UAB engage in collaborations with international colleagues at international experimental facilities dedicated to L-ICF. See Section A.3.3 for more information about UAB.
- **University of Toronto Institute for Aerospace Studies (UTIAS)**
    - Research staff at UTIAS have been actively involved in computational and experimental studies of plasma-surface interactions relating to fusion applications since the 1970s. There are two key professors at UTIAS doing fusion-related work.
    - Current work involves using computer simulation tools developed at UTIAS for modeling the interactions of ions and electrons in fusion plasma with the surfaces of components (such as divertors) typically found in magnetic

confinement fusion devices, such as Tokamak fusion reactors. The computer simulations have used to understand the behavior of experimental facilities, such as the General Atomics DIII-D Tokamak experiment in San Diego, CA, USA. See Section A.3.4 for more information about UTIAS.

- **Ontario Tech University (OnTechU), Oshawa, ON**
    - A small research group at OnTechU in the Faculty of Energy Systems and Nuclear Science have been carrying out experimental research in the areas of applied plasma physics and fusion on a part-time basis since 2010. There are two key professors at OnTechU doing fusion-related work.
    - Current studies in the Advanced Plasma Engineering Laboratory (APEL) at OnTechU are focused on investigating an alternative fusion concept known as the Dense Plasma Focus (DPF), a pulsed fusion device which may have applications beyond fusion, such as an intense neutron source for medical isotope production. See Section A.3.5 for more information about OnTechU.
- **Queen's University, Kingston, ON**
    - Since 2003, a single professor in the Department of Physics at Queen's University has been leading fusion-related research on a part-time basis, under the Applied Magnetics Program.
    - Recent studies in fusion at Queen's U. have focused on Tokamak diagnostics and on the use of compact toroids (CTs) as a means of refuelling steady state Tokamak discharges (such as that expected in ITER) and also as an alternative fusion reactor concept in their own right (similar to that found in the General Fusion magnetized target fusion approach, and others). The work at Queen's U. has helped support and complement work being done at USask-PPL, General Fusion, and other institutions. See Section A.3.6 for more information.

3.2.2 Canadian Private Sector Fusion Companies

The following are brief summaries of the current status of fusion-related activities within the Canadian private sector (but excluding efforts by members of OCNI):

- **General Fusion, Burnaby, BC**
    - General Fusion was founded in 2002, and focused on building a practical, commercially viable alternative path to fusion energy, based on the alternative fusion concept of acoustically-driven magnetized target fusion (MTF). General Fusion has now grown to 75 employees, and it has been successful in raising financial support from investors in both the public and private sectors. General Fusion has the largest group of fusion specialists in Canada.
    - In 2019, General Fusion was awarded a 4-year, $49.3 million grant from the Government of Canada through a Strategic Innovation Fund (SIF) program under the Ministry of Innovation, Science and Economic Development to support the development of the General Fusion MTF/MICF prototype device.

  - In addition, over the last several years, General Fusion has been to secure additional sources of funding from many private sector and venture capital investors, including Thistledown Capital, Temasek, BDC, Hatch, the DLF Group, Gimv, I2BF Global Ventures, DTA, Chrysalix Energy Venture Capital, Bezos Expeditions, Khazanah Nasional Berhad, Braemar Energy Ventures, Entrepreneurs Fund, SET Ventures, and others.
  - See Section A.3.7 for more information.
- **HOPE Innovations (Mississauga, Ontario)**
  - HOPE Innovations is a small, private start-up fusion company established in 2011, and is investigating an alternative fusion concept based on plasma confinement through the intersection of high-current discharges through a deuterium plasma, with similarities to Z-Pinch and X-Pinch devices. HOPE Innovations has up to 4 staff working on a part-time basis.
  - HOPE Innovations continues efforts to raise financial support through public and private sector sources in Canada and China, and is engaged in collaborations with Sichuan University (SCU) in Chengdu, China. Recently, HOPE Innovations established a small research facility in Etobicoke, Ontario where deuterated targets for plasma pinch experiments are being prepared. See Section A.3.8 for more information.
- **Fuse Energy Technologies (Napierville, Quebec)**
  - Fuse Energy Technologies is a small and relatively new start-up company based in Napierville, Quebec (near Montreal), and was established in 2018, with six staff members. Fuse Energy is focused on developing fusion reactor technology based on one or more alternative concepts. The current focus is on developing a variant of a Dense Z-Pinch device, known as the “Flow-Through Z-Pinch”.
  - Currently, Fuse Energy is constructing a small-scale experimental prototype Z-Pinch device, and expects to begin experiments with deuterium fuel later in 2021. See Section A.3.9 for more information
- **Plasmionique (Varennes/Montreal, Quebec)**
  - Plasmionique is a small plasma technology company based outside of Montreal, in Varennes, Quebec, and was established in 1999 by Canadian experts in plasma science and technology, following the shutdown of the Tokamak de Varennes (TdeV) fusion project (1985-1997). Plasmionique has over a dozen staff.
  - Recent and current fusion-related activities by Plasmionique include contracts with the ENEA (*Italian National Agency for New Technologies, Energy and Sustainable Economic Development*) in Frascati, Italy for integration of a diagnostic neutral beam injector; developing a scanning plasma edge probe for the Tore-Supra Tokamak experiment in France, and canning a retarding field analyzer for the ASDEX-Upgrade (Axially Symmetric Divertor Experiment) Tokamak facility at Max-Planck-Institut für Plasmaphysik, in Garching, Germany. See Section A.3.10 for more information.

- **Norax Atomics / Norax Induction Canada (Lévis, Quebec)**
  - Norax Canada Inc. is a Canadian manufacturer of customized resonant switched mode induction power supplies for industrial and research applications, and has been in existence for nearly 25 years. Since before 2012, a research group with Norax has taken an interest in the development of an alternative fusion plasma confinement system, leveraging its experience and expertise in radio-frequency power and control. While work on fusion by Norax has been kept confidential, it has been indicated recently that Norax expects to complete construction and begin testing on its first prototype fusion device, possibly in the 2021/2022 time frame. See Section A.3.11 for more information

3.2.3 Canadian Nuclear Laboratories – Tritium Facility and Other Research

Scientific and technical staff at the Canadian Nuclear Laboratory Tritium Facility (CNL-TF) execute research and development programs and commercial activities associated with tritium technology. The Tritium Facility commenced operations in 1979 and consisted primarily of an inert atmosphere glove box and associated supporting equipment, but the scope of the laboratory expanded to the point where CNL opened a new Tritium Facility in 2019, with new office space, laboratories and equipment.

CNL’s Tritium Facility is licensed to process 100 g (37 PBq) of tritium at any one time, with an additional 250 g (92.5 PBq) in storage. There are three main laboratory spaces to handle tritium and these house the following equipment: a tritium handling apparatus inside an inert atmosphere glove box (secondary enclosure) for tritium dispensing and loading operations, two additional inert atmosphere glove boxes for handling tritium in liquid or gaseous forms, several fume hoods and air-purged enclosures for experimental work as well as for maintenance activities, plus liquid scintillation counters, and several pieces of specialized experimental equipment.

The main capabilities of the facility include tritium handling at high levels (up to 100 grams) in specialized equipment, process engineering for tritium management, R&D activities for fission, fusion, environmental and tritium products and applications and a hands-on/class room training course for national and international tritium workers.

Commercial work in the Tritium Facility includes dispensing of high-purity tritium using the tritium handling apparatus in the inert atmosphere glove box as well as preparation of gas standards with customer-specified tritium content, carrier gas, cylinder size and pressure. The Tritium Facility has supplied the majority of the tritium used for JET fusion experiments. Past commercial work at CNL has also involved tritium loading for various manufacturers of tritium-powered betavoltaics, including custom-designed tritium loading vessels and packaging crates fabricated at CNL.

Experimental research within CNL’s Tritium Facility spans many disciplines from betavoltaics to coatings that resist tritium permeation, materials for tritium-compatible electrolyzers, tritium separation and tritium purification.

A major area of strength and proposed area of activity is in all aspects of tritium, production, extraction, purification, storage, and material interactions. Canada is a world leader in many of these areas at present. In addition, CNL has a strong program of work in environmental monitoring for tritium that couples well with its technologies for emissions reduction.

Other areas of strength include the development of improved processes for extraction and recovery of deuterium. CNL is working to commercialize new processes for this at present.

Further details on CNL's fusion-related work are discussed in the appendices, in Section A.3.1.

3.3 Deuterium and Short-Term Tritium Reserves & Market Opportunities

As noted previously, the materials necessary to fuel any D-T fusion reactor are simply deuterium (D) and tritium (T), heavier isotopes of hydrogen. The use of this fusion fuel combination is preferred because it has the highest probability of occurring, relative to other types of fusion fuel reactions, and it is scientifically and technologically easier to build a power-producing fusion reactor to run on D-T fuel.

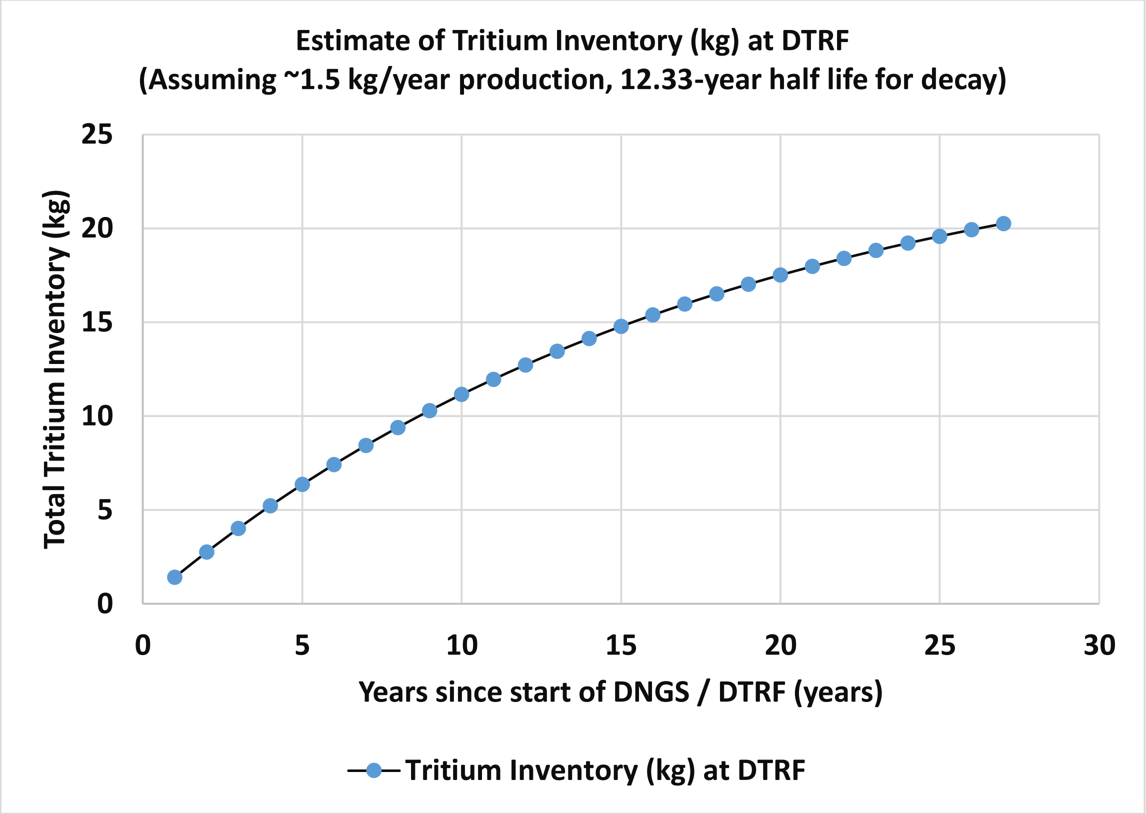
Ontario Power Generation (OPG) and Atomic Energy of Canada Limited (AECL) own many tonnes of heavy water (D_2O) originally extracted from water to support the construction and operation of domestic heavy water power reactors (CANDU reactors) and for carrying out research activities at the Chalk River Laboratories, as part of Canadian Nuclear Laboratories. A large amount of this is in storage and being marketed for a diverse range of non-nuclear uses. Elemental deuterium can be extracted and isolated from heavy water through well-established industrial processes (namely electrolysis, $D_2O + \text{electricity} \rightarrow D_2 + ½ O_2$) and hence no immediate shortage of deuterium is expected. With its expertise, technology, and industrial capability for recycling used heavy water and producing new heavy water, Canada is well-positioned to become a world supplier for deuterium for fusion fuel applications.

Supply and efficient use of tritium are the other side of fuelling a fusion reactor. Some tritium is available for this purpose. Through the operation of CANDU heavy water power reactors in Canada at the Pickering, Bruce, and Darlington nuclear generating stations (NGS), small amounts of tritium are created, due to the absorption of neutrons by deuterium nuclei in the heavy water moderator ($D + n \rightarrow T + \gamma$(gamma ray)). While the probability of producing tritium from neutron bombardment of deuterium is low, it is non-zero.

The Darlington Tritium Removal Facility (DTRF) at the Darlington NGS extracts and stores approximately 1.5 kg of tritium each year [270]. If fused with 1.0 kg of deuterium fuel in a fusion reactor (using the D-T fusion reaction: $D + T \rightarrow n + \text{He-4} + 17.6$ MeV of energy), this tritium production has the energy equivalency of approximately 8.5×10^{14} Joules, or 9,800 MW-days of heat. If converted into electricity with a 33% efficiency, this energy would be equivalent to ~3,300 MWe-days, or nearly the entire electrical power output of the Darlington Nuclear Generation Station (4 CANDU Reactor Units x 878 MWe/unit= 3,512 MWe) for one day.

Since the tritium removal facility at Darlington began operations in approximately 1989, and ramped up to accommodate the Darlington NGS at full capacity in 1993, up ~ 40 kg of tritium (gross) has been created (~27 years x 1.5 kg/year). However, with a half-life of ~12.3 years, the radioactive hydrogen isotope tritium decays at rate of approximately 5.5% per year, producing isotope Helium-3, and releasing a negative beta particle (T → He-3 + β (beta particle)).

Thus, while new tritium is being produced on a continuous basis, some of the inventory of tritium is being lost continuously through the natural radioactive decay process. Thus, after 27 years of operation, the net total inventory of tritium at the DTRF is in the range of 10 kg to 20 kg, where the production rate of 1.5 kg/year from the reactors is offset by losses of ~1.1 to 1.2 kg/year by radioactive decay. An estimation of the tritium inventory produced by the tritium removal facility in Darlington is illustrated in Figure 18.



* Note: Image provided courtesy of Blair P. Bromley, Canadian Nuclear Laboratories.

Figure 18: Estimate of Inventory of Tritium at the Darlington Tritium Removal Facility (DTRF) at the Darlington Nuclear Generating Station (DNGS).

This inventory of 10 kg to 20 kg of tritium in the DTRF is the kind of quantity that would be of prime interest for commissioning and demonstration of first power production in fusion power projects. For example, the potential energy content of 15 kg of tritium, fused with 10 kg of deuterium is ~98,000 MWth-days, which would be enough to support the operation of the ITER Tokamak reactor for 6 to 7 months of full power operation at 500 MWth of fusion power.

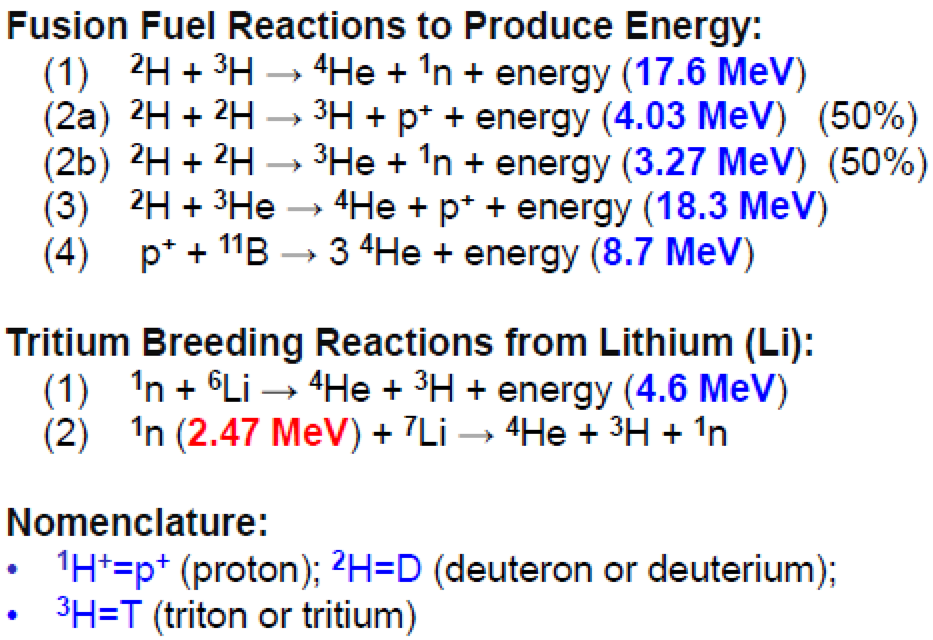
Thus, the inventory of tritium at Darlington would be sufficient to allow for initial fusion reactor trials to be performed in advance of full reactor operation. It is anticipated that the ITER project will be able to procure sufficient tritium from a global tritium inventory [269]. However, as noted above, long-term operation of a power reactor would require larger quantities of tritium, far in excess of that being recovered from heavy water reactors. Therefore, tritium production (breeding) from lithium-containing materials contained inside blanket regions within the fusion reactor will be essential for the needs of large-scale fusion power plants operating using the D-T fusion fuel cycle.

Tritium from the DTRF is already processed through CNL at the Chalk River Laboratories to supply small quantities of tritium to the JET (Joint European Torus) Tokamak fusion experimental facility in the United Kingdom for the fusion experiments there. Larger quantities are expected to go to ITER in the next decade, once the ITER facility is completed construction (expected in 2025) and initial experiments with deuterium-tritium fuel begin (expected in 2035), although, at this point in time, no agreement (formal or informal) has been made between OPG and ITER for tritium supply.

3.4 Long-Term Tritium Breeding and Production

It is clear that tritium supplies for fuelling future fusion reactors must come from tritium that is bred within the reactor, by bombarding lithium in target materials with neutrons ($\text{Li-6} + n \rightarrow \text{T} + \text{He-4} + 4.8\ \text{MeV}$; $\text{Li-7} + n\ (2.47\ \text{MeV}) \rightarrow \text{T} + \text{He-4} + n$), as illustrated in Figure 19**.** Since each D-T fusion reaction produces a neutron, arranging for the high-energy fusion neutron to react with lithium (enriched in Li-6; natural lithium is 7.5% Li-6, and 92.5% Li-7) to produce tritium and helium can provide a fresh supply tritium. This process for breeding tritium is the one used in most fusion reactors proposed. The process, known as tritium “breeding” is set up in a surrounding “blanket” exposed to fusion neutrons. Because not all these neutrons will be absorbed by lithium to release tritium, a method of neutron multiplication is included in the blanket breeding matrix. This process is the start of the tritium fuel cycle in a fusion reactor.

The lithium used in the tritium-breeding blanket of a fusion reactor could be in solid or liquid/molten form, depending on the design. Historically, through the Canadian Fusion Fuels Technology Project (CFFTP), in the period of 1987-1997, in cooperation with Ontario Hydro (now OPG), research scientists at AECL - Chalk River Laboratories (now CNL) investigated a wide variety of options for breeding tritium from solid lithium-based materials, such as lithium oxide (Li_2O), [264]-[268]. Other solid lithium-based materials of potential interest for tritium breeding include lithium titantate (Li_2TiO_3) lithium silicate (Li_4SiO_4), lithium deuteroxide (LiOD), and others. Other fusion reactor designers have considered using molten liquid metal lead-lithium eutectic (83 at% Pb + 17 at% Li, $Pb_{83}Li_{17}$) or molten salt combinations of lithium fluoride and beryllium fluoride ($LiF\text{-}BeF_2$, or “FLiBe”) to serve simultaneously as both as a fusion reactor coolant and a tritium-breeding blanket material.



Fusion Fuel Reactions to Produce Energy:

(1) $^{2}H + {}^{3}H \rightarrow {}^{4}He + {}^{1}n$ + energy (17.6 MeV)
(2a) $^{2}H + {}^{2}H \rightarrow {}^{3}H + p^{+}$ + energy (4.03 MeV) (50%)
(2b) $^{2}H + {}^{2}H \rightarrow {}^{3}He + {}^{1}n$ + energy (3.27 MeV) (50%)
(3) $^{2}H + {}^{3}He \rightarrow {}^{4}He + p^{+}$ + energy (18.3 MeV)
(4) $p^{+} + {}^{11}B \rightarrow 3\,{}^{4}He$ + energy (8.7 MeV)

Tritium Breeding Reactions from Lithium (Li):

(1) $^{1}n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H$ + energy (4.6 MeV)
(2) ^{1}n (2.47 MeV) $+ {}^{7}Li \rightarrow {}^{4}He + {}^{3}H + {}^{1}n$

Nomenclature:

- $^{1}H^{+}=p^{+}$ (proton); $^{2}H=D$ (deuteron or deuterium);
- $^{3}H=T$ (triton or tritium)

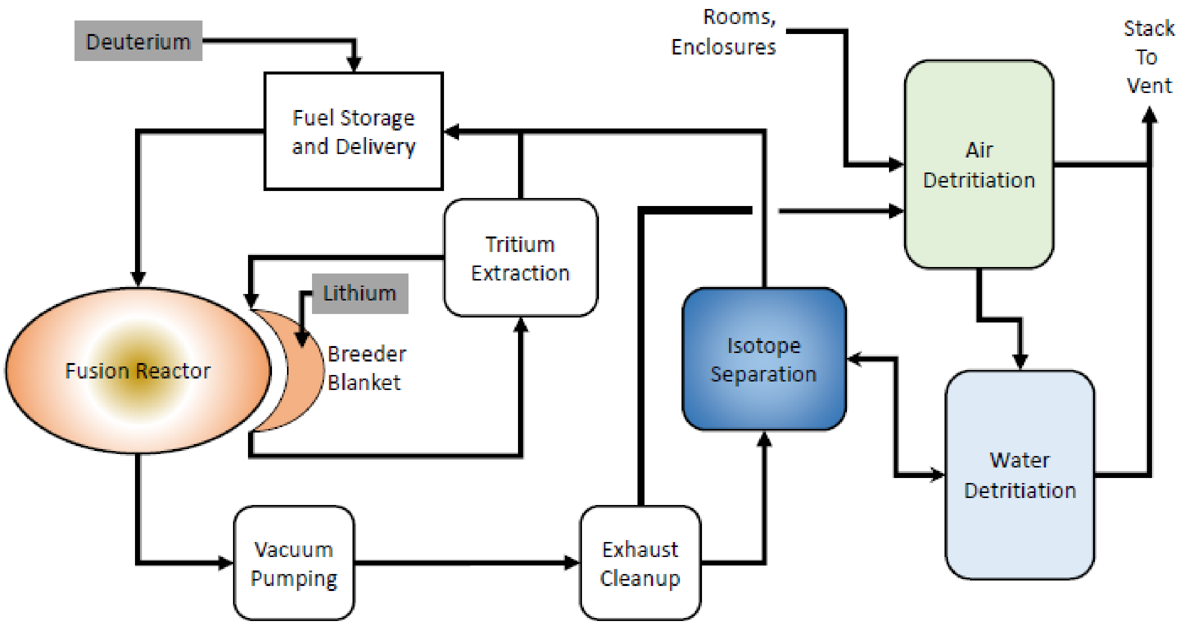
* Note: the preferred reaction for producing tritium is from Li-6, since it has a high-probability of occurring. Producing tritium from Li-7 has a lower probability of occurring, and requires high-energy neutrons.
* Note: Image provided courtesy and with permission of Professor Robert Fedosejevs, University of Alberta.

Figure 19: Fusion Fuel Reactions to Produce Energy and Nuclear Reactions to Breed Tritium from Lithium [8].

Other essential parts in the tritium fuel cycle include processes to: 1) capture the tritium in the reactor exhaust stream, 2) purify tritium, 3) separate hydrogen isotopes to allow correct mixing of fuel, 4) capture and recycle lost tritium and 5) basic storage. These processes and activities, as illustrated in Figure 20, are needed to ensure that tritium is in sufficient supply and is fully utilized, without being allowed to become a potential environmental hazard by being released.

The processes in the tritium fuel cycle require the application of a wide range of technologies. Most of such technologies have been studied and many have been applied in other areas by Canadian Nuclear Laboratories and other Canadian companies and organizations. The main technologies include:

- Extraction of tritium from molten materials, particularly lead-lithium ($Pb_{83}Li_{17}$).
- Extraction of tritium from gas mixtures
- Storage of tritium in stable solid matrices
- Separation of tritium from deuterium and hydrogen (e.g. by cryogenic distillation)
- Trapping of tritium from exhaust air flows before release to the atmosphere
- Extraction of tritium from waste water before release to the environment.



* Figure prepared courtesy and with permission of Dr. Hugh Boniface (CNL, 2021)

Figure 20: The Tritium Fusion Fuel Cycle – Illustrating the Processes Involved.

3.5 Canadian Engagement with ITER Project (OCNI/OPG)

After a 15-year hiatus, Canada began to re-engage with ITER in 2018, with the signing of Canada-ITER MOU on April 17, 2018, by Canadian Federal Minister of Trade, François Champagne, and ITER Director General, Bernard Bigot in Paris. The Canada-ITER MOU set a high-level framework for Canadian collaboration with ITER.

Simultaneously, representatives from both Ontario Power Generation (OPG) and the Organization of Canadian Nuclear Industries (OCNI) took the initiative to bring together representatives from the Canadian nuclear industry, academic institutions, and key stakeholders in agencies in the Ontario and Federal Canadian governments to advance the possibility of establishing cooperation between the ITER Project and Canada. For a short-term period (in 2019/2020), a ***"Canadian Fusion Services (CFS)"*** office was established temporarily and based at OPG's offices at the Pickering/Darlington nuclear generating stations.

These efforts culminated with a virtual signing ceremony of the Nuclear Cooperation Agreement (NCA) between Canada and ITER on October 15, 2020. This non-proliferation agreement opens the way to start a new dialogue between Canada and ITER to determine the basis for a commercial cooperation. Once this basis is defined, it should be possible to establish a practical way to organize and coordinate the fusion stakeholders in Canada to maximize future opportunities with ITER. It *may* be possible for Canadian companies to participate in the

ITER project with Canadian companies contributing effort through sub-contracts with current ITER member nations.

Further details on Canada's re-engagement with ITER and past history through OCNI and OPG can be found in the appendices, in Section A.4.

3.6 Regulatory Framework for Use of Fusion Energy

3.6.1 Canadian Regulatory Framework for Fusion

At present, the Canadian Nuclear Safety Commission (CNSC) is beginning the process to develop a framework or a guidance plan for the regulation of fusion reactors.

In November of 2020, the CNSC (via Daniel Tilsley) posted an advertisement and sent out a solicitation to various potential stakeholders in Canada with a request for proposals / bids for a review of the CNSC's Regulatory Framework for Readiness to Regulate Fusion Technologies, under Solicitation #5000055100.

This solicitation was posted at the following website:

- https://buyandsell.gc.ca/procurement-data/tender-notice/PW-20-00934212

The key summary of this request for proposals by the CNSC is the following:

- *"The Canadian Nuclear Safety Commission (CNSC) seeks to establish a contract for third-party research and an evaluation of the CNSC's Regulatory Framework's readiness to accept and evaluate a license application for a Fusion Power Reactor or Subcritical Nuclear Assembly, as defined in Annex A, Statement of Work."*

An extract of this "Annex A" is provided in the Appendices, in Section A.5.

3.6.2 United States Regulatory Framework for Fusion

For comparison, the United States Nuclear Regulatory Commission (US-NRC) has recently (in January, 2021) initiated public stakeholder meetings on the topic of discussing options for developing a regulatory framework that could be applied to future fusion energy systems. The key contact, organizer, facilitator, and moderator for these meeting is **William Reckley, US-NRC**. The website link to these meetings can be found at:

- https://www.nrc.gov/pmns/mtg?do=details&Code=20201431

This topic of discussion is motivated by the fact that both public ventures (such as the International Thermonuclear Experimental Reactor (ITER) project), and several private sector ventures (among different entrepreneurial start-up private sector companies) within the international community are getting closer to fruition with building and demonstrating fusion device prototypes that will generate significant levels of fusion energy, neutrons and radiation, and that will begin using and producing non-trivial quantities of tritium.

Within the United States, there are three proposed approaches for regulating fusion devices / fusion energy systems that are being considered, including:

1. Regulating fusion reactors in a way similar to how conventional fission power reactors (Gen-III+, Gen-IV, SMR technologies) are regulated.
   a. This approach is referred as **"Commercial Fission Reactor Model"**
   b. It is anticipated that some modifications would be made to this regulatory framework to take into account the basic fact that a fusion reactor does not involve the use of special nuclear materials (such as fresh or spent fissile or fertile nuclear fuel), and it does not produce radioactive fission products, or minor actinides. In addition, a fusion reactor does not face the risk of a "critical mass" or a power excursion / power pulse as such might be postulated to occur in a conventional fission reactor if there was a way to cause a reactivity initiated accident (RIA), such as a rod ejection accident in a pressurized water reactor (PWR).
   c. Although this approach might be considered more familiar to regulatory oversight bodies (such as the US-NRC, CNSC, and others), it could also be considered as being disproportionate, excessive, and much more onerous (time-consuming and expensive) for fusion reactor developers.
2. Regulating fusion reactors in a way similar to how large accelerator facilities (such as one producing radioactive isotopes) are regulated.
   a. This approach is referred as the ***"By-product Material Model"***
   b. It is anticipated that some modifications would be made to this regulatory framework to take into account the basic fact that a fusion reactor will involve the production and handling of tritium, the production of high-energy (>2 MeV) fast neutrons, and the production of neutron-activated structural materials and components. Such activated materials will need to be classified and treated as a form of radioactive waste, after a given fusion reactor is shutdown for component replacement / refurbishment or decommissioning. It is also recognized that the risk and hazard of tritium is highly dependent on how it is handled and stored. A fusion reactor is similar in many ways to a large accelerator, in that it involves the production, manipulation and control of high-energy charged particles, whether it is in the form of an ion or electron beam (in an accelerator) or a plasma (in a fusion reactor).
   c. This approach is likely to be considered much more convenient for fusion reactor developers, although it is not yet clear it would be adequate to regulate all key issues of concern. For some previous and/or existing experimental facilities at used for fusion research at universities and national laboratories, an adaptation of this regulatory approach has already been used.
3. Regulating fusion reactors in a way that combines features used for regulation of commercial fission reactors with those features used for regulating large accelerator facilities.
   a. This approach is referred as the ***"New or Hybrid Model"***

b. The challenge is to determine which features from each regulatory approach are directly relevant and essential and should be included, and also what features are not relevant, not essential, and should not be included.

Additional stakeholder meetings organized by the US-NRC to further discuss these options for regulating future fusion power reactors are expected to occur in 2021.

3.6.3 Fusion Industry Association (FIA) Position on Regulation for Fusion

Within the private sector in the United States, there is an industrial association known as the Fusion Industry Association (FIA), with Andrew Holland as its Executive Director. The FIA is based in Washington DC, and its objective is to represent and advocate the interests of private sector companies with regards to the development of fusion energy in the United States. It is noted that the FIA has recently prepared and issued a white paper on the topic of regulation for fusion, and it can be downloaded from the following website address:

- https:///www.fusionindustryassociation.org/post/fusion-regulatory-white-paper

The key recommendation from the FIA with regards to regulation of future fusion power plants in the United States is the following:

- *"U.S. policymakers should establish a broad legislative and regulatory framework that explicitly and permanently removes fusion energy from the regulatory approaches that the federal government has taken towards fission power plants."*

4. World Context: International Initiatives in Fusion Energy

4.1 Summary

The following chapter presents an overview of fusion projects around the world. From small private start-ups to large international partnerships, the development and demonstration of fusion energy generation is being undertaken using a number of different approaches. Globally, there are 97 separate/individual fusion reactor experiments currently in operation and over 27 projects in the design or construction phase. The discussion in Chapter 4 focuses on the most promising work being done currently at the largest and most significant fusion projects around the world. For a full list of every fusion project underway across the globe, the reader is encouraged to visit Fusion Device Information System (FusDIS) maintained by the International Atomic Energy Agency (IAEA), as discussed in Reference [382].

Table 4: Quantitative Breakdown of Each Nation's Fusion Projects [382].

Nation	Number of Operational Fusion Projects	Number of Fusion Projects Planned / Under Construction
USA	19	10
Japan	21	2
China	8	1
Russia	7	1
France	3	2
Pakistan	2	2
UK	4	0
Brazil	3	0
Czech Republic	2	1
Germany	3	0
India	2	1
Iran	3	0
Italy	2	1
Australia	0	1
Canada	**1**	**1**
Costa Rica	2	0
Rep. of Korea	2	0
Spain	1	1
Switzerland	2	0
Ukraine	2	0
Denmark	1	0
Egypt	1	0
Kazakhstan	1	0
Libya	1	0
Portugal	1	0
Sweden	1	0
Thailand	0	1

IMAGE REMOVED / REDACTED

Figure 21: World Map Highlighting all of the Operational & Planned Fusion Projects (from Reference [382]).

4.2 Private-Sector Fusion Industry

The growth of the global private-sector fusion industry has accelerated over the last few decades. Over $2 billion CAD in financing has been deployed to private fusion energy companies, the majority of which has been invested in the last 8 years, since 2013 [383].

IMAGE REMOVED / REDACTED

Figure 22: Investments made to Private Fusion Companies since the year 2000 (USD) [383].

Many venture capital firms, oil and gas companies, and notable high-net-worth investors (such as Bill Gates, Jeff Bezos, Tobias Lütke, and others) have started investing in private fusion companies as well. In addition to this increase in private fusion funding, there are now 28 private fusion energy companies and 22 private fusion projects (operational and planned) around the world. The number of private fusion companies entering the industry has grown each year (it has multiplied by more than a factor of 4 since 2008) [384], [385].

IMAGE REMOVED / REDACTED

Figure 23: Number of Private Companies Pursuing Fusion Energy over Time (from References [384], [385]).

4.3 Major Fusion Research & Development Projects in North America

4.3.1 DIII-D National Fusion Facility (General Atomics, USA)

The *DIII-D National Fusion Facility* which is operated by General Atomics (in San Diego) for the US Department of Energy (US DOE) is a plasma physics laboratory with a tokamak fusion device that is used to perform many fusion experiments. Their signature “D-shaped” cross section in the tokamak has been adopted by many other large fusion projects around the world such as JET (UK), EAST (China), KSTAR (South Korea), and others. The progress and success of the DIII-D facility has influenced the development of the international ITER project [271]. In late 2019, the US DOE announced finalization of a cooperative agreement with General Atomics to fund DIII-D and collaborating institutions with $121.5M USD per year for 5 years [272]. This number has risen by a few million USD per year. The US DOE also announced in mid-2019 that they will be providing $14M USD in funding for ten university led fusion research projects using the DIII-D facility [273].

4.3.2 National Ignition Facility (LLNL, USA)

The National Ignition Facility (NIF) is a large laser-based inertial confinement fusion device experimental research facility located at the Lawrence Livermore National Laboratory (LLNL) in California. The NIF is managed by the US DOE’s National Nuclear Security Administration (NNSA) and funded directly by the US DOE. It is one of the world’s largest and highest power lasers (500 trillion watts of peak power using 192 powerful separate laser beams) and the extreme densities and temperatures it generates can cause deuterium and tritium nuclei to fuse when targeted [274]. The NIF is the world's largest inertial confinement fusion project (whose goal is to reach *Fusion Ignition:* the point where a nuclear fusion reaction becomes self-sustaining). As of 2020, experiments that have been conducted at NIF have achieved approximately 33% of the conditions required for fusion ignition to occur. Recently, the NIF has been used for several scientific applications such as the study of material properties at high temperatures as well as studies of the phenomenon known as thermonuclear burn which causes the large instantaneous release of energy in modern thermonuclear explosive weapons. The total cost of installation, development, vendors, commissioning, and capital of NIF was approximately $3.5B USD [275]. Of the LLNL's $1.5B USD annual budget, the NIF typically receives about 20%. The US DOE provided NIF with $330M USD in funding for the 2017 fiscal year and $344M USD for the 2018, 2019, and 2020 fiscal years [276].

4.3.3 National Spherical Torus Experiment Upgrade (PPPL, USA)

National Spherical Torus Experiment Upgrade (NSTX-U) is another very large fusion research project run by the Princeton Plasma Physics Laboratory (PPPL) in New Jersey, in collaboration with Oak Ridge National Laboratory (ORNL), Columbia University (in New York), and the University of Washington. It has been operational since February 1999, originally just as the NSTX, then shut down in 2012 to undergo its upgrade until 2015 which cost $94M USD [277]. The NSTX-U is funded by the US DOE's Office of Fusion Energy Sciences (FES) and was awarded $93.5M USD in 2018, $96M USD in 2019 and $101M USD in 2020 [278].

4.3.4 Norman and Copernicus FRC Devices (TAE Technologies, USA)

TAE Technologies (formerly Tri Alpha Energy), a relatively large private fusion energy company, was founded in 1998. They are based out of Foothill Ranch, California and are completely privately funded. TAE Technologies has been carrying out fusion experiments on several different devices based upon the Field Reversed Configuration (FRC) fusion plasma confinement concept, which is similar to a magnetic mirror. The most recent devices under construction and operation are the Norman and Copernicus experiments. TAE Technologies has secured more than $980M USD in private capital [279], [280], [281], [282]. According to their website, TAE have conducted over 127,000 plasma experiments since 2015 [281]. They have a current project (and device) underway since 2017 called *C-2W (aka Norman)* and an upcoming project (and device) called *Copernicus* based on the same technology. The Copernicus device is estimated to cost about $200M USD and has the goal of beginning test runs in 2023 [282]. Both the Norman and Copernicus devices are similar to each other in that they are FRCs (field-reversed configurations) which use magnetic confinement to confine the plasma, however they differ from other designs because the orientation of the axial magnetic field inside the reactor is different (due to its reversal by very high plasma currents in the angular direction).

4.3.5 SPARC and ARC Devices (Commonwealth Fusion, USA)

Commonwealth Fusion Systems (CFS), a private fusion company founded in 2018 in Cambridge, Massachusetts plans to build a small-scale demonstration fusion power plant called *“SPARC”* along with the Plasma Science and Fusion Center (PSFC) at the Massachusetts Institute of Technology (MIT). SPARC is a demonstration spherical tokamak device that is based on the decades of research carried out on the Alcator C-Mod tokamak experiment at MIT. Commonwealth Fusion Systems has already raised $200M USD in funding primarily from venture capital firms, with $115M from their Series A1 funding round in June 2019 and $84M coming from their Series A2 funding round in May of 2020 [283]. An Italian oil and gas company, Eni, has already contributed $50M USD alone. The SPARC reactor is planned to have a Q-value of Q > 2, but estimates from the developers of SPARC point towards a Q-value closer to 10 [284]. The CEO of CFS, Bob Mumgaard, expects the SPARC project to cost around $400M USD in total. CFS also plans to launch a commercialized fusion reactor for power generation (called “ARC”) at sometime between 2025 and 2030 [285].

4.3.6 General Fusion (Burnaby, BC, Canada)

General Fusion Inc., founded in 2002 in Burnaby, British Columbia, is the largest private-sector fusion energy company in Canada and is one of the world leaders in private fusion research. The fusion power device that they are designing is based on a design variant of Magnetized Target Fusion (MTF) that relies on the adiabatic compression of magnetically insulated plasma target with liquid metal liner driven by an acoustically driven, spherically symmetric pressure wave. A large volume, low-temperature fusion fuel plasma torus is first injected into the hole of a rotating vortex of liquid metal (made of a lead-lithium) which forms a wall around the plasma. Then, a large number of steam-driven pistons are used to create a spherical shock wave that compresses the liquid metal liner, which in turn compresses the magnetized fusion fuel plasma target to a much smaller volume, increasing both the plasma density and temperature to much higher values where fusion reactions can occur. The lead-lithium liquid metal wall also protects the outer wall of the device from damage and it is also used to breed new tritium fuel to sustain the operation of the power plant [286].

In 2009, General Fusion received $13.9M CAD from Sustainable Development Technology Canada (SDTC) to work on Magnetized Target Fusion with Los Alamos National Laboratory (LANL) [287]. In a 2011 Series B funding round, General Fusion acquired $19.5M USD from a syndicate of venture capital funds, including Bezos Expeditions (a firm owned by Jeff Bezos, of Amazon.com) and the Business Development Bank of Canada (BDBC), among others [288]. In 2015, a funding round was led by the Government of Malaysia’s Sovereign Wealth fund, Khazanah Nasional Berhad, and $27M CAD was raised [289]. General Fusion also received $12.75M CAD in 2016 from SDTC in a consortium with McGill University and the Hatch consulting firm for a project with the aim of demonstrating fusion energy technology. General Fusion also received $49.3M CAD from the Canadian government in October of 2018 from the Strategic Innovation Fund (SIF), and then in 2019 received $65M USD during a Series E funding round from several large investors [290]. These investments led General Fusion to announce that they are ready to begin the planning and construction of their Fusion Demonstration Plant. General Fusion has also announced several other big investments that they have received over the last few years (e.g. the US DOE and also a firm established by the founder of Spotify called Thistledown Capital) however the dollar values have been kept private. NSERC has also allocated a $240,000 CAD alliance grant to General Fusion and McGill University in Montreal for collaborative work. Of the investments announced to the public, General Fusion has received more than $200M CAD of funding [287]. General Fusion also announced that they will partner with the UK-based architecture firm AL_A (founded by world-renowned architect, Amanda Levete) to assist in the design of their Fusion Demonstration Plant (FDP) [291].

In June of 2021, it was announced that General Fusion will be constructing and operating their FDP in the UK [386]. The site will be at the UK Atomic Energy Authority's (UKAEA) Culham Center for Fusion Energy (CCFE), where other large fusion projects such as JET and MAST Upgrade are currently hosted [387], [388]. The FDP is aiming to be on the scale of 115 MWth and is estimated to have a construction cost of about $400M USD. Construction will start in 2022 and operations are scheduled to begin in 2025. Details of the UKAEA and General Fusion partnership are not confirmed but sources report that the FDP will be financially backed by the UK government [387].

4.3.7 The Z Pulsed Power Facility (Sandia National Laboratory, USA)

Sandia National Laboratory (SNL) in Albuquerque, New Mexico is operated by National Technology and Engineering Solutions of Sandia LLC as a contractor for the US DOE's National Nuclear Security Administration (NNSA). SNL has a fusion experiment that involves a different technique called a Z-pinch at the *Z Pulsed Power Facility* [292]. The Z pinch device (also known as a Z machine) is conceptually very simple, using a very high pulse axial (in the "Z" direction) current running through a fusion fuel plasma target to create a strong angular magnetic field, which then interacts with the axial current to create a strong inward radial electro-magnetic force ($\boldsymbol{F_r = j_z \times B_\theta}$) that compresses the fusion fuel plasma to high densities and temperatures for a brief period of time (milliseconds, or less). The Z-pinch may be considered a type of inertial confinement fusion (sometimes referred as *"magneto-inertial confinement"*), although it operates with lower densities, and longer confinement time periods relative to laser-based ICF. With electromagnetic compression of plasmas to high densities and temperatures, the Z-Pinch / Z-Machine will also generate high-energy X-Rays and gamma rays, which can also be used for different research experiments. To create the very high current pulse of the Z-Pinch, a large capacitor bank is discharged rapidly through one or more fine tungsten wires. If fusion fuels such as deuterium and tritium (or perhaps lithium) are incorporated into the tungsten wires, or in thin-walled conducting metal tubes, then it would be possible to initiate fusion reactions [292]. This approach using the Z-Pinch device is often referred as the "MagLIF" (magnetized liner inertial fusion), and it is considered a variant of the magnetized target fusion (MTF) approach to fusion.

The “Z machine” (after several upgrades from older experiments) has been in operation since 1996. SNL also has lasers which are used in fusion experiments to augment the Z-Pinch approach to fusion, by providing an additional mechanism for heating the dense fusion fuel plasma to higher temperatures. This laser technique is ideal for concentrating power sharply on the target (atoms to be fused). Efforts on the use of concentrated particle beams/lasers was temporarily suspended so that their fusion research could be focused on improving the Z-Pinch technology. The US DOE’s *Inertial Confinement Fusion Program* funds the Z Pulsed Power facility each year and in the 2021 fiscal year it is set out to receive $67M USD in funding after receiving $67M USD in 2020, and $63M USD in 2019 [276], [268].

4.3.8 Alcator C-Mod (MIT, USA)

Another significant fusion project in the USA was the Alcator C-Mod. It was an experimental tokamak fusion device that operated from 1993 to 2016 at MIT’s Plasma Science and Fusion Center (PSFC) [293]. It was one of the major fusion experiments in the USA before its shutdown. The PSFC is one the world’s leading research centers for the study of nuclear fusion and collaborates with Commonwealth Fusion Systems on their SPARC project. A number of the magnetic fusion projects in which PSFC researchers participate in planning are in performed in conjunction with efforts with ITER.

4.3.9 Other Fusion Energy Projects in North America

There are several smaller-scale, fusion-related projects underway in Canada and the USA, at different universities, national laboratories, and private-sector companies. These projects are summarized briefly in the list below.

- The University of Saskatchewan’s Plasma Physics Laboratory (USask-PPL) hosts the STOR-M (Saskatchewan Torus-Modified) tokamak experiment, which was originally named the STOR-1M from when it was built in 1983.
- Plasmionique, a private company in Varennes, Quebec, specializes in engineering and designing customized plasma and laser systems for use in R&D.
- Princeton Plasma Physics Laboratory (PPPL) is running the LTX-β (Lithium Tokamak Experiment - Beta), a small-scale Tokamak-type experiment [294].
- University of Wisconsin-Madison is operating HSX (Helically Symmetric Experiment), a small-scale stellarator.
- Auburn University in Alabama is operating its CTH (Compact Toroidal Hybrid) device, another small-scale stellarator.
- The University of Illinois at Urbana-Champaign is operating its HIDRA device, another small-scale stellarator.
- The University of Washington is running several small-scale Field-Reversed Configuration (FRC) fusion experiments.
- Helion Energy, a private fusion energy company founded in 2013 in Redmond, Washington, is developing a FRC-based magneto-inertial fusion device referred as “The Fusion Engine” which is intended produce 50 MWe. Helion Energy has raised

approximately \$19M in funding from a series funding round, as well as funding from NASA and the US DOE [295].

- Phoenix Technologies is a nuclear technology company in Madison, Washington that develops Deuterium-Tritium Neutron Generators that are used in certain nuclear fusion experiments [296].

4.4 Major Fusion Research & Development Projects in Europe and the UK

4.4.1 ITER (CEA Cadarache, France)

ITER (International Thermonuclear Experimental Reactor) is the world's largest nuclear fusion project. It is an international tokamak project that was first planned in 1985 with over 35 nations contributing to it either directly or indirectly. The main ITER members are the United States, China, the European Union (Switzerland and the UK are also participating through Euratom), Japan, Korea, India, and Russia [297], [379]. Construction of the ITER tokamak complex next to the CEA's Cadarache facility in Saint Paul-lès-Durance, in Provence, France commenced in 2013. ITER's main goal is to demonstrate that net fusion power production is possible: a goal of 500 MWth of fusion power produced with a Q-value of at least 10 (therefore the 500 MWth will be produced with no more than 50 MWth of input heating power) [297], [298]. ITER is not designed for electrical power generation, however it aims to lay down the foundational research for net fusion energy production, so that future prototype demonstration fusion power plants will produce electricity. ITER also has other goals as well, including: successfully achieving a deuterium-tritium plasma where the reaction is sustained through internal heating, successfully demonstrating all of the various technologies in operation in a fusion power plant, testing the breeding of tritium, and successfully demonstrating both the safety protocols and characteristics of a fusion device.

The seven main members of the 2006-2007 ITER Agreement will share the cost of the ITER project's construction, operation, maintenance, and eventual decommissioning. They will also share all of the intellectual property generated throughout the course of the project as well as all of the experimental results. The total budget for the ITER project and the participation of additional states or organizations in the project is decided by the ITER Council, the governing body of the whole project. During the construction phase of the ITER project, Europe is responsible for 46.5% of the costs and the remaining 6 main members are each responsible for 9.1% of the costs [297]. For the operation phase of the ITER project, the cost sharing amongst the members will be as follows: Euratom 34%, Japan and the United States 13% each, and China, India, Korea, and Russia 10% each [297]. Rather than monetary contributions, many of the contributions to ITER made by the main members are "in kind", in the form of technology, components, buildings, systems, or expertise. Aside from the main 7 members, the ITER organization has established many cooperation agreements with individual nations such as Canada, Australia, Kazakhstan, and Thailand, as well as cooperation agreements with many different universities, national laboratories, institutions, and international organizations [297].

ITER has scheduled its first plasma for December 2025 and the follow-up objective is to achieve the campaign of full-power deuterium-tritium operations by 2035 [297]. As of the start of 2021, ITER is 72% of the way to achieving first plasma [297]. The construction of the ITER facility is a massive logistical task. Over one million components have been built by ITER member nations and shipped to the ITER facility in France. ITER has implemented a detailed timeline and plan for all of its key milestones and dates in which to achieve them.

The ITER Organization has estimated that the total cost of the entire ITER project is approximately €22B (~$26.6B USD) [298], [299], [300]. ITER does not provide an official cost estimate of construction because the member nations have different methods of pricing out their in-kind contributions (non-monetary contributions) that are mostly in the form of fabricated reactor components, and those estimates are not reported to the ITER Organization. In April of 2018, the US DOE challenged the ITER Organizations €22B cost estimate and stated that they believe that the total cost of construction alone (not including operation) for the ITER project to be ~$65B USD, based on extrapolating the predicted total US ITER contribution of $6.5B USD (as determined by a 2013 review committee and confirmed in a January 2017 report) and the USA's 9.1% cost share percentage [299]. The ITER Organization does not endorse this cost estimate and as of today, remains committed to their €22B total cost estimate [298]. As of the end of FY 2017, the USA has contributed approximately $1.1B USD to the project, $975M in-kind and $145M in cash.

4.4.2 Laser Mégajoule (CEA, Bordeaux, France)

The largest Inertial Confinement Fusion (ICF) project outside the United States is the *Laser Mégajoule* (LMJ) facility near Bordeaux, France. The LMJ facility was built by the *Alternative Energies and Atomic Energy Commission* (CEA) which is a French government-funded organisation and is managed by the Division of Military Applications (DAM) of the CEA. The LMJ first became operational in October of 2014 and was designed for the purpose of performing test experiments for France's own nuclear weapons; however it is also used by the international scientific community for ICF fusion research. LMJ is capable of delivering over 1 MJ of energy from its laser [301].

4.4.3 JET (Culham Centre for Fusion Energy, UK)

The JET (Joint European Torus) fusion project is located at the UK's national fusion research laboratory: Culham Centre for Fusion Energy (CCFE). The JET is a Tokamak design and it is a joint European project. JET is used by more than 40 European laboratories under the management of EUROfusion's management and more than 350 European scientists work at JET [305]. JET achieved its first plasma on 25 June 1983 and in November 1991, JET performed the world's first deuterium-tritium experiment. JET also has the unique distinction of setting the world record for fusion plasma confinement, achieving a Q-value of Q=0.67 in 1997, using deuterium-tritium fuel and producing 16 MWth of fusion power, while injecting 24 MWth of power to heat the fuel. JET is primarily funded through the UK Magnetic Fusion Research Program which receives about 30% of the funding from the UK EPSRC with the other 70% provided by Euratom, and shares the £164 million in funding for this program with other fusion projects at CCFE, such as the MAST Upgrade [304]. JET secured an additional €100M from the EU to keep it running in 2019 and 2020 as a contract extension [302], [303]. Until the construction of ITER is completed, JET will remain the largest fusion reactor in the world.

4.4.4 MAST Upgrade (Culham Centre for Fusion Energy, UK)

The MAST Upgrade (Mega Ampere Spherical Tokamak) project is the successor to the original MAST project, which ran from 2000 to 2013 and its goal is to improve upon the technology developed in the previous project [306]. The MAST Upgrade received a £45M upgrade and enhancement from its MAST tokamak predecessor from 1999; MAST Upgrade became operational in October of 2020 [307]. Like JET, the MAST-U project is located at the United Kingdom Atomic Energy Authority (UKAEA) CCFE in Oxfordshire. It has been anticipated that the MAST Upgrade, which is a spherical tokamak, has the potential to be more efficient and compact with its much larger magnetic fields in comparison to conventional tokamaks, such as JET and ITER. The UK government has announced that they will invest £21M in the MAST Upgrade from 2017 to 2022 for plasma exhaust enhancements. The European fusion research consortium EUROfusion and the UK's Engineering and Physical Sciences Research Council will be co-funding this £21M budget [308].

4.4.5 STEP (UK)

The UK government is also funding a prototype demonstration program for a fusion reactor concept proposed by the UKAEA, known as "STEP" (Spherical Tokamak for Energy Production). The goal of the STEP project is to produce net electric power from spherical tokamak by 2040 [309]. In September of 2019, the UK promised a £220M (or $248M USD) investment to support the development of a conceptual design for the STEP fusion facility. It is anticipated that the first phase of the STEP project will take 4 years, £20M of which will go towards the first year of development [310], [311]. STEP will then undergo a second phase for engineering design which will then be followed by construction of the facility.

4.4.6 ST40 (Tokamak Energy Limited, Oxford, UK)

Tokamak Energy Limited (TEL), the largest private UK fusion power research company, was established in 2009, and its goal is to demonstrate net fusion energy by 2030 [304], [312]. TEL is a privately funded company, which initially grew out of work from the UKAEA-CCFE at the Culham Laboratory in Oxford. TEL has at least 50 full time staff, and it has an experimental spherical tokamak device, ST40, which has been operational since 2018. TEL have announced publicly that they have raised £123.1M so far through seven funding rounds since 2014 [313].

4.4.7 First Light Machine 3 (First Light Fusion Limited, Oxford, UK)

The second largest private fusion energy company in the UK is First Light Fusion Limited (FLFL), headquartered in Oxfordshire, England. First Light Fusion was founded in 2011 (originally named Oxyntix Limited, until 2014), as a spin-off company from the University of Oxford [314].

FLFL started with seed capital from the IP Group plc, Parkwalk Advisors Ltd and a number of angel investors. FLFL's fusion device is called the "First Light Machine 3" which uses a type of inertial confinement fusion (ICF). The LFLF ICF approach use an electromagnetic rail gun to accelerate a projectile, and then to impact it into an optimized target to generate intense shock waves that compress a fusion fuel target to the high temperatures and densities required [315]. The construction cost of the First Light Machine 3 was reported to be £3.6M [316]. They also partnered with Mott MacDonald, a global engineering consultancy, to design a first of its kind commercial fusion reactor concept [316], [318]. In February of 2019, the CEO of FLFL indicated that they were confident that the company will be able to demonstrate first fusion using Machine 3 by mid-2019: *"After fusion, the next phase is to show energy gain, which we aim to complete by 2024"* [316], although fusion reactions do not appear to have been demonstrated yet as of 2021 [317]. First Light Fusion has accumulated more than $56M USD in private investments since its inception in 2011 [318].

4.4.8 HiPER (European Union) – Postponed Indefinitely

The High Power laser Energy Research facility (HiPER) is a proposed ICF fusion research project by the European Union [319]. The HiPER project was undergoing preliminary design, but as of 2019 the research and development efforts have been inactive. HiPER would have differed from most previous ICF projects in that it also has a second set of lasers for directly heating the compressed fuel, using one or more different methods of fast ignition. Although the HiPER project initiative appears to be inactive, it is anticipated that it could be restarted and revived, possibly depending on the results of progress being made at other ICF facilities in the USA (at NIF), France (at LMJ) and Japan.

4.4.9 Wendelstein 7-X (Max Planck Institute, Greifswald, Germany)

As of October 2015, the world's largest experimental stellarator fusion reactor, the Wendelstein 7-X (W7X), has been operational in Greifswald Germany [320], [321], [322]. It was built at the Max Planck Institute for Plasma Physics. The W7X research facility is a project that is partnered with the University of Greifswald. W7X is the successor to the previous German stellarator project "Wendelstein 7-AS". It is anticipated that by 2021 the Wendelstein 7-X will be able to operate and maintain a continuous plasma discharge for 30 minutes [320]. The funding for the Wendelstein 7-X project is approximately 20% from the European Union and 80% from Germany. For the funding that Germany provides, 90% of the money comes from the German federal government and the remaining 10% from the German state government of Mecklenburg-Vorpommern [323]. The total investment for the stellarator device itself from the years 1997-2014 was approximately €370M [320], [323]. In July of 2011, it was announced by the President of the Max Planck Society that the US-DOE would contribute $7.5M USD under their *"Innovative Approaches to Fusion"* program to help support the Wendelstein 7-X project. Over the coming years Princeton Plasma Physics Laboratory (PPPL), Oak Ridge National Laboratory (ORNL), and Los Alamos National Laboratory (LANL) all contributed to the construction of the stellarator device, which totalled the $7.5M investment. Later in 2015, it was announced that from 2015 to 2017 the US-DOE will contribute approximately $4M USD annually to the Wendelstein 7-X project in exchange for scientists at US universities being able to take an active role in the research project [321], [322], [323].

4.4.10 ASDEX Upgrade (Max Planck Institute, Garching, Germany)

The second largest fusion experiment in Germany is the ASDEX Upgrade, which is also located at the Institute for Plasma Physics (IPP) at the Max Planck Institute in Garching, Germany [324]. The ASDEX (Axially Symmetric Divertor EXperiment) Upgrade, or *"AUG",* is a tokamak reactor design. The AUG is classified as a "divertor tokamak" meaning that it has the capability to remove fusion products (the helium ash), along with any impurities that might enter the plasma from the first wall. The ASDEX Upgrade has been operational since 1991 and is the successor to the IPP's former ASDEX fusion experiment. The unique distinction of the ASDEX facility is that it is where the high-confinement mode, *"H-Mode*", a highly improved method of confinement for fusion plasmas in Tokamaks (and also applicable to Stellarators), was first discovered in 1982.

4.4.11 TJ-II (CIEMAT, Spain)

Spain's largest domestic fusion project is the TJ-II facility [325]. The TJ-II is referred as a *"flexible heliac"* type of fusion reactor, and is considered to be a variant of a stellarator. It was constructed at CIEMAT (the National Fusion Laboratory of Spain) from 1991-1997 and has been operational ever since. The TJ-II facility is the third fusion device in Spain. From 1983 to 1995, the TJ-I device was operational. In 1994, the TJ-IU device began operating, although it was later disassembled and moved to Kiel, Germany in 1999, renamed to TJ-K, and then moved again to Stuttgart, Germany, where it is still operational today. The TJ-II project received preferential financial support from Euratom in both 1986 and 1990 for physics and engineering respectively [325].

4.4.12 Frascati Tokamak Upgrade (Frascati, Italy)

The Frascati Tokamak Upgrade (FTU) is a fusion tokamak experiment that has been operating at the ENEA Frascati Research centre in Italy since 1990. It is the successor to the former Frascati Tokamak and was constructed along the line of the ALCATOR C-Mod fusion experiment at MIT in the USA [326]. The ENEA's fusion work has received an average annual €60M budget, and FTU receives some of this funding [327].

4.5 The Major Fusion Research & Development Projects in Asia and Russia

4.5.1 Chinese Fusion Engineering Testing Reactor (China)

The government of the People's Republic of China approved proceeding into the engineering design phase for the CFETR (Chinese Fusion Engineering Testing Reactor), which started in 2017; it will be a tokamak reactor [328], [329]. The fusion R&D community in China discussed for three years the future for China's fusion development. The three major tokamak fusion reactor experiments in China, HL-2M, EAST, and J-TEXT, will continue to operate, providing valuable testing data to support and guide the development of the CFETR. The roadmap and timeline for China's development program for magnetic confinement fusion is illustrated in Figure 24.

The CFETR is the next major device for the China's MCF program, and it is intended to be an intermediary step between ITER and a future prototype demonstration fusion power reactor, DEMO. The estimated fusion power of CFETR will be in the range of 200 MWth to 1,000 MWth [328], [329]. By conducting test and demonstration validation experiments respectively in two phases on CFETR, it is expected that significant improvements from a test reactor to a full-scale prototype demonstration reactor could be achieved. It is also expected that a prototype tokamak fusion power plant will eventually be built, based on the CFETR. The construction of CFETR is planned to start in the 2020s and be finished in the 2030s. The target fusion power for the CFETR in Phase I is between 100 MWth and 200 MWth. The Phase II of CFETR is targeted to be completed sometime after 2040 [328], [329]. Experimental research conducted in Phase II should help address and solve the most important issues for DEMO under a fusion power output greater than 1000 MWth. The prototype fusion power plant (PFPP), which is planned to be built at sometime between 2050 and 2060, is going to be a final step in the roadmap towards a commercial power plant.

The main objectives of the CFETR project are the following [329]:

- A good complementarity with ITER.
- Demonstration of a full cycle of fusion energy.
- Demonstration of a full fuel cycle of Tritium aiming at a tritium breeding ratio (TBR) over 1.0.
- Long pulse or steady-state operation with duty cycle about 0.3 – 0.5.
- Based on the existing ITER physics and technology together with advanced new technology development.
- Exploring physical and technical options for DEMO with an easily changeable internal components by remote handling technique.
- Addressing the DEMO relevant issues via a step-by-step approach.
- Exploring technical solutions for licensing a DEMO fusion device.

IMAGE REMOVED / REDACTED

Figure 24: China's Roadmap for MCF Development and Associated Projects [329].

4.5.2 EAST (ASIPP, Hefei, China)

The Experimental Advanced Superconducting Tokamak (EAST) is located at the Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) in Hefei, China. EAST was approved by the National Development and Reform Commission of China in July 1998, then was constructed and achieved first plasma in 2006. EAST has three distinct features: a non-circular cross-section, fully superconducting magnets, and fully actively water-cooled plasma facing components (PFCs). These features in EAST are beneficial to investigate and test advanced steady-state plasma operation modes [330]. China has spent 6 Billion Yuan (~$865M USD) on EAST and in early 2019 China invested another 6 Billion Yuan in EAST [331], [332]. The EAST experimental fusion reactor was designed to test various technologies, engineering designs, and physical properties for the upcoming ITER project. In July of 2017, EAST achieved a world record for the longest high-performance plasma operation (100+ continuous seconds at the time) [333].

4.5.3 HL-2M (SWIP, Chengdu, China)

The HL-2M facility is a copper-conductor tokamak that was recently completed construction at the Southwestern Institute of Physics (SWIP) in Chengdu, China. It is a continuation of a fusion reactor project that had been in operation at SWIP previously since 2002, called HL-2A. The HL-2M is expected to achieve temperatures in excess of 200 million degrees Celsius. The HL-2M facility achieved its first plasma in December of 2020 and China has already spent close to a billion dollars (USD) on the project [334].

4.5.4 KSTAR (NFRI, Daejon, South Korea)

South Korea’s largest fusion project is KSTAR (Korea Superconducting Tokamak Advanced Research) at the National Fusion Research Institute (NFRI) in Daejeon. The KSTAR project was approved in 1995, was finished construction in late 2007, and achieved first plasma in mid-2008. In December 2016, KSTAR achieved a world record for the longest high-performance plasma operation (70 continuous seconds at the time); China’s EAST project now holds this record [335]. In November of 2020, K-STAR managed to operate its plasma at 100 million degrees Celsius for more than 20 seconds – the world’s first nuclear fusion reactor to have maintained plasma for more than 10 seconds at that temperature [336]. KSTAR’s experiments and research will be used to help contribute to the development of the ITER project.

4.5.5 JT-60SA (JAEA, Naka, Japan)

Japan’s largest fusion project is the JT-60, an experimental tokamak facility which first began operation in 1985 [337]. This experiment was initially being conducted by the Japanese Atomic Energy Research Institute (JAERI) and is now currently being run by the Japan Atomic Energy Agency’s (JAEA) Naka Fusion Institute (NFI, part of Japan’s National Institutes for Quantum and Radiological Science & Technology (QST)) in the city of Naka. JT-60’s initial goal was to achieve a Q-value equal to 1.0, however it initially performed well below this goal. From 1999 to 2005, JT-60 received several modifications and improvements where it was renamed to JT-60A, and then eventually to JT-60U (Upgrade) [337]. To date, the world record for the hottest ion temperature ever achieved by a fusion reactor (522 million °C) is held by JT-60U. Operations of JT-60U finished in mid-2008; further extensive modifications and upgrades were to be made to create Japan’s next tokamak project: JT-60SA (Super Advanced) [338]. The main modification to JT-60SA is the addition of superconducting coils to the tokamak design. It is a joint experiment being built by both Europe and Japan.

By the end of 2020, the vast majority of the construction and assembly of JT-60SA has been completed; first plasma is scheduled for 2021 [339]. JT-60SA has the performance capability such that, if deuterium-tritium reactions were pursued (unlike the deuterium-deuterium reactions that JT-60U was limited to), a Q-value of greater than 1 should be achievable and net fusion energy could be demonstrated. For this reason, JT-60SA has been designed to support the operation of ITER by following a complementary research and development program. JT-60SA is funded jointly by Euratom and Japan (50% financing each) [340], [341].

4.5.6 Large Helical Device (NIFS, Toki, Japan)

In addition to the JT-60SA Tokamak, Japan is also operating the Large Helical Device (LHD), a large experimental stellarator fusion reactor facility, at the National Institute for Fusion Science (NIFS) in Toki, Japan [342]. The LHD (also referred as a *"heliotron"*) is the world's second largest stellarator project, after Germany's Wendelstein 7-X. Construction started on the LHD in 1990 and first plasma was achieved in 1998 [343]. After many experiments with hydrogen, LHD began its second experimental phase with deuterium in March of 2017. The cost of construction for LHD was approximately ¥50B (~ $461M USD). The LHD costs the government of Japan approximately ¥5B per year (~ $46M USD per year) to run [343].

4.5.7 GEKKO XII (Osaka University, Osaka, Japan)

The GEKKO XII Laser at Osaka University's Institute for Laser Engineering in Osaka, Japan is a facility dedicated to laser-based inertial confinement fusion research and development, and has been operational since 1983. The 12 beams of the GEKKO laser are capable of delivering about 10 kilojoules per 1 nanosecond to 2 nanosecond pulse (10–20 terawatts) [344]. GEKKO is currently being upgraded with the addition of a second *"side-by-side"* laser, the LFEX (Laser for Fast Ignition Experiment), part of the FIREX-1 program, in order to deliver a 10 kJ pulse of energy to a target in 10 picoseconds, further exploring the fast ignition regime [344].

4.5.8 T-15MD (Kurchatov Institute, Moscow, Russia)

The T-15 tokamak experimental fusion reactor is located at the Kurchatov Institute in Moscow, Russia. The original Russian T-1 tokamak was the first industrial prototype fusion reactor to use strong superconducting magnets to control the plasma. The later T-15 reactor, based on the original T-1 tokamak design, achieved its first plasma in 1988. The T-15 remained operational until 1995, when the project was suspended due to a lack of government funding [345]. However, nearly 15 years later in 2010, it was decided that T-15 should receive an upgrade to become Russia's upcoming large fusion project: T-15MD (Modified Divertor). The T-15MD facility will explore the practical feasibility of generating power from a hybrid fusion-fission reactor (HFFR) by using the neutrons generated from the fusion reaction to cause fission in a surrounding blanket of containing various fissile, fissionable, and fertile nuclear fuels [346]. It was announced at the 2020 IAEA Fusion Energy Conference (FEC2020) that all preparations for the physical operation of T-15MD were completed [347]. The first plasma for T-15MD is scheduled to occur in 2021.

4.5.9 IGNITOR (Kurchatov Institute, Troitsk, Russia)

The IGNITOR device is a highly compact tokamak fusion relying upon copper field coils to generate extremely high magnetic fields and plasma pressures, and is based on earlier research studies for the Alcator-C at MIT, also in collaboration with fusion research scientists in Italy. The IGNITOR has been planned to be constructed sometime in the mid-to-late 2020s in Troitsk, near Moscow, Russia. IGNITOR is aiming to produce ~100 MWth of fusion energy and will be dramatically smaller than ITER (less than 5% of total size). Initially, it was being planned for IGNITOR to be constructed in Italy through the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA); however the plans changed and through international collaboration efforts, Russia was chosen to host the IGNITOR facility. The project was initially planned in 2010; a number prototype components have been built in Italy however no construction of IGNITOR has commenced yet in Russia [348].

5. Government Programs and Laboratories in Support of Fusion

5.1 Canada

5.1.1 Government of Canada Involvement and Support (1960-2004)

From the years from 1960 to 1980, there were small groups at several universities across Canada studying plasma physics and fusion energy, including in particular the Institut National de la Recherche Scientifique (INRS) associated with the University of Quebec at Montreal (UQAM) [349]. The Laser-Plasma group at the National Research Council of Canada (NRCC) was also an important player in laser-fusion research at the time. Following the initial establishment of the National Fusion Program (NFP) by the NRCC in 1978, the Government of Canada increased its financial support for Canadian efforts in fusion research and development.

As part of Canada’s new NFP, the Canadian Fusion Fuels Technology Project (CFFTP) was established in Ontario in 1982 as a collaboration between Ontario Hydro and Atomic Energy of Canada Limited (AECL). By 1987, AECL took over responsibility from NRCC for administering the NFP on behalf of the Government of Canada [1], [2], [3]. As a result of increased government support for fusion R&D in Canada, by 1987 two major tokamak experiment projects were established: the STOR-M research tokamak at the University of Saskatchewan, and the Tokamak de Varennes, TdeV, at the Canadian Centre for Fusion Magnetics (CCFM) in the Varennes suburb of Montreal, in association with INRS and UQAM. In addition, in 1987, the US-DOE signed a 5-year memorandum of understanding (MOU) with Canada through AECL to share fusion research data and facilities to help enable further progress in fusion science and technology research [349]. In 1988, Canada got involved with the ITER project through EURATOM. Canada’s initial ITER contributions included R&D support for tritium production and handling systems, breeder blanket design, and general assembly/maintenance.

However, after a decade of substantial progress, Canada’s NFP was placed under program review, the decision was made by the Government of Canada to end all funding for it in 1997 [349], [350]. This cut in government support was part of a larger effort by the Government of

Canada in the period of 1995 to 1997 to drastically reduce expenditures in order to balance its budget, eliminate deficits, and to avert a financial debt crisis [351]. As a result, Canada's Tokamak de Varennes facility was shut down. Initial plans to sell the TdeV device and all its components to Iran did not materialize. Instead, several of the TdeV components (mainly the gyrotrons and heating systems) were sold to General Atomics for subsequent use in their DIII-D tokamak experiment [350]. The remainder of the Tokamak de Varennes now remains as an exhibit at Canada's Science & Technology Museum in Ottawa [350]. In 2001, a consortium in Canada, largely driven by those involved previously in the CFFTP in Ontario, had submitted a proposal for Canada to make a bid for the ITER project to be built in Canada at a site adjacent to the Darlington Nuclear Generation Station (DNGS). However, in 2004, the Government of Canada also decided to withdraw its participation in ITER, after the escalation of siting bids put Canada in a more non-competitive position [349].

5.1.2 Renewed Interest by the Government of Canada (2018-Present)

After a dormancy period of nearly 15 years, in 2018, the Government of Canada and the ITER Project re-engaged, and signed a Memorandum of Understanding (MoU) to identify key areas where Canadian suppliers could export expertise and technologies on a commercial basis [352]. More recently in October of 2020, a Nuclear Cooperation Agreement (NCA) was signed between the Government of Canada and the ITER Project to facilitate some degree of Canadian participation in the ITER project [352].

Canada has a significant market opportunity to supply ITER with tritium that is needed to fuel its fusion reactor. Tritium is extremely valuable, with a market cost of up to $40,000 CAD per gram. The ITER project could require up to 4 kg by 2032, with an ongoing demand of 1 kg per year starting in 2035. This anticipated demand for tritium by ITER represents a market opportunity of $160M, and $40M annually for 10 to 15 years.

5.1.3 Canadian Fusion Nuclear Cooperation Agreements

A Nuclear Cooperation Agreement (NCA) for Canada sets up the conditions under which Canada can undertake significant nuclear cooperation with another nation. The purpose of an NCA is to prevent diversion of nuclear materials and technology from their intended peaceful use. In October of 2020, a NCA was signed between Canada and ITER to allow Canada to participate in the ITER project [352]. Canada's CANDU heavy water reactors produce tritium as a by-product, and tritium is a key fuel required for fusion reactors. Canada will be able to provide expertise in tritium technology and handling to the ITER project as well as the transfer of Canadian-supplied tritium and tritium-related technology [352]. The NCA between ITER and Canada falls under Global Affairs Canada (GAC) authority and the NCA was ratified by Canadian Parliament in May 2021. Canada's status remains the same: the NCA does not grant Canada ITER membership. However, it is anticipated that it might be possible for Canada to negotiate to join the ITER project at a later date as an associate member.

5.2 Foreign Government Funding Support for Fusion R&D

5.2.1 Europe

EUROfusion, the European Consortium for the Development of Fusion Energy, manages and funds all European fusion related research activities on behalf of the European Commission's Euratom program. EUROfusion is composed of more than 30 fusion research institutes across Europe and is hosted by the Max Planck Institute for Plasma Physics (IPP) in Germany. EUROfusion funds all fusion research activities in accordance with the *Roadmap to the realization of fusion energy* [354]. From the years 2014 to 2020, EUROfusion had a budget of €555.3M from member states, and €678.8M from Euratom's Horizon 2020 program (H2020). H2020 is the largest EU Research and Innovation program that has ever existed, with nearly €80B of funding available from 2014 to 2020 – in addition to the private investment that this money will attract [355].

Established in April of 2007 for a period of 35 years, Fusion for Energy (F4E) is the European Union organisation that is in charge of managing all of Europe's contribution to the ITER project. Europe is responsible for about 50% of the ITER project, whereas the other participating nations are responsible for the other half. F4E has its headquarters in Barcelona (Spain) and offices in Cadarache (France), Garching (Germany) and Rokkasho (Japan) [356].

5.2.1.1 Germany

The Max Planck Institute for Plasma Physics (IPP) does scientific work on potential future fusion power plants and has two sites in Germany: Garching near Munich and Greifswald. The IPP works closely with other large fusion projects, such as ITER, JET, and the future DEMO. The IPP is an institute of the Max Planck Society, part of Euratom, and is an associate member of the Helmholtz Association. IPP also hosts EUROfusion, *the "European Consortium for the Development of Fusion Energy".* In 2019, IPP received €130M in funding, which was provided by the Federal German Government (~75%), the German states of Bavaria and Mecklenburg-Vorpommern (~4% each), the European Union's EUROfusion (~16%), and third parties (~1%). The same cost breakdown applies to the €135M that the IPP received in 2020 [357].

5.2.1.2 Italy

The ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) is a research and development agency that is sponsored by the Government of Italy. The only Italian agency that interfaces with EURATOM is the ENEA. The ENEA plans all fusion-related research activities under the Contract of Association EURATOM-ENEA by working on specific collaboration agreements with other Italian national research organizations [358]. The ENEA hosts many scientific research centres across Italy including *the "Frascati Research Centre",* where they specialize in nuclear fusion research, among other things. The National Institute for Nuclear Physics (INFN) in Italy set up the Frascati Research Center in 1956 with the staff and funding from what is now the National Committee for Nuclear Energy (CNEN) in Italy. The original Frascati Tokamak (FT) was designed and built starting in the 1970s, and later in

1975 the CNEN and INFN made their definitive separation. Fusion research activities at the Frascati Research Center are carried out within the European Fusion Programme and the EURATOM - ENEA Fusion Association, where ENEA also contributes to major projects such as JET and ITER. The ENEA's involvement in nuclear fusion research landed them the largest orders for the construction of ITER's core components for a total amount of approximately €500M [359]. The ENEA's fusion work has received an average annual €60M budget, and its programme involves 600 researchers and technologists working to gather knowledge and gain expertise in fusion science and technology [359]. Additional funds are granted by the EURATOM/ENEA Association on nuclear fusion; in 2013 the ENEA was granted €4.5M for this purpose [360]. An Italian power company's nuclear branch, "Ansaldo Nucleare" and its partner company Monsud have signed a five-year contract for €100M with F4E to design, test, commission, and implement the emergency power distribution system for the ITER project [361].

5.2.1.3 Spain

The Laboratorio Nacional de Fusión (LNF) is Spain's National fusion laboratory that specializes in magnetically confined plasma experiments. LNF is a member of the EUROfusion consortium that was initiated in 2014. LNF is leading Spain's participation in the construction of ITER, and is included in the Spanish Map of Unique Scientific and Technical Infrastructure. LNF is also part of the CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas), an Organization within the Spanish Ministry of Science and Innovation [362]. Research at LNF focuses primarily on both developing technology required for the operation of future fusion reactors and also the study of very high temperature confined plasmas.

5.2.1.4 France

The CEA (Alternative Energies and Atomic Energy Commission) is a French government-funded organisation, which operates Europe's largest technological and research development centre for energy, *Cadarache* [363]. Cadarache hosts the ITER project as well as the CEA's research activities and is located in Saint Paul-lès-Durance, France.

5.2.2 United Kingdom

The UK's Engineering and Physical Sciences Research Council (UK EPSRC) is part of the UKRI (UK Research & Innovation) which is a public body of the UK government. The UK EPSRC are collaborating with the European Atomic Energy Community (Euratom) to jointly fund the Culham Centre for Fusion Energy (CCFE). Established in 1965 by the United Kingdom Atomic Energy Authority (UKAEA), CCFE is the UK's national fusion research laboratory that specializes in magnetic confinement fusion [364]. The UK EPSRC provides about 30% of the funding to CCFE's "UK Magnetic Fusion Research Program" with the other 70% provided by Euratom [365]. There is currently a £164 million investment for fusion related research activities in CCFE [366]. CCFE is also a member of the EUROfusion consortium which is constituted of more than 30 fusion research institutes across Europe. The Joint European Torus (JET) fusion project, the Mega Ampere Spherical Tokamak Upgrade (MAST Upgrade) fusion project, and the upcoming

Spherical Tokamak for Energy Production (STEP) fusion project are all hosted at CCFE in the UK. In addition, a £86M government investment in the UKAEA's CCFE to start the UK's National Fusion Technology Program (NFTP) was announced in 2017 and is scheduled for 2020 [367]. On 24 December 2020, a Nuclear Cooperation Agreement (NCA) concluded between the UK and Euratom which makes clear the intent for the UK to remain participating in the ITER project [379].

5.2.3 United States of America

The U.S. Government supports fusion through a number of different offices and programs within the Department of Energy, and these are illustrated in Figure 25. The Office of Science is a component of the U.S. Department of Energy (US-DOE). The Office of Science is the lead federal agency in the U.S. supporting fundamental scientific research for energy and the largest supporter of basic research in the physical sciences. The Office of Science funds several of the U.S. National Laboratories dedicated to fusion research, including in particular, the Princeton Plasma Physics Laboratory (PPPL). The Office of Science has multiple program offices, one of which is based on Nuclear Physics. The Fusion Energy Sciences organization (FES) is part of this office and supports the U.S. participation in the ITER project. The FES had a budget of $564M USD in 2019, $671M USD in 2020, and $425.15M in 2021 [273], [371]. The United States is to pay 9% of the ITER project's construction costs, including contributions of components, cash, and personnel [299], [300]. The total US share of the cost was estimated in 2015 to be between $4.0 billion and $6.5 billion, up from $1.45 billion to $2.2 billion in 2008 [368]. The US DOE's contribution to the ITER project was $132M USD in 2019, $242M USD in 2020, and is $107M USD in 2021 [278]. The FES and the US DOE's Advanced Research Projects Agency-Energy (ARPA-E) are overseeing a joint program called GAMOW (Galvanizing Advances in Market-aligned fusion for an Overabundance of Watts). Over a three year program period, GAMOW will receive up to $15M USD from ARPA-E and $5M USD a year for three years from FES [369]. ARPA-E also announced in April 2020 that its "Breakthroughs Enabling Thermonuclear-fusion Energy" (BETHE) program will award 15 fusion energy USA projects with a cumulative $32M USD [370]. The USA's National Nuclear Security Administration (NNSA) also has an "Inertial Confinement Fusion Ignition and High Yield Program (ICF)" that provides funding for some ICF fusion projects. The NNSA's ICF Program received a budget increase from $545M USD in 2019, to $565M USD in the 2020 fiscal year to $567M USD in the 2021 fiscal year (the current ICF program is being restructured into the Stockpile Research, Technology, and Engineering program of the NNSA starting in FY 2021) [371], [372].

The FES also has an awards program called INFUSE (Innovation Network for Fusion Energy) which is a US DOE initiative to give the private nuclear fusion industrial community access to technical and financial support to help with fusion research initiatives [374]. The U.S. government provides level funding of $4 million USD per year for the INFUSE program for collaboration between US DOE labs and private fusion energy ventures [373]. The leading private Canadian fusion company, General Fusion, was awarded a funding partnership in September 2020 from the INFUSE program. General Fusion will be partnering with PPPL to help develop Magnetized Target Fusion models. In addition to this program, on December 27, 2020, the USA's "Energy Act" created a new program that supports private fusion companies with funding, only once significant milestones have been achieved and reviewed. The costs will be paid up front by the private fusion ventures, and then reimbursed later by the government program once specific milestones have been verified. This act will recommend that the US Congress will allocate $325M USD distributed over 5 years to qualifying private fusion ventures [373].

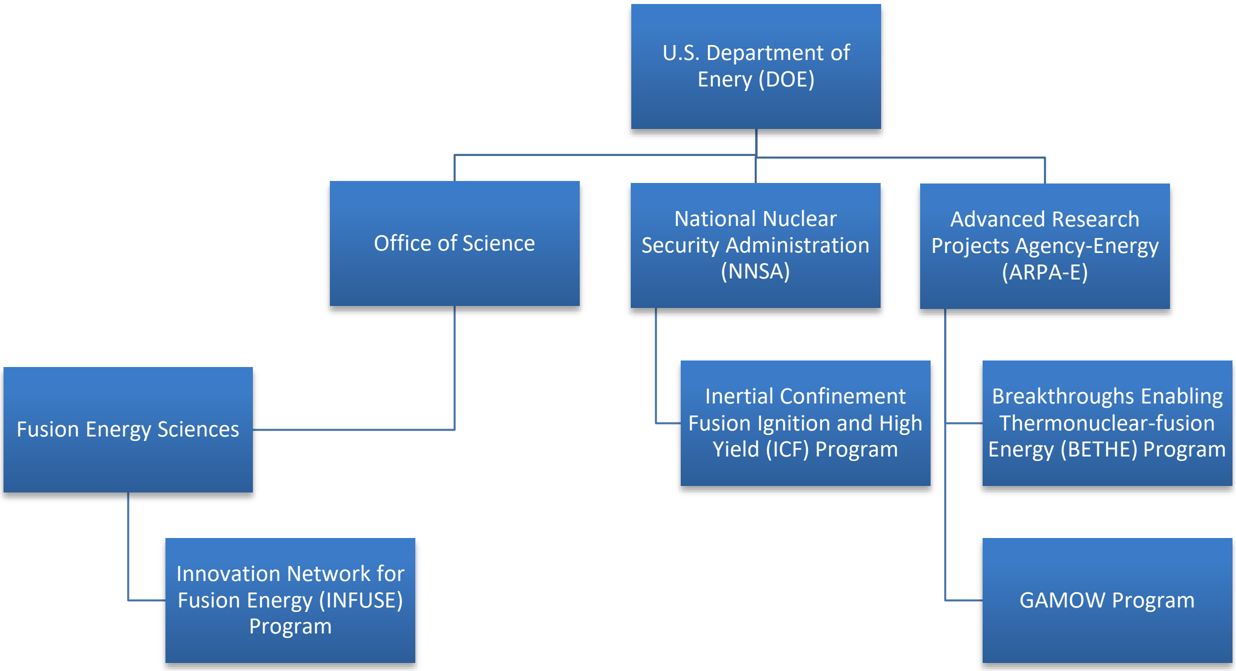


Figure 25: The Structure of the U.S. Government Fusion Energy Programs.

5.2.4 Japan

The Japan Atomic Energy Agency (JAEA) was formed in 2005 when the Japanese Atomic Energy Research Institute (JAERI), initially established in 1956, merged with the Japan Nuclear Cycle Development Institute. Nuclear fusion research and development activities were transferred to Japan's National Institutes for Quantum and Radiological Science & Technology (QST) in April of 2016 [375]. All fusion research in Japan is overseen and managed by QST. The QST receives Japanese government funding to help with the development of fusion research in Japan. The National Institute for Fusion Science (NIFS) in Toki, Japan, is an inter-university research institute that is playing an active role in mutual cooperation with research organizations and universities both in Japan and in foreign countries [376]. NIFS was established in 1989. Japan also joined the ITER project as one of the 7 main members, and are responsible for 9.1% of ITER's construction costs [297].

5.2.5 Korea

South Korea has been involved in nuclear fusion research since 1995. They entered into the ITER project in 2003 as one of the 7 main members, and are responsible for 9.1% of ITER's construction costs [297], [298]. They established the National Fusion Research Institute (NFRI) in 2005 (formerly the National Fusion Research Centre and renamed in 2007) in the city of Daejeon. South Korea's main fusion research project is KSTAR (Korea Superconducting Tokamak Advanced Research). In 2020, the Korean Institute of Fusion Energy (KFE) was established; Korea's only research facility that specializes in nuclear fusion [377].

5.2.6 Russia

The Kurchatov Institute (KI) is Russia's leading research institution in nuclear energy. Major experimental research in plasma physics and nuclear fusion has been performed there since 1955. The very first tokamak fusion reactors were designed and constructed at the Kurchatov Institute. As of 1991, the Kurchatov Institute is sub-ordinate to the Government of Russia [378]. Russia joined the ITER project as one of the 7 main members, and are responsible for 9.1% of ITER's construction costs [297], [298].

5.2.7 China

China's domestic program in magnetic confinement fusion research started in the 1960s. There are two main research institutes that are responsible for most of the significant fusion research and development in China. They are the Institute of Plasma Physics at the Chinese Academy of Sciences (ASIPP) and the Southwestern Institute of Physics (SWIP). SWIP was established in 1965 and was China's first nuclear fusion institute (affiliated with China National Nuclear Corporation (CNNC)) [380]. Over the last 50 years, SWIP has built more than 20 experimental devices for controlled nuclear fusion research. Several test reactors were developed and experimented on over the years which laid a foundation of knowledge and experience for the upcoming fusion reactor: CFETR (Chinese Fusion Engineering Testing Reactor). In 2003, the Government of China formally joined the ITER project as one of the 7 main members, and are responsible for 9.1% of ITER's construction costs [297], [298], [381]. Shortly after, this commitment led to a fully planned magnetic confinement fusion program, the Chinese Magnetic Confined Fusion energy project (CN-MCF), which receives stable government funding. China also launched an ambitious and comprehensive fusion education program after joining ITER. More than ten top institutes and ten top universities in China have gotten involved in this program that intends to train "fusion talent". There are more than 1000 young students that have been trained in the field of fusion for 2020. Training starts as early as introducing courses to third year undergraduate students and then the program is fully developed for Master's and PhD level students. Over 200 Master's and 150 Ph.D. students each year have been involved in fusion research in China [382]. The Chinese fusion community agreed upon a roadmap for Chinese fusion developmental research in 2015 [328], [329].

6. Conclusions

There is a large effort and investment of people and experimental facilities by many nations to prove that nuclear fusion can become a practical source of zero-carbon energy. Abundant and economical zero-carbon energy is needed to raise the standard-of-living and the quality-of-life for all of humanity, while also minimizing pollution, and preventing or mitigating the effects of greenhouse gas emissions, and their impact on global climate change.

Rapidly increasing efforts are being applied to develop effective nuclear fusion technologies with a wide array of approaches. This document provides an overview and some insights into the majority of these efforts. An outlook is also provided on the current nuclear fusion energy landscape of the world. Key fusion technologies that are in active development today are highlighted. Canada's past and present involvement in fusion research is reviewed and can be compared to that of other nations. The majority of the significant fusion projects underway around the world are also highlighted. The goal of this comprehensive reference report on fusion is to inform the Canadian reader of the current state of affairs in nuclear fusion energy around the world and to give a better sense and appreciation of the problems, challenges and innovations in the industry.

Historically, investment in research and development in fusion energy as a new and alternative energy source has been considered a high-risk, high-reward endeavor. The risk has been high, because of the many great scientific and technological challenges, some which are still emerging and unknown ones that are yet to be discovered. There are also risks because of the great challenges associated with the issues of practicality and economics. Attempting to shrink the Sun down to a power plant that is comparable to the size of a Hockey Arena or even smaller is no easy feat. However, in spite of the risks, the potential rewards for the successful development of fusion energy are far greater. With fusion, there is promise of an abundant, almost unlimited supply of zero-carbon energy. Hence, there is also a risk in not supporting and pursuing the development of fusion energy.

Given the current state of fusion research around the world, the rising number of public-sector and private-sector participants, and the increasing funding levels by both governments and private investors, many of the earlier scientific and technological problems are being solved, reducing the risks, and increasing the probability of ultimate success. Brief demonstrations of experimental fusion reactors operating at close to scientific breakeven ($Q\sim1.0$) have been achieved. Building upon previous knowledge and experience, it appears that net power generation ($Q\geq5.0$) in one or more different fusion reactor concepts should be achievable in the next 10 to 20 years.

It is recognized that many problems and challenges remain to be solved and addressed before fusion can become a practical and economical zero-carbon energy source. To ensure these problems can and will be solved, and will also be solved on an expeditious and credible timescale, there needs to be a strong and steady effort in scientific and technology research and development, with active participation by industry.

Over the last 60 years, fusion research and development has gone through cycles of growing and shrinking financial support from government and industry, which has slowed the rate progress. Investments and commitments by certain nations have been modest or relatively strong -- motivated and incentivized by long-term concerns about energy security and clean energy supplies. In other nations, the investment in fusion science and technology / research and development has been relatively miniscule. In more recent years, groups of nations have found it advantageous and necessary to pool funding and resources to enable the construction and operation of larger experimental fusion facilities. Like other emerging high-tech sectors, fusion research and development would greatly benefit from a steady, long-term funding commitment provided by government and private sector investments.

In spite of the historical funding and financing problems for fusion research and development, slowing its development, there have been three recent changes on the international landscape that may very well shorten the time to commercialization of fusion technology: 1) Significant increases in private-sector investments for fusion R&D, 2) Significantly increased financial support by a number of governments (particularly the USA, UK, and China) and 3) A wider range of technologies are now being actively pursued. The progress is such that demonstration plants are now projected to be operational in the 2030s and 2040s.

Canada’s participation in fusion energy development has been sporadic. Based upon decades of academic research, Canada at one point had a thriving domestic fusion energy program. Canada’s National Fusion Program (NFP) was initiated in 1978, and grew to become a modest, but well-respected, and world-renowned fusion program that was making important and impactful contributions to the international effort on fusion in the 1980s and early 1990s. Unfortunately, in an effort to drastically reduce government expenditures, eliminate budget deficits, and avoid a financial debt crisis, support for the NFP, along with other programs, was terminated by the Government of Canada in 1997. Within a few years (by 2004), the Government of Canada also withdrew its participation in the ITER project. In spite of this withdrawal of government support, fusion-related research has continued at a small-scale level at several universities across Canada, while work on tritium-related technologies has continued with AECL/CNL at the Chalk River Laboratories.

In the period of 2010 to 2021 (the present), there has been some renewed, and growing interest by the Government of Canada in Fusion R&D, initially focusing on supporting innovative ideas (such as fusion) that are aligned with sustainable technology development. There has also been an incentive for the Government of Canada to provide technology development investments, which could be leveraged to attract more private-sector investment. Thus, the nearly $76M CAD that the Government of Canada has invested in General Fusion over the last 10 years has been relatively successful and quite helpful to General Fusion in securing an even greater amount of private sector investment.

Very recently, with leadership and encouragement provided by the Organization of Canadian Nuclear Industries (OCNI), Ontario Power Generation (OPG), and other fusion grassroots and stakeholder groups in Canada, and following multiple meetings, discussions and negotiations, the Government of Canada signed a Nuclear Cooperation Agreement (NCA) with the ITER project, to enable Canada to share tritium and tritium-related technologies to support the development and operation of the ITER facility.

It is encouraging and exciting to see that progress in fusion energy development has accelerated over the last decade, with increasing interest, involvement and investment by industry, the private sector, and start-up fusion companies. Over $2 billion CAD in investments has been raised by private fusion energy companies around the world in the last ten years. In many nations, government spending has grown significantly as well. Recent combined expenditures by governments in the USA, UK, and European Union exceed 1.7 billion CAD annually. Furthermore, 35 countries are currently working collaboratively on the construction of ITER, which has an estimated $32 billion CAD price tag. ITER member nations are providing both in-kind and monetary contributions. In return, ITER member nations will share expertise, experimental results and intellectual property rights from the project to reap long-term economic benefits.

Humanity is getting closer to achieving the goal of being able to successfully harness the power of fusion. Canada could act as both a supplier and enabler of fusion technologies, and could help enable achieving the goal of fusion more quickly. Such an achievement would be a proud legacy for Canada, and for all Canadians.

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Appendix A Appendices

A.1 Technical Description of Fusion Technologies

The following sub-sections provide a high-level description of various fusion reactor concepts and plasma confinement technologies.

A.1.1 Fusion Plasma Confinement Criteria

In fusion plasma confinement, the goal is to meet the energy breakeven requirements (i.e., the Lawson Criteria, $n\tau \geq 10^{20}$ seconds/m^3 at ~ 10 keV, or a triple-product of $n\tau T \geq 10^{21}$ ion-second-keV/m^3). The triple product is product of the fusion fuel ion density, and the confinement time, and the ion temperature.

As illustrated in Figure 26 (a), the probability of fusion (the reaction rate) is maximized for the deuterium-tritium (DT) fusion fuel combination at a plasma temperature in the range of 10 keV and 50 keV (or between 100 million and 1 billion Kelvin). As illustrated in Figure 26 (b), when other physics factors affecting energy losses and plasma confinement are taken into account, the triple product is found to be minimized for DT fuel at a value of approximately $n \times \tau \times T \sim 10^{21}$ ion-seconds-keV/m^3 at ~10 keV. Alternative fusion fuel combinations such as deuterium-deuterium (DD) or deuterium-helium-3 (D-^{3}He) have a lower probability of undergoing fusion, and also have much higher minimum triple products. Thus, the DT fusion fuel combination is the easier option for achieving fusion.

IMAGE REMOVED / REDACTED	IMAGE REMOVED / REDACTED
(a) Fusion Reaction Rate vs. Plasma Temperature	(b) Triple Product of $n \times \tau \times T$ vs. Plasma Temperature

Figure 26: Fusion Reaction Rate and Triple Product vs. Plasma Temperature of Different Fusion Fuel Combinations (from References [19], [20]).

Sufficient confinement for DT fusion can be achieved through a number of ways, such as with low density ($n > 10^{20}$ D,T ions/m^3) and relatively long time periods ($\tau \geq 1.0$ seconds), such as found with conventional mainstream magnetic confinement approaches. Alternatively, sufficient confinement could be achieved with very high densities ($n > 10^{30}$ D,T ions/m^3) and very short time periods ($\tau \geq 100$ pico-seconds),, such as found with conventional laser-based inertial confinement fusion. The third option is to use an intermediate value of densities and confinement times, similar to what is used in various types of pulsed electro-magnetic plasma confinement systems, including those used with magneto-inertial confinement (MICF) or magnetized target fusion systems (MTF).

A.1.2 Magnetic Confinement Fusion

In magnetic confinement fusion, the goal is to meet the energy breakeven requirements (i.e., the Lawson Criteria, $n\tau \geq 10^{20}$ s/m^3 at ~ 10 keV) through relatively long energy confinement times, τ > few seconds, but at relatively low density, $n > 10^{20}$ D,T/m^3. Confinement is achieved through the use of strong magnetic fields which limit the outward diffusion of particles and energy from the core plasma to the surroundings.

The primary magnetic confinement configurations are the Tokamak and the stellarator (or similar helical devices), both of which have generally toroidal geometry, looking very much like a large donut. See Figure 27**,** Figure 28, Figure 29, Figure 30, and Figure 31. See References [19] to [41] for more information.

Because of this toroidal geometry, plasma confinement requires a combination of toroidal and poloidal magnetic fields. In Tokamaks, the poloidal field is created by a plasma current, while in stellarators, the entire field is created by complex external coils. The Tokamak requires a very high toroidal current in the plasma to generate the poloidal magnetic fields, and usually requires the use of a transformer to induce the current (see Figure 30). Thus, the Tokamak is pulsed device with a time-dependent toroidal plasma current, although it is usually a long, slow pulse lasting tens of minutes to nearly an hour. In contrast, the stellarator has a complex combination of external field coils to create the steady state magnetic field to confine the high energy fusion plasma with very low or no plasma currents (see Figure 31).

A design variant of the Tokamak is the spherical Tokamak, or spherical torus (ST), which has a much smaller aspect ratio (AR = R/a, where “R” is the radius of the torus, and “a” is the radius of the plasma cross section), making it look like a donut with barely any hole (see Figure 32 and Figure 33). See References [43] to [55] for more information.

Spherical Tokamaks are designed to use much higher magnetic fields, taking advantage of the use of high-temperature super-conductors (HTS) for the operation of the toroidal field coils. With higher magnetic fields, an ST can operate with much higher plasma pressures, plasma densities, and fusion power densities, given that the pressure created by a magnetic field varies as the square of the magnetic field ($P \sim B^2/2\mu_0$, where “P” is the plasma pressure, and “B” is the magnetic field).

IMAGE REMOVED / REDACTED

Figure 27: Schematics of Tokamak and Stellarator Fusion Reactor Configurations (from Reference [21]).

IMAGE REMOVED / REDACTED	**IMAGE REMOVED / REDACTED**
(a) Tokamak with Pulsed Operation	(b) Stellarator with Steady-State Magnetic Fields, but Complex

Figure 28: Illustration of Magnetic Field Coils in Tokamak and Stellarators (from References [26], [31]).

IMAGE REMOVED / REDACTED

Figure 29: A Three-Dimensional CAD (Computer Aided Design) Image of the ITER Tokamak (from References [19], [26]).

IMAGE REMOVED / REDACTED	**IMAGE REMOVED / REDACTED**
(a) Illustration of Transformer Action for Inducing a Toroidal Current in Plasma in a Tokamak	(b) Cross Section View of Fusion Plasma Chamber in a Tokamak

Figure 30: Illustration of Transformer Action in a Tokamak (from References [19], [26]).

IMAGE REMOVED / REDACTED	**IMAGE REMOVED / REDACTED**
(a) Photograph of Wendelstein 7-X Facility	(b) Illustration of Magnetic Field Coils and Plasma

Figure 31: Photograph and Illustration of Wendelstein 7-X Stellerator Experimental Facility (from References [31], [40], [41]).

IMAGE REMOVED / REDACTED

Figure 32: Artistic Illustration of the ARC (Affordable, Robust, Compact) Spherical Tokamak / Spherical Torus Fusion Device under Development by Commonwealth Fusion (from References [22], [23]).

IMAGE REMOVED / REDACTED	**IMAGE REMOVED / REDACTED**
(a) Cut-out View of Spherical Tokamak (China) [44]]	(b) View of Plasma in a Spherical Tokamak (Tokamak Energy, UK) [55]

Figure 33: Illustration of Spherical Tokamak / Spherical Torus Fusion Devices (from References [44], [55]).

In addition to meeting the confinement criteria, it is also necessary to maintain a temperature sufficient for the fusion reactions to proceed. Thus the "fusion triple product", $n \times \tau \times T$, which is the density of the fusion ions, times the confinement time, times the fusion fuel temperature, is sometimes used to indicate the progress made over the years, as shown below in Figure 34.

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** The above image taken from Figure 7 of Daniel Clery, 2019 "Alternatives to Tokamaks: a faster-better-cheaper route to fusion energy?", Phil. Trans. R. Soc. A 377: 20170431.* http://dx.doi.org/10.1098/rsta.2017.0431

Figure 34: Evolution and Progress in Achieving Fusion Triple Product in Different Fusion Reactor Experiments over the Period of 1960 to 2040 (Projected) [24].

It is often noted that, by this measure, the improvement in Tokamak performance from about 1965 to 1995 is faster than Moore's law. Because of this extraordinary success, the Tokamak dominates as the leading approach to fusion, although further progress in other fusion concepts can be expected.

A.1.3 Laser-Based Inertial Confinement Fusion

A.1.3.1 Introduction To L-ICF / IFE

The main approach to inertial confinement fusion energy (IFE) pursued to date is based on laser drivers (L-ICF), with the lead facility being the National Ignition facility (NIF) located at the Lawrence Livermore National Laboratory (LLNL) in California. The choice of laser is determined by requirements of drive laser intensity, laser efficiency and scaling of target parameters such as energy absorption, energy conversion, hydrodynamic efficiency and laser-plasma instabilities. More information about L-ICF/IFE is found in References [56] to [90].

Because of these considerations, short-wavelength lasers are preferred as driver lasers for such systems. The goal is to compress and heat a DT fuel mass to ignition conditions where the fusion reactions are ignited at a very high rate in a small region called the ignition hot spot and subsequently through alpha particle heating burns through the assembled fuel mass on a time scale of around 100 picoseconds.

To date great strides have been made with the most recent milestone being the achievement of alpha particle heating generated exceeding the initial energy put into heating the ignition hot spot [72] and fusion energy neutron yield of 54 kJ [73]. The L-ICF community is now within reach of achieving full ignition and burn in the next several years.

The basic concepts for inertial fusion [74] are shown in Figure 35 for two alternate approaches: indirect drive [75] and direct drive [76], [77] with advanced concepts of Fast Ignition (FI) [78], [79] and Shock Ignition (SI) [80], [81], [82] also shown. The basic principles of fuel compression, central core ignition and propagating burn generated through self-heating by helium produced in fusion reactions are described. Advanced concepts of fast ignition and shock ignition, also illustrated, hold the promise of higher gain and area active areas of current investigation.

To satisfy the Lawson criteria and to ensure an efficient burn, the compressed fuel mass must have a minimum product of mass density times radius; the ρxR or rho-R product for the assembled fuel must typically exceed ~2 g/cm^2 to 3 g/cm^2. Because the compressed fuel mass is fairly small, on the order of 100 microns in diameter, the required densities are on the order of 300 g/cm^3 (or ~ 3.0x10^{31} ions/m^3), requiring extreme fuel compression to ~1000 times normal liquid density of DT, ~ 0.2 g/cm^3.

IMAGE REMOVED / REDACTED

Figure 35: Basic Concepts (left to right) of Indirect Drive and Direct Drive IFE and Advanced Techniques of Fast Ignition and Shock Ignition (from Reference [82]).

A.1.3.2 Indirect Drive For Pellet Compression

The most developed approach to IFE is based on the indirect drive technique. The largest laser system in the world, the National Ignition Facility (NIF) at 1.8 MJ per pulse, has been built at the Lawrence Livermore National Laboratory (LLNL) in order to demonstrate ignition and net energy gain by means of laser driven fusion (see Figure 36). Operation of the system started in 2009 and NIF scientists are actively pursuing a systematic study of ignition and gain.

A similar system, Laser Megajoule (LMJ) is partially operational near Bordeaux, France and will start ramping up to full-scale operation from 2020 to 2030. Both NIF and LMJ have identified indirect drive as the most straight forward approach with the highest probability of success to implement laser fusion in the near term. Because of the inefficiency of converting laser light into x-rays which then acts as the ablation driver, indirect drive systems will have lower gains for a given laser driver energy.

Current challenges for indirect drive are in the crossing of beams in the entrance cones where cross beam energy transfer (CBET) due to the Brillouin instability in the plasma and stimulated Raman backscatter (SRS) cause an imbalance in drive beam energy and non-uniformities in the hydrodynamic implosion from beam non-uniformities and geometric non-uniformities (target holder). The CBET can be controlled both by detuning crossing beams to reduce the interaction and by heading towards broader bandwidth lasers in the future. Remaining hydrodynamic non-uniformities are being addressed by careful beam balance inside the hohlraum cylinder, reducing the mass of the supporting elements for the target fuel capsule and more robust multilayer target designs to reduce growth rates of these non-uniformities. These are all areas of ongoing research.

Typical calculations of expected scaling of gain indicate that laser energies of over 2 MJ probably will be required for the indirect drive approach to achieve gains of Q = 10 or more. Upgrades are currently proposed to raise the output energy of the NIF system to above 2.2 MJ in the next few years in order to achieve ignition.

IMAGE REMOVED / REDACTED

(a)

IMAGE REMOVED / REDACTED

(b) Laser Bay (Left), Target Chamber (Right)

Figure 36: National Ignition Facility 1.8-MJ Laser System (Top) & Photos of Laser bay (Left), Target Chamber (right) (from References [8], [57], [91]).

A.1.3.3 Direct Drive For Compression Of Fusion Fuel Target Pellet

The most efficient use of laser drivers involves direct irradiation of the target surface with the laser beams. This approach requires a large number of laser beams and careful design of beam overlap in order to achieve the percent level irradiation uniformity required in order to ensure a very symmetric implosion. Such designs have been developed and implemented on the largest operating direct drive system in the world which is the 60-beam, 30-kJ OMEGA laser facility at the University of Rochester. Beam energy balance on the order of 1% is routinely achieved in this system.

Current challenges for direct drive are in laser-plasma interactions in the under-dense plasma regions both leading to irradiation non-uniformity and also generating hot electrons which can preheat the DT fuel and thus raising the amount of energy required to compress the fuel to ignition conditions. The non-uniformities arise from laser plasma instabilities (LPI), including stimulated Brillouin instability (SBS) and stimulated Raman instability (SRS) backscattering light and cross beam energy transfer (CBET) redirecting the light [83]. These instabilities will then seed non-uniformities in energy absorption and drive pressure on the capsule which will then be amplified through hydrodynamic instabilities such as the Rayleigh Taylor instability.

In addition the SRS instability and a further instability, the two Plasmon decay (TPD) instability generate hot electrons with energies in the range of 30 keV to 80 keV, which can penetrate into the fuel core in advance of compression, preheating the fuel and increasing the required compression energy considerably. All the laser plasma instabilities and their consequent effects can be mitigated by the use of broad band laser pulses, which is a feature to be designed into future laser driver systems.

The expected scaling of fusion yield versus driver energy indicates that target gains of 50 to 150 (energy output / energy input) should be achievable for optimized direct drive systems with drive laser energies of the order of 2 MJ or more. These gains are higher by a significant factor compared to the expected gains for an indirect drive laser reactor system at comparable laser energies. To realize these improvements, cross beam energy transfer (a laser-plasma instability) must be mitigated [83]. However, scaling of the direct drive physics to ignition conditions still has to be demonstrated and this will require much higher laser energy than existing lasers such as OMEGA can deliver.

A.1.3.4 Fast Ignition Of Compressed Fusion Fuel Target

One of the more advanced concept designs is the idea of separating fuel compression from fuel ignition in the concept called Fast Ignition. By utilizing a separate laser pulse for ignition the requirements for fuel compression can be reduced considerably. The first pulse is used to assemble a large high density fuel mass and a second laser much shorter laser pulse is introduced to create a high temperature hot spot to ignite fusion reactions. This approach is analogous to using a spark plug in an internal combustion engine. This approach reduces the overall laser energy requirements considerably, requiring a main compression laser pulse of ~ 1 MJ, and a Fast Ignition Driver pulse of ~ 0.5 MJ. This approach also allows for more tolerance in irradiation non-uniformity and target preheat. This scale size laser is similar to the currently operating NIF laser in California though configured into different beam lines. In order to create the short ignition laser pulse, the pulse compression techniques co-invented by Donna Strickland, our Canadian Nobel prize winning physicist and Gerard Mourou are required.

The investigation of fast ignition (FI) is incomplete and ongoing but the rewards in terms of smaller scale size reactor systems are quite attractive. The scale size of a high yield reactor system with a gain of over 100 (energy output / energy input) has the potential to be on the order of 1.5 MJ. The remaining hurdle in terms of the science for the success of Fast Ignition is the requirement for intense magnetic guide fields to couple the energy from the laser pulse to the compressed fuel core using MeV-energy electrons generated in the interaction, an area of current investigation.

A.1.3.5 Shock Ignition Of Compressed Fusion Fuel Target

Another advanced approach using a separate laser pulse to create the ignition event is through shock ignition (SI). In this case, a higher-intensity laser spike is added to the main laser pulse and focussed onto the target. With careful engineering this laser spike can be generated using the same laser amplifiers as the main compression pulse by injecting a seed pulse at the end of the main compression pulse.

The investigation of shock ignition (SI) is ongoing to address the issues of control of laser plasma instabilities (LPI) and optimization of conditions to form the strong ignition shock. One of the key strategies for mitigation of LPI is the introduction of larger bandwidth lasers which reduce the coherent coupling to the plasma and reduce LPI growth. From hydro-dynamic simulations, it is found that the hot compressed capsule is also more tolerant to non-uniformities in the ignition shock spike and more tolerant to hot electrons from the late time LPI allowing more flexibility in laser intensities and irradiation geometries for the late time laser spike.

The overall effect of shock ignition, like fast ignition, would be to reduce the laser driver requirements from the multi-megajoule level to around the megajoule level for an operating system. Scaling laws for expected target yield versus laser system drive energy based on numerical simulations are shown in Figure 37. Again, these predicted yields are much higher than equivalent yields from indirect drive or direct drive systems alone for similar laser energies. Given that such laser pulses can be generated by the main laser system itself there is no requirement for an additional high intensity short pulse laser system, as in fast ignition.

Because of its attractive features, shock ignition has become one of the favored approaches for groups pursuing direct drive ICF and was proposed for incorporation in the proposed HiPER laser fusion demo project in Europe [84]. Shock Ignition will be explored in some of the direct drive experiments planned for the LMJ laser facility in France and potentially at NIF later this decade. Already there have been some scaling experiment studies carried out at NIF led by the University of Rochester group on laser-plasma instabilities at the higher intensities required for the shock driving spike [85].

IMAGE REMOVED / REDACTED

Figure 37: Shock Ignition Yield Versus Laser Energy (from Reference [82]).

A.1.3.6 L-ICF Power Reactor Systems

The most developed approach to IFE/L-ICF is based on the indirect drive technique as outlined above and LLNL has used this technology as a basis for a detailed power reactor design called LIFE (for Laser Inertial Fusion Engine). See Figure 38.

In fact the easiest approach to a first generation reactor would be hybrid fission fusion reactor (HFFR) where the high energy neutrons from a low gain fusion reactor could be used to burn up radioactive waste (spent fuel) from fission reactors, also addressing the reduction of the inventory of spent fuel from current generation fission reactors. Such an approach was proposed for the initial version of the LIFE reactor [86]. LLNL considered that construction of such a system is feasible using a mixture of existing technologies (59%), extensions to existing technologies (28%) and development of new technologies (13%). IN the LIFE project envisage an aggressive 5 year program focussed on technology demonstration concurrent with a ten year building phase for a LIFE demo system.

There are a number of other past conceptual design studies of IFE reactors including the HAPL study in the USA and Koyo and Koyo-FI for fast ignition in Japan and the HiPER proposal in Europe [84]. Critical design issues for IFE include: materials, optics, laser systems, chamber wall and, target fabrication & delivery. Technical solutions include: annealing optics, diode pumped solid state lasers, hot swapping of line replaceable units, replaceable grazing incidence optics, chambers with a liquid metal wall or ceramic liner tiles, magnetic shielding or a few year replacement cycle, choice of materials, microelectronics fabrication techniques.

IMAGE REMOVED / REDACTED

Figure 38: LIFE Inertial Fusion Power Plant Concept (from Reference [91]).

The smaller scale size of Fast Ignition and Shock Ignition approaches, compared to indirect drive or direct drive systems, would allow for even more rapid development cycles and the fielding of smaller but still highly efficient reactor systems. However, more scientific studies are required to address the remaining technical hurdles for these systems, primarily magnetic guiding of hot energetic electrons for the former and minimizing laser-plasma generated hot electrons for the latter. These are areas of current research in the field.

Currently both indirect drive and direct drive are pushing forward with increasing neutron yields every year or two. Both are within a factor of a few in the yield required to reach ignition and burn leading to multi-megajoule energy yields. The progress of indirect drive is shown in Figure 39 and direct drive (scaled to equivalent NIF energies) is shown in Figure 40.

Currently, the record energy and neutron yield is from the indirect drive approach of NIF with a reported yield of 54 kJ of fusion energy form the ignition hot spot, which is significantly higher than the 21 kJ of energy injected into the hot spot region of the fuel (a gain factor of more than 2.0). Yields of 100 kJ to 200 kJ of fusion energy are anticipated in the next few years based on minimal extrapolation from current data when NIF is upgraded to 2.2 MJ of energy as proposed.

IMAGE REMOVED / REDACTED

Figure 39: Recent Progress towards Ignition in Indirect Drive at NIF with 1.8 MJ laser pulses (from References [87], [88]).

IMAGE REMOVED / REDACTED

Figure 40: Recent Progress towards Ignition Indirect Drive on the OMEGA laser at the University of Rochester, scaled to 1.8 MJ laser pulses (from References [87], [88]).

A.1.3.7 MAGLIF - IFE Approach To Fusion

Recently based on the success of the Sandia National Laboratories' Z-pinch experiments, another approach to IFE called magnetized liner inertial fusion (MagLIF) [89] has been initiated using lasers to preheat a plasma column containing a preformed magnetic field and then imploding a surrounding liner with mega-amp current pulses to compress and heat the plasma to ignition conditions for fusion in an axial geometry. In this case the peak densities are less than in spherically compressed targets but the confinement time is increased significantly due to the strongly compressed and amplified magnetic field embedded in the plasma core. The advantage of such a system is that most of the compression drive energy comes from an electrical pulse-power source. At present it appears that these schemes could be scaled up to ignition conditions with lower gain, but probably not to higher-gain systems due to the limited compression. As such, they could serve as an intermediate platform for studying the ignition and burn of fusion reactions in dense targets.

A.1.3.8 Computer Modeling and Simulation Codes for L-ICF

One of the key reasons that approaches to laser fusion energy has advanced significantly in the past two decades is the rapid development of sophisticated computer modeling and simulation codes giving accurate insight into the very complex non-linear processes occurring in these systems. However, even with today's most powerful (high-speed, large-memory) computers, modeling is mostly compartmentalized to look at one particular part of the physics at a time.

For laser fusion modeling there are three levels of codes predominantly in use. The first are hydrodynamic codes tracking the energy absorption, implosion dynamics, fusion reactions and fusion burn.

The second set are detailed particle in cell (PIC) codes. They model the plasma at the particle level using billions to 100's of billions of representative electron and ion particles to mimic a tiny piece of the interacting plasma. The PIC approach, is considered a "direct simulation" approach, which is conceptually simpler to implement in modeling, but much more computationally expensive, requiring more computer memory and simulation time.

The third level - so called kinetic codes - are used to calculate the intermediate scale interaction of high energy particle propagation and transport of energy by such particles over larger distance scales than can be done with PIC codes.

Full three-dimensional (3D) time-dependent simulations are very demanding in terms of computer computational effort (time and memory) and therefore tax the most powerful supercomputers at LLNL and elsewhere today [90]. Only a limited number of full 3D simulation runs are carried out each year, whereas many full two-dimensional (2D) simulation runs can be carried out yearly. It is expected that full 3D runs will become more commonplace as the power and availability of supercomputers increases, which will help address the remaining issues in the successful deployment of inertial fusion energy. The proposed "exascale computing project" of DOE targets a factor of 50 improvement over the current state of art computing power by the mid 2020's in order to address these challenges for inertial confinement fusion.

In short, advanced, comprehensive and detailed computer simulation methods and tools are of key importance to developing and improving fusion energy technologies.

A.1.3.9 Laser Drive Development

One of the critical technologies for laser-based inertial confinement fusion will be the development of more efficiency high-power laser systems. Fortunately, reliable, high efficiency, and high-repetition-rate lasers are required in many different industrial applications of lasers, which is driving the industry forwards at a very rapid pace.

Two Mega-Joule-class (2 MJ), high-energy lasers have already been demonstrated with the NIF system at LLNL. The scaling of such systems to high repetition rate (10 Hz or more) just requires the same high efficiency diode pumping techniques used in today's high-power industrial laser systems.

Thus it is expected that the generation of suitable megajoule-class laser driver systems is now quite feasible. Additional improvements may still be required to introduce larger bandwidth to the laser drivers in order to reduce the level of laser-plasma instabilities.

A.1.4 Magneto-Inertial Fusion (MICF) / Magnetized Target Fusion (MTF)

Many innovative new approaches lie in a branch of fusion research called Magneto-Inertial Confinement Fusion or Magnetized Target Fusion (MTF) (See References [92] to [102]). Magnetic Fusion (MF) systems are typically envisioned as low-density, steady-state systems, where the cost of confining large plasmas dominates. Inertial Fusion (IFE) systems have very small plasmas, but are dominated by the cost of the very high power driver systems (such as lasers). In both cases, recent advances are leading to opportunities to significantly reduce those costs.

MTF spans the intermediate regime between MF and IFE, using small plasmas confined by magnetic fields and rapid compression for heating to fusion conditions. The aim is power plants where both the cost of confinement and the compression driver can be dramatically lower, as illustrated in Figure 41 [93].

IMAGE REMOVED / REDACTED

Figure 41: Magnetized Target Fusion compared to Inertial and Magnetic Fusion (from References [6], [7]).

The MTF approach was under investigation initially in the 1970s with the LINUS imploding linear concept [101], [102], and then later in the 1990s by researchers at Los Alamos National Laboratory (LANL) [92]-[94]. General Fusion began its investigations on a modified version of the MTF approach starting in 2002 [98].

The LINUS, Imploding Liners, Magnetized Target Fusion (MTF) and the General Fusion concept all involve the adiabatic compression of a compact torus (CT) of plasma by a surrounding, electrically-conducting material shell. The compact torus has its own self-generated magnetic field that confines and holds the shape of the CT. See Figure 42. The CT is generated by a plasma gun and injected into a vacuum chamber. The CT is surrounded by material shell that conducts electricity. Because the material shell is a conductor, the self-magnetic field of the CT cannot penetrate the conductor, and is therefore insulated.

By means of electromagnetic compression, or by high-speed mechanical or pneumatic compression, the conducting shell is compressed, which in turn leads to an adiabatic compression of the CT inside, raising it to a high temperature and density. The following gives a brief summary of each MICF/MTF approach.

- LINUS Concept
    - Researchers at the Naval Research Laboratory (U.S.) who developed the LINUS concept in the 1970s [101], [102] envisioned using a high-speed pneumatic compression system to compress a liquid metal liner, which would then compress the CT.
- Conventional Magnetized Target Fusion (MTF)
    - Researchers at LANL have investigated the MTF concept since the 1990s [95], [96] using a pulsed current to compress a conducting cylindrical shell (such as an aluminum can), to compress a CT. Related work is going on at Sandia National Laboratory, making use of technology developed for Z-Pinch experiments.
- Acoustically Driven MTF (General Fusion)
    - Since 2002, an MTF-type concept is being investigated by General Fusion in Burnaby, B.C. [99]. It is a pulsed device. See Figure 44 and Figure 44. Two opposite CTs are injected axially inside a rotating sphere of a lead-lithium liquid metal liner, which is then compressed by the activation of multiple pneumatic cylinders, which create shockwaves that drive the liner inwards. Both computer simulations and experimental development and testing are underway.

Although the MTF/MICF approach is traced back to research first undertaken in the 1970s, the science in this regime remains less explored than MF or IFE. Recent efforts by LANL and General Fusion are aiming to close this gap [97]-[98]. In Canada, a world leader in MTF research, General Fusion, is undertaking pioneering research to explore the behaviour of compressed magnetized plasmas. In 2015, in the USA, the Department of Energy’s Advanced Research Projects Agency for Energy (ARPA-E) launched their ALPHA program, funding nine different groups pursuing variations of MTF and supporting science. ARPA-E grant recipients include private companies such as Helion Energy in Seattle, national laboratories such as Los Alamos National Laboratory, and universities such as Swarthmore College and the University of California. Sandia National Laboratory, also a recipient of ARPA-E funding, is researching another approach to magneto-inertial fusion using an extremely large pulsed magnetic field to compress the fuel, called Magnetic Liner Inertial Fusion (MagLIF) [100]. Research efforts on these concepts are also underway in China.

IMAGE REMOVED / REDACTED

Figure 42: Compact Torus (Magnetized Plasma Target) to be compressed by Liquid Lead/Lithium Blanket (from Reference [99]).

IMAGE REMOVED / REDACTED

Figure 43: Cross-Section of General Fusion's Acoustically-Driven Magnetized Target Fusion Concept (from Reference [103]).

IMAGE REMOVED / REDACTED

Figure 44: Illustration of System Layout for General Fusion's Acoustically-Driven Magnetized Target Fusion concept (from Reference [99]).

A.1.5 Alternative Fusion Concepts

In addition to the mainstream fusion concepts (Tokamaks, Stellarators, L-ICF) and the MTF/MICF concept, there are many other alternative fusion plasma confinement concepts that have been under investigation over the last fifty or more years. Most of these alternative systems rely upon a unique alternative combination of electromagnetic fields or electrostatic/magneto-static fields to confine the plasma, and operate in either a transient/pulsed mode, or a steady-state mode.

Due to a number of scientific and technical problems with such concepts in the past, many of them were abandoned. However, in recent years, various university research groups and private sector companies, enthusiasts, and entrepreneurs have been revisiting alternative fusion concepts, and implementing a number of innovative design changes to improve performance. These efforts have been aided and guided by modern advances in computer simulation methods, and various technological improvements in materials, and control systems.

Indeed, many of the scientific and technology improvements that have enabled performance improvements for mainstream fusion technologies can be leveraged and applied to alternative fusion concepts. Given the opportunity and further investment and effort to be developed further, such alternative concepts may have some practical advantages over conventional mainstream fusion concepts. See References [104] to [187] for more information on alternative fusion concepts.

The following is a list of alternative fusion reactor concepts, and their usual, expected mode of operation (steady-state, or transient/pulsed). Many of these are discussed in several historical references, including Brunelli [101], Bromley [104], Nickerson [105], Gierszewski [106], Dolan [107], and Hagler and Kristiansen [108].

- Electromagnetic Pinch Devices:
    - Z-Pinch - pulsed.
    - Extrap (External Ring Trap) Concept.
    - Dense Plasma Focus (DPF) – pulsed.
    - Linear Theta Pinch – pulsed.
    - Toroidal Theta Pinch – pulsed.
- Electrostatic / Magnetostatic Confinement Devices:
    - Inertial Electrostatic Confinement (IEC) – steady state device.
    - Penning Traps – steady state.
    - Polywells / Intersecting Magnetic Cusps – steady state.
- Magnetic Field Coil Confinement Systems:
    - Magnetic Mirrors – steady state.
    - Tandem Magnetic Mirrors – steady state.
    - Field-Reversed Configuration (FRC) Mirrors – steady state and pulsed.
    - Ion Ring Compressor (IRC) System – pulsed.
    - Migma System – steady state.
    - Magnetic Cusps – steady state.
- Multi-pole and Surmac Systems – steady state.
- Large Linear Systems:
    - Laser-heated Solenoid.
    - Cusp-Ended Solenoid Reactor (CESR).
    - Electron beam Heated Multiple Mirror (EBMM) Reactor.
- Large Toroidal Systems:
    - Reversed Field Pinch – pulsed.
    - ELMO Bumpy Torus (steady state).

In recent years, a number of entrepreneurial private companies have pursued development of alternative fusion concepts, leveraging previous research and development, and introducing design modifications and innovations that they anticipate will be successful. A number of these companies are listed below.

- **TAE Technologies (formerly Tri Alpha Energy) [170], [171]**
    - TAE is an American company based in Foothill Ranch, California, founded in 1998, and created for the development of a neutronic fusion power, using the D-^{3}He fusion fuel combination. The company's design relies on a field-reversed configuration (FRC), which combines features from other fusion concepts in a unique fashion. See Figure 45.

- **Lockheed Martin Skunkworks [172], [173], [174]**
    - Lockheed is developing its Compact Fusion Reactor (CFR), based on a combination of previous fusion technologies, including the magnetic mirror, magnetic cusp, and the multi-pole/surmac system with both external and internal magnetic field coils. See Figure 46. With this configuration, it is anticipated that such a system will be able to operate with a much higher plasma pressure and power density, and with a plasma-to-magnetic pressure ratio close to unity (β~1.0), while still maintaining plasma stability. This value is nearly twenty times higher than that found in a Tokamak reactor (β~0.05).
- **Helion Energy [175], [176], [177]**
    - Helion Energy, Inc. is an American company in Redmond, Washington developing an alternative fusion concept which is considered a magneto-inertial fusion technology, and is intended to use the D-^{3}He fusion fuel combination, although it could likely be adapted for using D-T or D-D fusion fuels.
    - The Helion Energy fusion approach uses two opposing plasma guns, each which creates a field-reversed configuration (FRC) plasma toroid, which is then accelerated and compressed in a central chamber, utilizing a combination of pulsed and steady-state external field coils. See Figure 47. This approach combines the features of an FRC, a magnetic mirror, and the ion ring compressor (IRC) approaches.
    - Similar to other FRC devices, the Helion system is expected to be able to achieve much higher plasma pressures and power densities in comparison to Tokamak reactors.
- **Energy Matter Conversion Corporation (EMC2) [178], [179], [180], [181]**
    - EMC2 is a private fusion research and development company founded in 1985, and has dedicated its efforts over a period of nearly 30 years to develop fusion on the basis of magneto-static/electrostatic confinement utilizing intersecting pairs of magnetic cusps, which create a very stable system for plasma confinement. See Figure 48.
    - Since the 1990s, EMC2 had built and operated 20 test devices to validate Polywell technology and is currently focusing its efforts toward high performance computing (HPC) model to optimize its reactor approach.
    - Since 1985, EMC2 has relied on funding for its work from a combination of U.S. government grants and research contracts from NASA, LANL, and the U.S. Navy, private sector contracts from EPRI (Electric Power Research Institute), and other sources.
    - The Polywell approach has attracted much attention from many other private groups and university researchers due to the simplicity and practicality of the concept, although more effort appears to be required to overcome scientific and technical problems to move it to the next stage of development. Such a device,

even if eventually only partially successful, could become a practical fusion-based neutron source [182], [183], [184].

- **Lawrenceville Plasma Physics Fusion (LPPFusion) [185], [186]**
    - LPPFusion is a private fusion research company that was been working on developing the Dense Plasma Focus (DPF) for more than 20 years as an alternative fusion device, capable of using different types of fusion fuel combinations (p-^{11}B, D-D, D^{3}He, and D-T).
    - The DPF is a pulsed electromagnetic fusion device which involves the use of a plasma gun with concentric electrodes. A radial plasma discharge is formed at the base of the gun, and then it is accelerated axially, with very high currents flowing radially through the plasma discharge and generating very high internal magnetic fields that confine the plasma. When the accelerated plasma reaches the end of the electrodes, it collapses upon itself from its self-generated internal magnetic fields, creating a high-density plasma pinch. The DPF is similar to a "Z-Pinch" Device. See Figure 49.
    - While it is yet unclear if the DPF, scaled up to higher energy and current levels, will lead to a fusion power plant (See Figure 50), the DPF continues to show promise as a useful pulsed fusion neutron source.
    - Because of the relative design simplicity of the DPF, many universities around the world have opted to build DPF devices for small-scale testing. The DPF concept is under investigation by researchers at the Ontario Tech University and the University of Saskatchewan [187].

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Figure 45: Illustration of Tri-Alpha Energy (TAE) Technology Fusion Plasma Confinement Concept Based on Modification of the Field-Reversed Configuration (FRC) and Magnetic Mirror System – the "Norman" Device (from References [170], [171]).

IMAGE REMOVED / REDACTED

Figure 46: Illustration of Lockheed Skunkworks Fusion Concept Based on Modification of Field-Reversed Magnetic Mirror Configuration (from References [172], [173], [174]).

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** Above image taken from https://www.helionenergy.com/technology/*

Figure 47: Illustration of Helion Energy's Pulsed Compact Toroid Collision System Concept (Similar to an Ion Ring Compressor) (from References [175], [176], [177]).

IMAGE REMOVED / REDACTED

(a) Three pairs of orthogonal magnetic Cusps (left)

IMAGE REMOVED / REDACTED

(b) Simulation of trajectories of ions and electrons in Polywell (right)

IMAGE REMOVED / REDACTED

(c) Experimental Demonstration of Small-Scale Polywell Device

Figure 48: Illustration of Polywell / Intersecting Magnetic Cusp Fusion Plasma Confinement System (from References [178], [179], [180], [181]).

IMAGE REMOVED / REDACTED

(a) Concentric Electrodes of DPF

IMAGE REMOVED / REDACTED

(b) Concentric Electrodes in DPF Experiment.

IMAGE REMOVED / REDACTED

(c) Capacitor energy storage bank used to provide high-current pulsed power to DP.

IMAGE REMOVED / REDACTED

(d) Computer simulation of DPF, illustrating dense plasma pinch at the end of the electrodes.

IMAGE REMOVED / REDACTED

(e) Shadowgraphs from DPF Experiment Showing Plasma Pinch Formation

Figure 49: Illustrations of Dense Plasma Focus (DPF) Fusion Device (from Reference [187]).

IMAGE REMOVED / REDACTED

Figure 50: Artist Conception of a Dense Plasma Focus (DPF) Fusion Power Device (from Reference [187]).

A.1.6 Hybrid Fusion-Fission Reactor Concepts

A unique alternative application for fusion reactors is that they can be used as an efficient neutron source to drive a sub-critical nuclear fission reactor. Such a system is known as a hybrid fusion fission reactor (HFFR). A HFFR can be used for generating power, and/or breeding fissile nuclear fuel for conventional nuclear fission reactors.

A conceptual illustration of an HFFR is shown in Figure 51. Various HFFR concepts have been under study for several decades, nearly as long as fusion reactors. See References [188] to [220]. Prominent scientists and Nobel Prize winners, such as **Andrei Sakharov** (who was a co-inventor of the Tokamak fusion reactor concept) [218] and **Hans Bethe** [193] were early and strong advocates for the development and use of HFFRs. During the 1970s and 1980s, many groups around the world were closely investigating HFFRs, including scientists at AECL Chalk River Laboratories [196], [197], [198], [199]. In more recent years, especially since 2010, there has been renewed interest in HFFRs, particularly in China [203], [204], [213].

In a HFFR, a sub-critical “blanket” region surrounds the central fusion region. Fusion neutrons produced in the fusion reactor stream outwards, and bombard a blanket made of a mixture of fissile (such as U-233, U-235, Pu-239, or Pu-241) and fertile (such as Th-232 or U-238) nuclear fuels. When bombarded with fusion neutrons, the fissile isotopes can undergo fission, releasing energy, while fertile isotopes can undergo neutron absorption, and will be transmuted into fissile isotopes.

For example, when thorium (in the form of Th-232) absorbs a neutron, it is eventually converted into the fissile isotope U-233 (Th-232 + n → Th-233 → Pa-233 → U-233). When the fertile isotope U-238 (which is the main component (over 99.3 atom%) of natural uranium) absorbs a neutron, it is eventually converted to the fissile isotope Pu-239 (U-238 + n → U-239 → Np-239 → Pu-239).

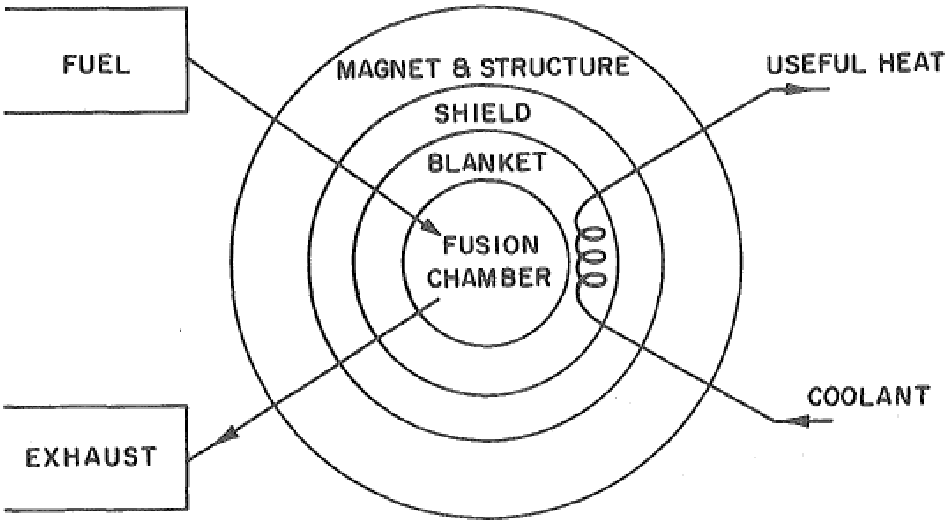
In a conventional fission reactor (such as CANDU reactors in Canada, or pressurized water reactors (PWRs) in other nations), a nuclear reactor is maintained in a “just critical” state, where the neutron multiplication factor (keff), the ratio of the production rate of neutrons from fission to the loss rate of neutrons by absorption and leakage is exactly unity (keff= neutron production rate / neutron loss rate = 1.000). To maintain criticality (keff=1.000) in a conventional nuclear reactor, new nuclear fuel must be added on a periodic basis, as fissile fuel is consumed, while also control rods are inserted to absorb excessive amounts of neutrons produced. Maintaining criticality in a fission reactor is somewhat analogous to the cruisecontrol in an automobile. Adding fuel is analogous to the *"accelerator",* while the control rods are analogous to the combined effect of the *"rolling friction from the tires"*, *the "wind resistance on the vehicle"* and *"the brakes"*.

In a HFFR, the fission reactor component is designed to be always sub-critical (keff < 1.000). Thus, control rods are not needed, and the system can never undergo an accidental power pulse due to an accidental increase in the neutron multiplication factor. The fission power level is directly proportional to the fusion power level. Thus, the HFFR is considered an "energy multiplier" that can generate part of its power from fusion, but most of its power from fission, depending on the multiplication factor of the sub-critical blanket. A plot of the ratio of the fission-to-fission power in an HFFR is shown in Figure 52.

For example, if the blanket in a HFFR is designed to be modestly sub-critical with keff=0.90, then the ratio of the fission-to-fusion power will be nearly 40. With such a high energy multiplication, it is possible for a HFFR with a highly sub-critical blanket (keff << 1.000) to operate with a low-performance fusion reactor (Q~1.0), while still generating net power (Pnet ≥ 0.0). For a conventional fusion reactor, such as the ITER Tokamak, a much higher performance fusion confinement system (with Q>10) is typically required to generate a substantial amount of net electrical power. Therefore, in principle, a number of existing lower-performance fusion reactors (such as the Joint European Torus, JET, and others with Q ≤ 1.0), or other lower-performance fusion reactor concepts could be adapted to serve as fusion neutron sources in an HFFR system. Such systems would represent an early application of fusion reactors.

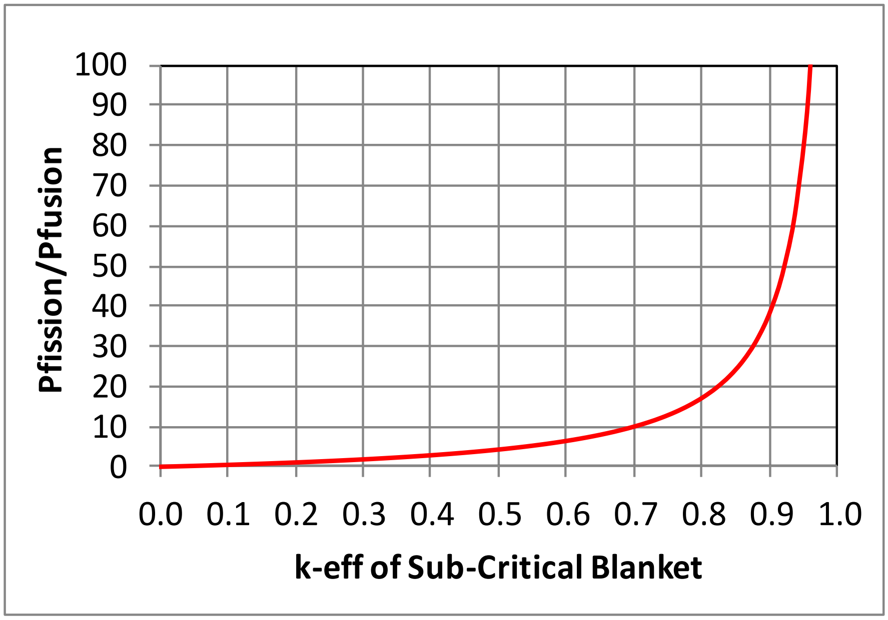
While an HFFR can be used to generate net power and electricity, it is usually more cost-effective and more attractive to use an HFFR to operate as a special breeder reactor, to breed fissile fuel (such as U-233 and Pu-239) from thorium and depleted uranium. The fissile fuel can then be extracted, recycled, and used in conventional nuclear fission reactors, such as CANDU reactors and PWRs. In this application, the HFFR would be an alternative to using a fast breeder reactor. For some design scenarios, the fissile fuel bred from a single HFFR could support a fleet of 10 or more CANDUs or PWRs, a much higher support ratio than could be achieved with a more conventional fast breeder reactor. This special application and advantage of HFFRs was recognized by many prominent Canadian scientists during the 1970s and 1980s [196]-[199], and also by Nobel-prize-winning scientist **Hans Bethe** [193].

Since 2010, several different groups within the international community (particularly in the United States, Russia, and China) have been investigating new options for using HFFRs, and for adapting existing fusion reactor concepts, including Tokamaks and L-ICF (see Figure 53). In principle, any fusion reactor could be adapted as an HFFR, although some fusion concepts, because of their geometric or operational simplicity, may be more suitable for use in HFFRs [104], [220]. It appears however, that China has one of the more ambitious programs to develop HFFRs, as a parallel and complimentary effort to developing pure fusion reactors [203], [204], as illustrated in Figure 54.



* The “blanket” can be a sub-critical (keff ≤ 1.000) fission reactor containing a mixture of fissile isotopes (such as U-233, U-235, Pu-239, and Pu-241) and fertile isotopes (such as Th-232 and U-238). Neutrons from the inner fusion reactor drive the outer fission reactor.

Figure 51: Conceptual Illustration of Fusion-Fission Hybrid Reactor (from Reference [197]).



* Note: if fission blanket is sub-critical with keff=0.9, the fission power will be ~40 times the fusion power. Typical values are $E_{fission}$ ~ 200 MeV, E_{fusion}~17.6 MeV, ν ~ 2.5 neutrons/fission.

Figure 52: Energy Multiplication in a Sub-Critical Fission Reactor Blanket Driven by Neutrons from a Fusion Reactor (from Reference [220]).

IMAGE REMOVED / REDACTED	IMAGE REMOVED / REDACTED
(a) Chinese Design for HFFR Based on Tokamak [203]	(b) U.S. Design for HFFR Based on LIFE L-ICF [216]

Figure 53: Mainstream Fusion Reactor Concepts for Potential Adaptation for Hybrid Systems (from References [203], [216]).

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Figure 54: China's Potential Roadmap for Developing Fusion-Fission Hybrid Reactors (from References [203], [204]).

A.2 Fusion Energy Applications

In a sense, fusion reactors can be considered as an alternative energy/power source that could be used to complement, augment, or replace several different existing energy sources, including fossil fuels (such as oil, natural gas, and coal), renewable energy resources (wind, photovoltaics, solar-thermal, hydroelectric, biomass, geothermal, and others), and nuclear fission (in both large-scale reactors and small modular reactors (SMRs)). It may be particularly attractive to co-locate fusion reactors with other facilities, and to the use the heat and electricity from fusion reactors for a number of co-generation options, as illustrated in Figure 55.

In principle, the energy/power provided by various types of anticipated fusion reactors could be used to complement/replace existing energy sources for several primary and secondary applications, including the following:

- **Base-load Electric Power Generation**
    - Similar to what is provided currently by large hydro-electric dams, natural-gas power plants, coal-fired power plants, and nuclear power plants.
- **Production of Hydrogen**
    - Using low-temperature electrolysis methods (from 20°C to 90°C).
    - Using high-temperature electrolysis methods (from 200°C to 800°C) [222].
    - Using intermediate-temperature (400°C to 700°C) thermo-chemical methods [223], such as the copper-chlorine (Cu-Cl) cycle.

        - This method of hydrogen production is suited for a number of SMR and Generation-IV Reactor technologies that can operate above 400°C, such as high-temperature gas-cooled reactors (HTGRs), liquid sodium-metal-cooled reactors (SFRs), liquid lead cooled fast reactors (LFRs) and molten-salt-cooled reactors (MSR). It is anticipated that fusion reactors could operate with the same or similar coolants and operating temperatures.
    - Using very high-temperature (> 850°C) thermo-chemical methods such as the sulfur-iodine (S-I) cycle [223],
        - This method of hydrogen production may be suited especially for very high-temperature gas-cooled reactors (VHTRs). Fusion reactors could be used in this capacity as well if pressurized gas coolants (such as Helium, Neon or Argon) were used.
- **High-temperature heat for chemical processing, etc.**
    - There are certain chemical synthesis, metallurgical, and petro-chemical processes that require very high-temperature heat, in the range of 600°C to 1000°C (or perhaps even higher). See Figure 56 and Figure 57. Examples include: iron & steel mills, specialty foundries, non-ferrous metals; copper, aluminum, lead, nickel, tin, & zin, oil production and refining, and others [225].
    - Generation-IV/SMR technologies, such as HTGRs/VHTRs, are well suited for this application. It is expected that fusion reactors operating with gaseous coolants (pressurized Helium) could be also used for such applications.
    - For processes that are well above 1000°C, particularly for certain types of metal smelting, concrete kilns, and glass making (see Figure 56 and Figure 57), it appears unlikely that a fusion reactor could be used directly, but the same assessment would be true for advanced nuclear reactors. However, electricity and hydrogen produced from fusion reactors, along with synthetic hydro-carbon fuels made from fusion-based hydrogen could be used as a substitute for fossil fuels to generate the high-temperature heat required for such very-high-temperature applications.

IMAGE REMOVED / REDACTED

See Figure 2 from Reference [224]

Figure 55: Range of Options for Co-Generation with Fusion Power Plant Exist, Using Both Low-Temperature and High-Temperature Heat (adapted from Reference [224]).

IMAGE REMOVED / REDACTED

See Figure 6 from Reference [224]

Figure 56: Potential Process Heat Applications for Fusion Reactors (from Reference [224]).

IMAGE REMOVED / REDACTED

Figure 57: Potential Process Heat Applications for Nuclear Fission Reactors Applicable to Fusion Reactors (from Reference [226]).

- **Desalination of sea-water, to produce distilled, fresh water**
    - Using simple distillation methods at temperatures below 200°C [227].
    - Using vacuum distillation (requiring electricity and low-temperature heat) [228].
    - Using reverse osmosis methods (requiring electricity).
    - More important for nations with a limited supply of fresh water.
- **Direct Air Capture and Removal of Carbon Dioxide from the Atmosphere**
    - To mitigate concerns about the levels of carbon dioxide (CO_2) in the atmosphere, the electricity produced from fusion power plants could be used to operate an atmospheric scrubber facility, which would actively remove CO_2 from the atmosphere using what is known as the "Direct Air Capture (DAC)" method [229].
- **Production of Medical and Industrial Radio-Isotopes**
    - Similar to a nuclear fission reactor, fusion reactors generate radiation in the form of high-energy neutrons and X-Rays.
    - The neutrons and X-rays produced in a fusion reactor could be used to irradiate special target materials to generate different medical and industrial radio-isotopes, similar to how fission reactors and accelerators are used to produce such isotopes. Examples of such isotopes include Mo-99, Tc-99m, Co-60, I-125, I-131, and others [230], [231].
    - A private company in the United States, Phoenix Technologies, in cooperation with SHINE Medical Technologies, are working currently towards producing medical isotopes using a small-scale, fusion-based neutron source [232].
- **Production of Synthetic Low-Carbon Transportation Fuels**
    - As a source of electricity, high-temperature heat, and hydrogen, fusion power plants could be co-located with chemical manufacturing facilities, or existing refineries in the petrochemical and oil and gas industries for the production of synthetic low-carbon transportation fuels [233], [234], [235].

  - Examples of such low-carbon fuels include methanol, ethanol, di-methyl ether, propane, butane, ammonia and others. In particular, low-carbon liquid fuels such as methanol and ethanol could be used to replace gasoline, while dimethyl ether could be used to replace diesel fuel. Ammonia (NH_3) produced from such facilities could also be used as an artificial fertilizer, and its production from fusion energy would displace the current use of methane/natural gas for producing fertilizer.
  - Hydrogen and/or very high-temperature steam from a fusion power plant would be the primary energy input and material feedstock for making synthetic fuels.
  - The carbon feedstock for such fuels could be derived from atmospheric carbon dioxide, or harvested biomass (from forestry and agricultural activities), or from low-grade, high-carbon fossil fuels (coal, oil, shale, bitumen from oil sands).
  - Hence, fusion energy could be used to leverage, upgrade and improve existing high-carbon fossil and biomass fuels to practical, low-carbon transportation fuels, to replace the use of gasoline, diesel, and kerosene/jet fuels.
- **Production/Breeding of Fissile Nuclear Fuels from Fertile Nuclear Fuels**
  - As discussed in Section A.1.6, a low-performance ($Q \leq 1.0$) fusion reactor can be used as a fast neutron source in a hybrid fusion-fission reactor (HFFR) to breed fissile nuclear fuels (such as U-233 and Pu-239) from fertile nuclear fuels (such as Th-232 and U-238) by neutron bombardment and absorption.
  - In addition to breeding fuel, the HFFR will generate power through fission, depending on the multiplication factor (keff) of the sub-critical blanket surrounding the fusion reactor core.
  - The HFFR as a fissile fuel breeder can be considered an alternative option, or a competitor to using a fast breeder reactor for breeding fuel. As mentioned previously, the HFFR has the advantage in that it has a greater support ratio, and could supply enough makeup fissile fuel to support the operation of 5 to 20 fission reactors [193]-[201]].
- **Transmutation/Destruction of Radioactive Waste**
  - Similar to a nuclear fission reactor, or an accelerator with a target for producing neutrons, fusion reactors generate radiation in the form of high-energy neutrons, and high-energy photons / X-Rays.
  - In a way that is similar to how fusion reactors can be used to produce medical or industrial isotopes by neutron or X-ray/photon bombardment of target materials, or similar to how fissile nuclear fuel can be bred from fertile nuclear fuel in a HFFR, the neutrons and photons/X-rays from a fusion reactor could be used to bombard a special targets containing various types of radioactive nuclear waste, to transmute or destroy radioactive isotopes.
  - This type of application helps reduce the amount of radioactive waste, and also the size and number of Deep Geological Repositories (DGRs) for the long-term

storage of radioactive waste, until such waste can decay to insignificant levels that are of no risk or danger to the environment.

- Examples of radioactive waste found in spent/used nuclear fuel include long-lived fission products (LLFPs) which remain highly radioactive for millions of years. For example, the LLFP isotope Tc-99 has a half-life of ~211,000 years, and it takes up to 3 million years to decay to relatively insignificant levels. Other type of radioactive nuclear waste include various minor actinides, such as isotopes of Neptunium (Np), Americium (Am), Curium (Cm), Berkelium (Bk) and Californium (Cf)). Some of these minor actinide isotopes can remain radioactive for thousands to millions of years. For example, the isotope Am-241 has a half-life of 432 years, and it takes up to 6,000 years to decay to relatively insignificant levels [236], [237], [238].
- By placing special irradiation targets containing LLFPs or minor actinides in the blanket region of a fusion reactor, it is possible to irradiate these targets with fusion-based neutrons, to cause transmutation of these isotopes into shorter-lived or stable isotopes, or to cause destruction by fission. Therefore, instead of being highly radioactive for thousands to millions of years, the target materials could be transmuted such that their radioactivity levels drop to relatively insignificant levels, in a matter of 100 years, or even just a few decades.
- For example, if the radioactive LLFP isotope Tc-99 is placed in a special irradiation target in the blanket of a fusion reactor, if the fast fusion neutrons entering the blanket are slowed down/thermalized, and if the neutron flux is on the order of 2.0×10^{14} neutrons/cm^2/s, then the concentration of Tc-99 could be reduced to 1/10,000 of its initial concentration within 100 years, rather than being radioactive for nearly 3 million years [236].
- Similarly, if the radioactive minor actinide isotope Am-241 (a common by-product found in spent nuclear fuel) was put into special irradiation targets in a fusion reactor blanket, its concentration could be reduced to 1/10,000 of its initial value by transmutation and/or destruction by fission within a period of 6 years, rather being radioactive for nearly 6,000 years.
- The use of a fusion reactor for transmuting and destroying radioactive nuclear waste (LLFP and MA isotopes) can be considered as an alternative technological option, in comparison to using thermal or fast-spectrum nuclear reactors, or using sub-critical accelerator-driven systems for transmuting/destroying LLFPs and MA's . See References [236] to [245], and [246] for more background information.

A.3 Canadian Experience and Expertise in Fusion Energy

A.3.1 Canadian Nuclear Laboratories (CNL)

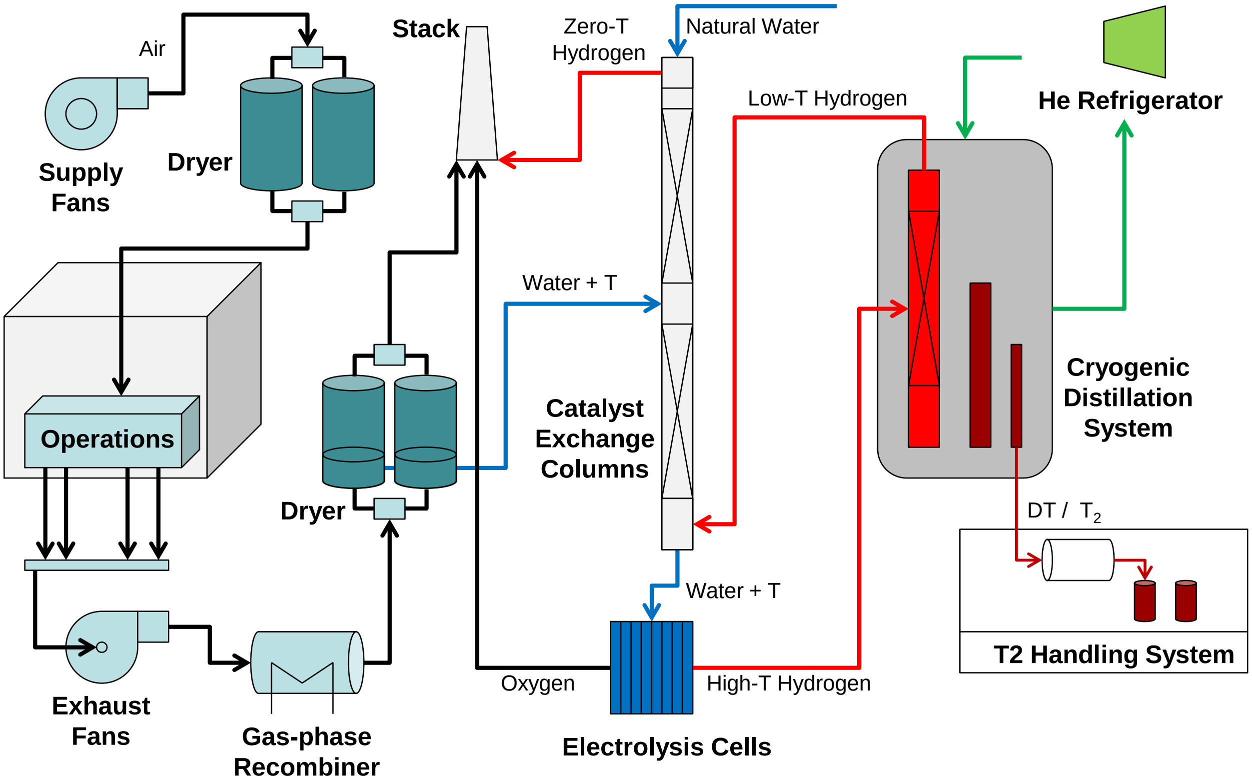
Scientific and technical staff at CNL's Tritium Facility executes research and development programs and commercial activities associated with tritium technology. The Tritium Facility commenced operations in 1979 and consisted primarily of an inert atmosphere glove box and associated supporting equipment (see Figure 58), but the scope of the laboratory expanded to the point where CNL opened a new Tritium Facility in 2019, with new office space, laboratories and equipment.

CNL capabilities and facilities include the following:

1. Expertise in hydrogen isotopes (hydrogen, deuterium and tritium), including production, storage and handling.
2. In 2019, CNL opened a specialized, licensed facility dedicated to handling tritium and tritiated water. The new $40M Tritium Facility is unique to Canada. It is licensed to contain 1 MCi (37 PBq) of tritium for use within the facility and an additional 2.5 MCi (92.5 PBq) in storage. There are three main laboratory spaces which contain: a tritium handling apparatus inside an inert atmosphere glove box (secondary enclosure) for tritium dispensing and loading operations, two additional inert atmosphere glove boxes for handling tritium in liquid or gaseous forms, several fume hoods and air-purged enclosures for experimental work as well as for maintenance activities, plus liquid scintillation counters, and several pieces of specialized experimental equipment.
3. Commercial work in the Tritium Facility includes assay and dispensing of high-purity tritium using the tritium handling apparatus in the inert atmosphere glove box as well as preparation of gas standards with customer-specified tritium content, carrier gas, cylinder size and pressure. Past commercial work has involved tritium immobilization and absorption in solids for targets for neutron generation.
4. Experimental research within CNL's Tritium Facility includes many research areas pertinent to fusion such as tritium-compatible materials for isotope separation, plus tritium concentration, recovery. Research is also conducted on tritium permeation barriers to prevent tritium diffusion through materials.
5. Range of methods for safe storage as elemental, water or organics, tritium compatible materials study and development.
6. Back in the 1990s, CNL performed research on extraction of tritium from breeder blankets based on lithium ceramics using an online tritium recovery and analysis system.
7. Helium-3 extraction (removal) and purification.
8. CNL is also involved in tritium education and offers a Tritium Safe Handling Course which combines in-class and laboratory training for the safe handling of tritium in the industry community of users.

In addition to the tritium-related strengths, other areas for expertise and support at CNL are available in the following areas:

1. Licensed nuclear fuel fabrication and testing facilities that could be adapted for research on fusion blanket materials and components.
2. Expertise and facilities for carrying computational and experimental thermal-hydraulic studies for components that are used on the primary or secondary side of a fusion power plant.
3. Expertise in computational neutronics and radiation transport modeling, which is relevant for modelling the neutron activation of system components, and blankets for breeding tritium or breeding fissile fuel in hybrid fusion-fission reactor concepts.



* Image provided courtesy of Hugh Boniface, Canadian Nuclear Laboratories

Figure 58: Diagram of Tritium Processing System at Canadian Nuclear Laboratories.

A.3.2 University of Saskatchewan – Plasma Physics Laboratory

The Plasma Physics Laboratory (PPL) at the University of Saskatchewan (USask-PPL) was established in 1959 by Dr. H. M. Skarsgard and early experimental work was centered on the study of electron acceleration in the Plasma Betatron. These early experiments led to the study of plasma turbulence and some of the earliest work on turbulent heating in toroidal geometry. Successful experiments in toroidal turbulent heating, which resulted in keV-level (>10,000,000 C) electron temperature, led to the construction of STOR-1M, Canada's first Tokamak experiment (1983) and was soon followed by a larger Tokamak, STOR-M (1987), which is still active and in use today. Both machines have been used to carry out unique experiments including turbulent heating, AC (alternating current) Tokamak operation, plasma biasing, anomalous transport, and Compact Torus (CT) injection. Currently the STOR-M is the only device in Canada devoted to magnetic fusion research. USask-PPL is a member of the IAEA-CRP (International Atomic Energy Agency - Collaborative Research Projects) for small fusion devices.

USask-PPL offers training of graduate students and post-doctoral fellows (PDFs) in broad programs of plasma science and plasma-assisted material science. Five comprehensive graduate level courses are available and experimental programs range from Tokamak physics to plasma assisted material synthesis, both in experiments and in theory.

The research contributions made by the faculty members are recognized internationally. USask-PPL has been funded by NSERC (Natural Sciences and Engineering Research Council of Canada) through Discovery Grants, Strategic Project Grants, and Research Tools and Instruments (RTI) Grants, and also through research grants from the Government of Saskatchewan, and the University of Saskatchewan.

Fusion Related Research Programs at USask-PPL

Experimental Studies in Magnetic Fusion

STOR-M Tokamak

The STOR-M Tokamak (see Figure 59) is a small-scale research Tokamak experiment designed and built at USask-PPL for studies on plasma heating, anomalous transport, and for developing novel Tokamak operation modes and advanced diagnostics. After the closure of Tokamak de Varennes (TdeV) at the University Quebec at Montreal in 1997, STOR-M became the only device in Canada devoted to magnetic fusion using the Tokamak concept.

The design and operational parameters of the STOR-M Tokamak are the following: Major radius: 46 cm	Electron density: 1.0 to 3.0×10^{13} electrons/cm^3
Minor radius: 2.5 cm	Electron temperature: ~ 200 eV (~1,600,000 °C)
Toroidal magnetic field: 0.5 to 1.0 Tesla	Confinement time: ~ 1 milli-seconds
Plasma current: 30 kA to 60 kA	

STOR-M is equipped with a sophisticated feedback control system for horizontal / vertical plasma positions, a driver for fast-rising Ohmic current, a circuit system for alternating current (AC) operation, Compact Torus Injector (CTI), injector of magnetized plasma flow, and various diagnostic instruments. An upgraded version of STOR-M (STOR-U) is under conceptual design analyses and development (see Figure 60).

In the following sub-sections, major experiments carried out with STOR-M and their impacts and contributions to Tokamak scientific research are described.

Alternating Current (AC) Tokamak Operation

Stable alternating current operation of a Tokamak was first demonstrated in STOR-1M (1987) and subsequently reproduced in STOR-M and the Joint European Torus (JET) in the United Kingdom at 2-MA currents. Genuine steady state Tokamak fusion reactors require non-Ohmic current drive. For example, injection of microwaves at the lower-hybrid resonance frequency (LHRF) is a well-developed approach and technology for non-inductive current drive. However, the power requirement for driving multi mega-ampere (MA) Tokamak currents is a significant fraction of reactor output, even if a large fraction of the toroidal current is self-generated as the bootstrap current. Inductive (Ohmic) current drive is highly efficient and not subject to plasma density limitation as radio-frequency (RF) wave current drive. The principal objective of the AC operation experiments carried out on STOR-1M and STOR-M Tokamaks is to demonstrate the feasibility of quasi-steady-state (rather than genuinely steady state) Tokamak reactors. Recently, 1.5-cycle AC operation has been achieved in STOR-M without the feared accumulation of impurities during the current reversal phases. This demonstration of AC-drive by USask-PPL in the STOR-M experiment is a significant accomplishment, and could have important implications for the practical use and operation of Tokamak-type fusion reactors.

Compact Torus Injection

Compact torus (CT) injection is an emerging new technology to fuel the core of Tokamak fusion reactors in the future. Fueling technologies currently available, such as cryogenic deuterium-tritium pellet injection, may not be adequate to fuel directly the core of reactors where most fusion reactions take place. The compact torus is a fully ionized, self-confined high density plasmoid (a plasma donut) and if accelerated to a velocity larger than the Alfven velocity, it will penetrate deep into a Tokamak discharge. The first non-disruptive CT injection has been demonstrated on Tokamak de Varennes (TdeV) using the Compact Toroid Fueller designed and fabricated in the Laboratory under a contract with the Canadian Fusion Fuels Technology Project. Subsequently, a smaller Compact Torus Injector was built with the funds provided by NSERC through the Strategic Program. It was installed on STOR-M in 1995. In addition to expected plasma fueling (increase in the plasma density), CT injection has been found to induce a phenomenon similar to the Ohmic H-mode (high confinement mode) discovered earlier on STOR-1M and STOR-M Tokamaks. Similar improved confinement after CT injection has been observed in other Tokamaks as well. Recently, toroidal momentum injection by CT has been directly confirmed by Doppler spectroscopy in STOR-M.

Ohmic H-Modes

H-mode is an improved confinement phase in Tokamaks over nominal (L-mode) confinement. In large Tokamaks with powerful supplementary heating, transition to H-mode occurs when the heating power exceeds a threshold. In STOR-1M and STOR-M Tokamaks, a unique heating method, turbulent heating, developed earlier in the USask-PPL for non-Tokamak toroidal devices, has been applied. After the current pulse, the plasma confinement time is tripled. This observation of Ohmic H-mode was made first on STOR-1M and later on STOR-M and other Tokamaks with various means including fast gas puffing and electrode biasing. The significance of the observation is in demonstrating that there is room for improved confinement even in Ohmic discharges. Concurrent with improved confinement, significant reduction of the fluctuations of plasma density and of magnetic fluctuations at the plasma edge have been observed. The plasma potential is lowered and an edge transport barrier develops. At present, the causality problem remains unresolved, that is, it is not clear plasma auto-biasing is a cause or result of improved confinement.

Resonant Magnetic Perturbation

Applying a steady, direct current (DC) magnetic field produced by helical coils having $m = 2$ and $n = 1$ structure has been observed to significantly affect the amplitude of magneto-hydro-dynamic (MHD) instabilities naturally present in normal plasma discharges in STOR-M. It has also been observed that the toroidal velocity of impurity ions changes significantly toward the co-current direction when RMP field is applied.

Advanced Plasma Diagnostics

Microwave reflectometry has been developed not only for measuring the amplitude of plasma density fluctuations but also for correlation length measurements which is an important quantity in estimating the anomalous plasma diffusivity. In the core region of STOR-M, plasma density fluctuation measurement based on scattering of 2 mm microwave is being conducted with emphasis on short wavelength modes driven by the electron temperature gradient (ETG mode). X-ray tomography for fast magnetic reconnection phenomena during CT injection is planned. Measurement of edge ion temperature in Tokamaks has been difficult because it is too low for the conventional ion temperature diagnostics. In the USask-PPL, a retarding field, bidirectional ion energy analyzer has been developed which allows measurement of electron temperature as well.

Theoretical and Computational Studies in Plasma Physics and Magnetic Fusion

Recent theoretical contributions by research staff at USask-PPL to magnetic fusion research include: (a) linear stability analyses of the kinetic ballooning mode, electromagnetic drift type mode and finite beta effects on those modes, (b) nonlinear saturation of drift type modes, (c) strong turbulence theory, and (d) Hall MHD. A common objective of these studies is to provide a better understanding of transport in Tokamaks which may ultimately lead to control of plasma instabilities and realization of more compact Tokamak reactors.

Studies of Plasma Immersion Ion Implantation (PIII) for Fusion Plasma-Facing Components

The research group of Professor Michael P. Bradley operates a Plasma Immersion Ion Implantation (PIII) system (the first of its kind in Canada), and the only one optimized for semiconductor and metal target processing. The PIII system is a unique plasma technology in which a high flux of energetic ions are implanted into a target immersed in a plasma.

High ion fluences (ions implanted per cm^2 of a target) can be implanted into broad-area targets in short times relative to conventional accelerator beamline ion implantation. This unique PIII machine has been used for radiation damage studies in a variety of materials including semiconductors as well as acousto-optic and electro-optic crystals.

Adjustable energy and precision dose control makes the PIII facility an excellent tool for studying materials for fusion reactor Plasma Facing Components (PFCs). The USask-PPL PIII system is currently being used to study ion bombardment damage under fusion-relevant conditions for ITER, in collaboration with a research group at Aix-Marseille University in France.

Samples of publications generated as result of work performed at the USask-PPL PIII facility include the following:

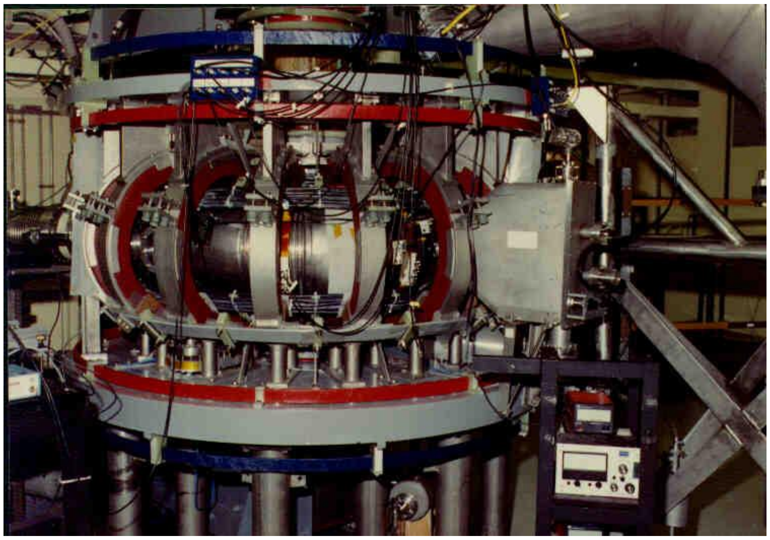
- M. Risch and M.P. Bradley, "Prospects for Band Gap Engineering by Plasma Ion Implantation", *Physica Status Solidi* (c) 6, S210-S213 (2009).
- P.R. Desautels, M.P. Bradley, J.T. Steenkamp, and J. Mantyka, "Electroluminescence in plasma ion implanted silicon", *Physics Stat. Sol.* (a) 206, 985-988 (2009).
- M. Risch and M. Bradley, "Predicted depth profiles for nitrogen-ion implantation into gallium arsenide", *Physics Stat. Sol.* (c) 5, 939-942 (2008).
- B.J. Taylor and M.P. Bradley, "Characterization of Hydrogen Ion Implantation Damage in Quartz, Lithium Niobate and Tellurium Dioxide by Raman Spectroscopy", *Radiation Effects and Defects in Solids*- accepted 12 Feb. 2021 (2021).
- B.J. Taylor, A.E. Bourassa, M.P. Bradley , "Charged particle radiation induced changes to optical properties of acousto-optic materials", *Applied Optics* 59, 3706-3713 (2020).

Faculty at USask-PPL

The following professors and research staff at USask-PPL contribute to experimental, theoretical and computational studies in plasma physics and fusion:

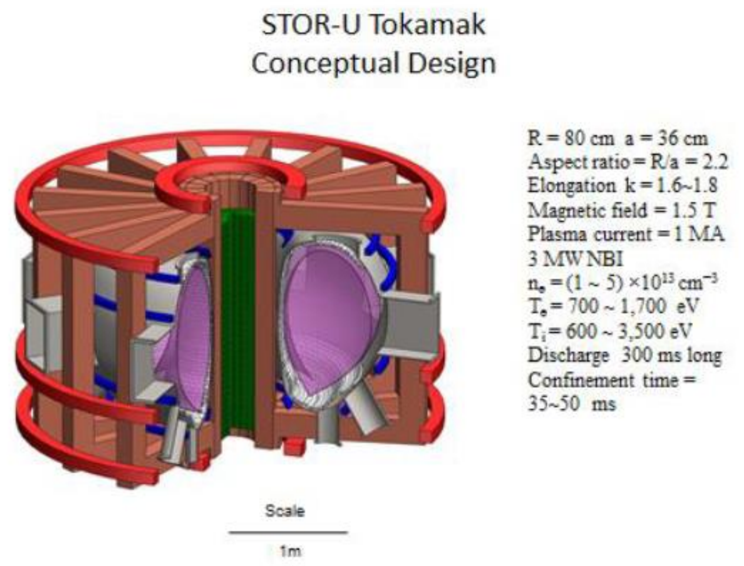
- Professor Michael P. Bradley (Ph.D., P.Eng.)
    - Ion implantation, photonics, mass standards
- Associate Professor Lenaic Couedel (Ph.D.)
    - Dust plasma studies, Dust dynamics in Tokamak
- Professor Andrei Smolyakov (Ph.D., P.Eng., FAPS)
    - Theoretical/computational plasma physics, nonlinear plasma dynamics
- Professor Chijin Xiao (Dr. rer. nat., P.Physics)
    - Magnetic fusion, plasma diagnostics, plasma materials synthesis

USask-PPL website: http://research-groups.usask.ca/plasma-physics



* Image provided courtesy and with permission of Professor Chijin Xiao, University of Saskatchewan

Figure 59: Photograph of STOR-M Experimental Tokamak Device at the University of Saskatchewan Plasma Physics Laboratory.



STOR-U Tokamak
Conceptual Design

$R = 80$ cm $a = 36$ cm
Aspect ratio = $R/a = 2.2$
Elongation $k = 1.6 \sim 1.8$
Magnetic field = 1.5 T
Plasma current = 1 MA
3 MW NBI
$n_e = (1 \sim 5) \times 10^{13}\ \text{cm}^{-3}$
$T_e = 700 \sim 1{,}700$ eV
$T_i = 600 \sim 3{,}500$ eV
Discharge 300 ms long
Confinement time =
35~50 ms

* Image provided courtesy and with permission of Professor Chijin Xiao, University of Saskatchewan

Figure 60: STOR-U Experimental Tokamak Device under Conceptual Design Development at the University of Saskatchewan Plasma Physics Laboratory.

A.3.3 University of Alberta Laser-Plasma Group

The laser-plasma group at the University of Alberta is the leading laser-based inertial confinement fusion (L-ICF) research group in Canada. It has been actively involved in laser fusion related studies since the 1970's when the first 500-Joule, 100 nanosecond carbon dioxide laser system was built in the Department of Electrical Engineering for investigating laser heated solenoids. It was followed by short pulse nanosecond Carbon Dioxide lasers and a world leading (at that time) Ultraviolet Krypton Fluoride laser system which was pulse compressed to below one nanosecond using advanced nonlinear optical pulse compression techniques. This system was subsequently converted into a femtosecond laser via injection of up-converted titanium/sapphire laser pulses.

At the same time, a theoretical group was established in the Department of Physics, with links to all the major international laser fusion projects in the world and hosting international workshops in the Banff Centre. Members of the laser plasma group at the University of Alberta are actively collaborating with most of the major international groups and facilities in laser fusion. They also maintain smaller scale experimental facilities in order to investigate aspects of laser-plasma interaction science and to develop advanced diagnostics for collaborative experiments on major facilities around the world.

The members of the group are currently active in most areas of importance to laser fusion development from theoretical modeling to large scale numerical simulations, in advanced optical, x-ray and particle diagnostic development, in laser development and in collaborative investigations of laser-plasma instabilities, properties of high energy density plasmas, magnetic field generation, efficient energetic electron generation, plasma hydrodynamics and thermal transport in high temperature plasmas.

The group is also active at the leading edge of ultra-short high-intensity laser-plasma interactions which is both relevant to fusion and also opening up a whole new area of applications such as advanced particle accelerators, advanced MeV particle and gamma ray inspection techniques for industrial applications and medical isotope production.

Current experimental research facilities at the University of Alberta include a variety of laser systems at the joule level and less including nanosecond Krypton Fluoride lasers, nanosecond Nd:Yag lasers and harmonics, picosecond Yb:YAG laser and femtosecond Ti:Sapphire lasers.

A new high power, 15TW laser will be installed in 2021. A number of vacuum chambers are available for carrying out high intensity laser-plasma experiments. In addition, numerous diagnostic capabilities have been developed for both in-house use and for collaborative experiments in high power and high energy international laser user facilities. These diagnostic tools include: UV/visible streak cameras, an x-ray streak camera, gated intensified spectrometers, X-ray Bragg crystal spectrographs and Bragg imager systems, X-ray diode and scintillator detectors, X-ray CCD cameras, Faraday cups for time of flight measurements, magnetic particle energy spectrometers and multichannel hard x-ray, Bremsstrahlung emission detectors.

The group has access to a variety of radioisotope sources, a micro x-ray source and a pulse height radiation counter for diagnostic development and calibration.

The theoretical and computational investigations are supported by the availability of small cluster computer systems within the University of Alberta research groups for small scale computations and program development and access to the Canadian Compute Canada high power computer network for parallel processing jobs accessing up to several thousand CPUs for a computational run.

The following gives brief synopses of the active research areas of the current group members relevant to laser fusion energy.

Robert Fedosejevs (Professor, Department of Electrical and Computer Engineering):

- Robert Fedosejevs has pursued laser fusion related studies throughout his career since his PhD research into Ponderomotive steepening of laser-plasma profiles due to light pressure. He is actively involved in a number of laser fusion related investigations. He currently is developing a 1 TerraWatt prototype laser driver system for laser fusion applications and a new 15 TW femtosecond laser system for laser fusion and high intensity interaction studies. He currently is collaborating on studies of proton and electron generation for fast ignition at CLPU Spain and in the recent past at the Titan Laser facility of LLNL.
- He also is involved in studies of magnetic field generation for guiding of Fast Ignition electrons at the LULI facility in Paris and studies of laser-plasma instabilities relevant to Shock Ignition at the PALS laser facility in Prague. He is internationally recognized for his experimental expertise in these areas.

Richard Sydora (Professor, Department of Physics)

- Professor Sydora’s research spans a wide range of areas in plasma science that includes theoretical and computational studies of turbulence, transport, heating and energy conversion processes in magnetically-confined, laser-produced and space/astrophysical plasmas. These studies include development and application of advanced kinetic plasma simulation models to investigate nonlinear phenomena in magnetic reconnection, collision-less shocks, and particle acceleration in laser pulses and plasma waves.
- Since 2015, Professor Sydora’s research group has been modeling several key experiments, in addition to leading an experiment, on the Large Plasma Device (LAPD) at the Basic Plasma Science Facility (BaPSF), at the University of California at Los Angeles (UCLA), involving energy and particle transport in filamentary plasma structures and magnetic flux ropes, as well as parametric processes associated with Alfven waves.
- Professor Sydora is also carrying out modeling studies of plasmas used in industrial applications, such as pulsed power arc discharges in gases and liquids. In addition, he collaborates with researchers at the University of California, Irvine (UCI) and University of Strasbourg, France on topics related to the design of laser-based transmutation devices for treatment (destruction) of radioactive isotopes found in spent nuclear fuel.

Ying Y. Tsui (Professor, Department of Electrical and Computer Engineering):

- Ying Tsui is carrying out research to better understand the behavior of matter under extreme conditions, including Warm Dense Matter and High Energy Density Plasma using various ultrafast pump-probe techniques. He is collaborating on studies on the generation of high-repetition rate pulsed proton, ion, and neutron beams with multi-MeV energies using terawatt and petawatt lasers.
- He has also studied pre-pulse, pre-plasma and electromagnetic pulse effects from petawatt lasers. These research studies are important for inertial confinement fusion and fusion reactor materials applications.

Jason F. Myatt, (Professor, Department of Electrical and Computer Engineering)

- Jason Myatt has over 20 years' of experience in a range of topics that include: high-performance computing and the numerical simulation of plasmas, high intensity laser-matter interactions, high-energy-density physics, and laser-plasma interactions in the context of inertial confinement fusion (ICF), hard x-ray and secondary particle production. Formerly the Plasma Physics Group Leader at the Laboratory for Laser Energetics (LLE) at the University of Rochester, in Rochester, NY. He has been responsible for many experiments on the OMEGA laser at the LLE and the National Ignition Facility (NIF), the world's most powerful laser, located at the Lawrence Livermore National Laboratory (LLNL) in the United States.
- Dr. Myatt led the development of the *Laser Plasma Simulation Environment* (*LPSE*) simulation code system that is now used by several universities and laboratories around the world to understand and control laser-plasma instabilities. Dr. Myatt has authored over 100 peer-reviewed scientific papers and is a frequent invited speaker at the annual meeting of the American Physical Society, division of plasma physics. He is an associate editor (one of 5) for the American Institute of Physics journal *Physics of Plasmas* and is active in various review panels – these include the National Science Foundation (NSF), the U.S. Department of Energy (DOE), and LLNL's Computing Grand Challenge awards.

Amina E. Hussein (Assistant Professor, Department of Electrical and Computer Engineering)

- Amina E. Hussein leads an experimental research group studying laser-driven compact radiation sources and the characterization of novel states of matter produced through intense laser-matter interactions. She has led research on electron acceleration and associated hard X-ray generation using ultrashort (picosecond and femtosecond duration) pulses, relevant to radiography of inertial confinement fusion conditions and high-resolution X-ray probing of advanced materials.
- She has also led and conducted experiments performing high-resolution X-ray spectroscopy of non-equilibrium matter using the ALEPH laser at Colorado State University, ion stopping in magnetized plasmas using the ELFIE laser at the LULI facility in Paris, high-resolution X-ray imaging of metallic alloys using the Gemini laser in the UK, and numerous compact electron accelerator experiments on the HERCULES laser system at the University of Michigan. She will collaborate on particle acceleration and radiation

production experiments using the upcoming 15-Watt femtosecond laser system at the University of Alberta.

Wojciech Rozmus (Professor, Department of Physics):

- In the context of laser-based inertial confinement fusion (L-ICF), Professor Wojciech Rozmus has been involved over the years in theoretical and numerical studies of particle transport, plasma fluctuations and Thomson scattering, and laser plasma instabilities. Since 2018 he has been a consultant to the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL). He is a principle investigator (PI) on the NIF experiment funded through the Discovery Science program in LLNL and design to investigate bow shock in the large scale plasma flow across NIF laser beams.
- He has been a collaborator on the NIF laboratory astrophysics campaigns related to interpenetrating plasmas and collisionless shock formation. In addition to LLNL he collaborates on research topics related to ICF with groups from Laboratory for Laser Energetics, University of Rochester, Ecole Polytechnique and CEA, France and SLAC, Stanford University. He is a fellow of the American Physical Society.

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IMAGE REMOVED / REDACTED

* Image provided courtesy of Professor Robert Fedosejevs, University of Alberta

Figure 61: Illustration of Titan PetaWatt Laser Facility at Lawrence Livermore National Laboratory (LLNL) where Laser-Plasma-Target Interaction Experiments have been Modeled by Faculty from the University of Alberta (from References [8], [57]).

A.3.4 University of Toronto Institute for Aerospace Studies (UTIAS)

Fusion research at the University of Toronto grew out of the upper atmospheric and rocket re-entry work at the Institute for Aerospace Studies (UTIAS) in the 1950s and 1960s. The current focus on plasma-surface interactions for fusion applications began in the late 1970s.

Key individuals leading fusion-related research at UTIAS include Professor Jim W. Davis, and Professor Emeritus Peter Stangeby.

Research activities fall into two main categories:

1) Tokamak edge plasma physics and computational modelling
2) Experimental first wall material studies

The United States Fusion Energy Science Advisory Committee (US-FESAC), which is responsible for advising the United States Department of Energy's Office of Science, has recently released a report "*Powering the Future: Fusion and Plasmas*", a 10-year vision for fusion energy and plasma science, and is available at the following website address:

- https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/DRAFT_Fusion_and_Plasmas_Report_120420.pdf?la=en

The US-FESAC report makes the following explicit recommendation:

- *"The Fusion Science and Technology area should focus on establishing the scientific and technical basis for a fusion pilot plant by the 2040s:*
  - *Sustain a burning plasma. – Build the science and technology required to confine and sustain a burning plasma.*
  - *Engineer for extreme conditions. – Develop the materials required to withstand the extreme environment of a fusion reactor.*
  - *Harness fusion power. – Engineer the technologies required to breed fusion fuel and to generate electricity in a fusion pilot plant by the 2040s."*

The areas of fusion research at UTIAS fall directly within the second of these high-priority research topics.

The focus of the experimental materials work at UTIAS has been to investigate the complexities of multi-species bombardment of proposed plasma-facing materials. Topics include: material erosion, tritium trapping and transport, and co-deposited materials. Materials being studied include tungsten, carbon and silicon carbide. UTIAS laboratory facilities include high-flux, low-energy particle accelerators which allow the simulation of some of the particle-materials interactions processes occurring in Tokamak-type reactors, and potentially other types of fusion reactors.

The Tokamak edge physics work involves the investigation of the effects of impurities created by plasma-material interactions on the edge plasma. The computational physics simulation code developed at UTIAS, DIVIMP (DIVertor IMPurity), is a plasma transport code that is used throughout the international community for modeling many different Tokamak experimental facilities (ITER, JET, DIII-D, ASDEX-Upgrade, EAST, and others). There are over 634 citations on the use of the DIVIMP code, according to Google Scholar. The DIVIMP codes is used to model and predict the transport of impurity species (i.e., non-hydrogenic) in Tokamak edge plasmas. In addition, UTIAS has also developed the computational physics simulation code OEDGE, which is used for interpretive modeling of edge experiments in Tokamak facilities throughout the international community, to help identify the controlling physics of the edge plasma. Similarly, the OEDGE code is widely cited, with over 518 citations, according to Google Scholar.

Fusion-related research at UTIAS over the last 20-plus years (since 1999), including Tokamak edge plasma physics and computational modelling work, has been funded primarily by contracts or sub-contracts with the United States Department of Energy (US-DOE) through General Atomics (1999-2017) and Oak Ridge National Laboratory (2017-2022). Experimental fusion-related work at UTIAS has received support from NSERC (Natural Sciences and Engineering Research Council of Canada) Discovery grants and other funding programs.

Extensive and substantial computational modeling work has been carried out by UTIAS researchers for the D-IIID Tokamak experimental facility at General Atomics in San Diego, California, United Sates (see Figure 62, Figure 63, and Figure 64).

More details and information about fusion research activities at UTIAS can be found at the following website:

https://www.utias.utoronto.ca/research-and-centres/fusion-energy-plasma-materials-interactions/

IMAGE REMOVED / REDACTED

* Image downloaded from https://fusion.gat.com/

Figure 62: Illustration of General Atomics DIII-D Tokamak Experimental Facility.

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* Image downloaded from https://fusion.gat.com/

Figure 63: Illustration of Inside Plasma Chamber of General Atomics DIII-D Tokamak Experimental Facility.

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* Images provided courtesy of Professor J.W. Davis, University of Toronto

Figure 64: Simulation of Particle Transport in Tokamak Using Computational Tools OEDGE and DIVIMP Developed at UTIAS (from Reference [42]).

A.3.5 Ontario Tech University (OnTechU)

A small research group dedicated to applied plasma physics research and the investigation of fusion energy technologies has been in existence at Ontario Tech University (formerly University of Ontario Institute of Technology, UOIT), in the Faculty of Energy Systems and Nuclear Science since 2010. Work within the Advanced Plasma Engineering Laboratory (APEL) is being led by Professor Hossam Gaber (https://faculty.ontariotechu.ca/gaber/).

Currently, Professor Hossam and his team of colleagues, post-doctoral fellows, graduate students, and collaborative partners at other institutions have been working on investigating the Dense Plasma Focus (DPF) alternative concept for fusion. (https://faculty.ontariotechu.ca/gaber/ESCL-APEL-Newsletter.pdf)

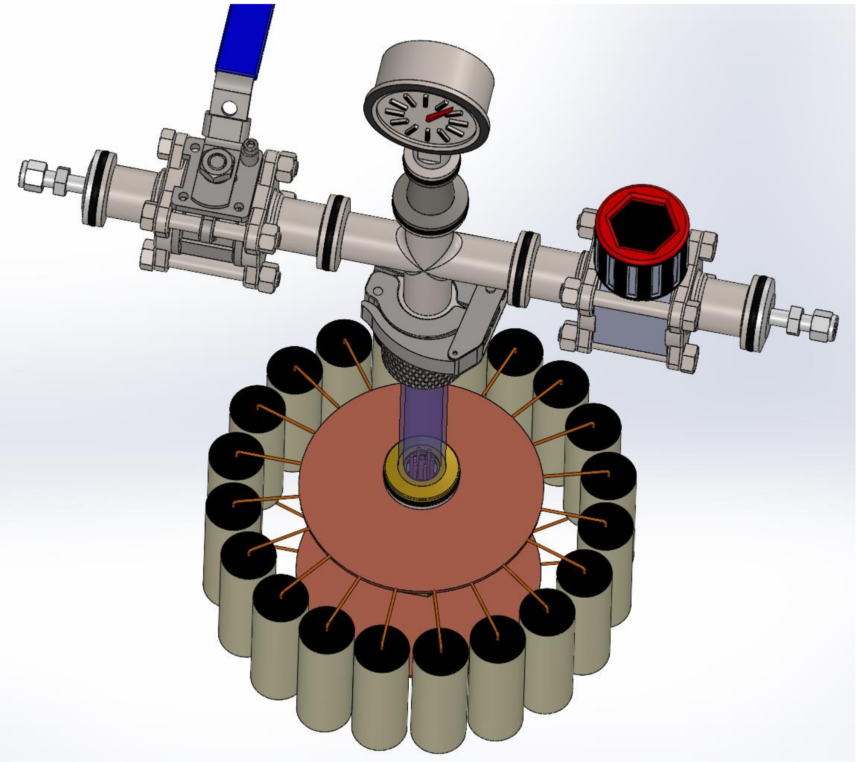
The following is a more detailed description of the project they are working on:

APEL Miniature Dense Plasma Focus Device (miniPF)

- Principle Investigator: Professor Hossam Gaber (OnTechU).
- Research Team: Dr. Vahid Damideh.
- Collaborator: Dr. Sing Lee (Institute for Plasma Focus Studies, Melbourne, Australia)
- The dense plasma focus (DPF) is a pulsed device and apparatus for generating plasmas at high temperature and high density. It operates with an axial phase followed by a radial compression leading to an intense pinch phase. Copious multi-radiations including x-rays and ion/electron beams are emitted from the pinch. When operated with deuterium gas filling, nuclear fusion occurs at more than 10,000,000 °C (> 1.3 keV) temperature and 2.45-MeV neutrons produced from D-D fusion reactions are emitted.
- Applications include use of the dense plasma focus pinch as a source of intense pulsed x-rays when operated in a noble gas such as Argon, Krypton, Xenon, and use as a source of high-energy neutrons for irradiation purposes when operated in pure deuterium

(producing 2.45-MeV neutrons) or a deuterium-tritium mixture (producing 14.1-MeV neutrons) for enhanced neutron production. The plasma focus may be scaled up for development as a plasma fusion energy device or scaled down as a small device for the purpose of plasma nuclear fusion energy research and education.

- Education in applied plasma physics and fusion energy is important, as the world moves towards an imminent era of the application of nuclear fusion reactors for producing energy. Central to the implementation of nuclear fusion energy education is the availability of a simple, low-cost, efficient, and portable nuclear fusion device. The dense plasma focus is such a device.
- The dense plasma focus under development in the APEL at OnTechU (as illustrated below in Figure 65) has several design and operational parameters. The total stray inductance (termed static inductance) of the miniPF apparatus is 40 nH, and is reduced compared to the value of 75 nH of the present-generation plasma focus using a single metal can capacitor. The miniPF operating voltage can be increased to 10 kV. The reduced stray inductance and higher operating voltage improves the peak discharge electric current amplitude of the paralleled film capacitor to a value of 70 kA from that of the comparable present day plasma focus of 51 kA. It is estimated that the neutron yield scales as current to the power of 4 ($Yn \propto I^4$). Hence, if the current can be increased by a factor of ~1.37, the total fusion neutron yield could be increased by a factor of ~ $(1.37)^4$ ~ 3.6. This increase factor is similar for other forms of radiations from the plasma focus. For research and for education demonstration this increase factor is significant and substantial, resulting in neutron yield of 1.5×10^4 neutrons per shot (10 kV at 12 Torr Deuterium) and 10^{12} neutrons per second peak rate during pulse time.
- The DPF fusion device has a multitude of research and practical industrial applications beyond fusion, including the following:
  - Neutron Source / Proton Source / Electron Source
  - Ultra-Fast Hard X Ray Source / Ultra-Fast Soft X Ray source
  - SLR for Medical Applications (PET, ^{13}N, ^{18}F, …)
  - Microelectronics Lithography / Surface Micromachining
  - Security Inspections (Detection of Explosive Materials)
  - Material Sciences, Nuclear Diagnostics,
  - Education (Pulsed Power and Plasma Fusion Engineering)



* Image provided courtesy and with permission of Professor Hossam Gaber, Ontario Tech University.

Figure 65: Illustration of Dense Plasma Focus (DPF) Fusion Device under Development at Ontario Tech University by Professor Hossam Gaber and Co-Workers.

A.3.6 Queen’s University, Kingston, Ontario

Fusion research at Queen’s University has focused on Tokamak diagnostics and on the use of compact toroids (CTs) as a means of refuelling steady state Tokamak discharges (such as that expected in ITER) and also as an alternative fusion reactor concept in their own right (similar to that found in the General Fusion magnetized target fusion approach, and others).

The Queen’s University fusion research group is headed by Professor Jordan Morelli in the Department of Physics, and is part of the Applied Magnetics research program which includes research into non-destructive evaluation techniques such as pulsed eddy current inspection and magnetic Barkhausen noise inspection, as well as research into electromagnetic propulsion technology such as linear induction motors.

Diagnostics on STOR-M at U. Saskatchewan and FAT-CM at Nihon University

In collaboration with the Plasma Physics Laboratory at the University of Saskatchewan (USask-PPL), members of the Queen’s University fusion research group have developed a multi-chord soft x-ray detection array for the PPL STOR-M Tokamak experiment.

In partnership with the Plasma Physics Laboratory at Nihon University in Japan, the Queen's University fusion research group has been developing a novel Langmuir probe array, the 'skewered' probe, for radial potential profile monitoring in the FAT-CM device, a type of field reversed configuration (FRC) fusion device.

Compact Torus (CT) Injection Modelling

Beginning in 2007 with the work of Geoff Olynyk, the Queen's University fusion research group has been modelling the magnetic reconnection event that occurs when a compact torus (or toroid) is injected into a Tokamak and the two plasmas merge together at a magnetic reconnection event. A proposed design was developed for using a CT injector to refuel the ITER Tokamak during its steady-state operation. This model has been refined over the years, and a focus on the magnetic reconnection event itself has been carried out more recently.

Spheromak and Field Reversed Configuration (FRC) as reactor concepts:

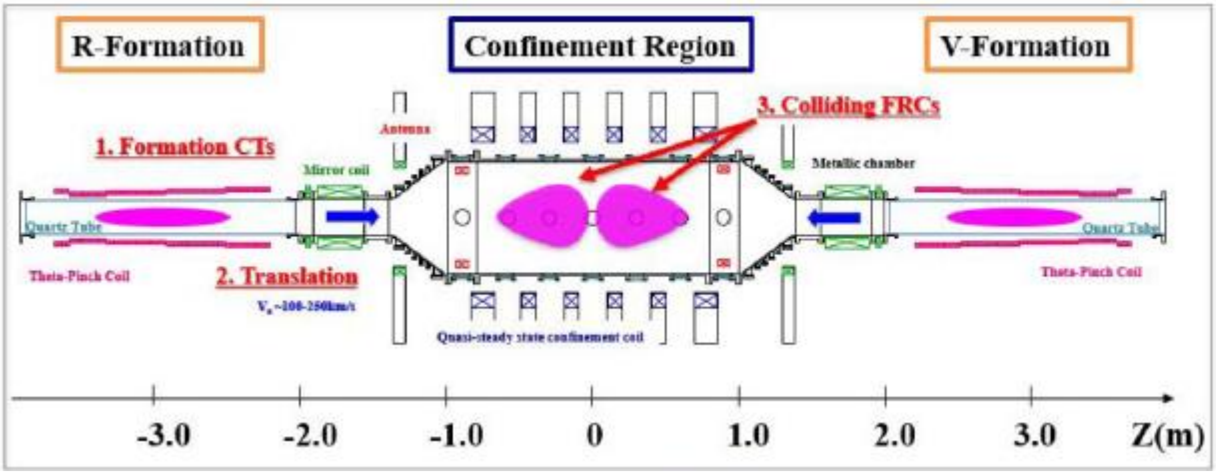
The two main types of compact tori are the spheromak and the Field Reversed Configuration (FRC). A spheromak has mainly poloidal magnetic fields at its edges and a mainly toroidal magnetic field along is centre, whereas the FRC in contrast has no toroidal field.

The FRC, like that in the FAT-CM (FRC Amplification via Translation – Collisional Merging) device at Nihon University (see Figure 66), is typically formed by the field-reversed theta pinch. The resulting FRC can be confined in an open-ended magnetic mirror style system. If the confined FRC or spheromak can be accelerated and linearly translated, then it may be accelerated to high speed and made to collide with another FRC or spheromak. The two colliding compact toroids merge together into a quickly relaxed state. The kinetic energy of the individual CTs prior to their merging is converted into thermal energy within the merged CT. If this merged CT can then be compressed further, then the conditions necessary for fusion reactions to occur may be obtained. This approach is similar to what is being proposed at General Fusion and at Tri-Alpha Energy (TAE) among other private companies that are vying to develop alternate fusion reactor concepts commercially.

Through a recent collaboration with the Plasma Physics group at Nihon University, the Queen's group is developing modelling capabilities using Comsol® to model the magnetic field configurations of the FAT-CM.

Sample publications relevant to fusion-related research work performed by academic staff at Queen's University includes the following:

- C. Xiao, T. Niu*, **J.E. Morelli**, C. Paz-Soldan*, M. Dreval*, S. Elgriw*, A. Pant*, D. Rohraff*, D. Trembach*, and A. Hirose, "Design and Initial Operation of Multichord Soft X-Ray Detection Arrays on the STOR-M Tokamak", *Review of Scientific Instruments*, Volume 79, November, 2008.
- Geoff Olynyk*, **Jordan Morelli**, "Development of a Compact Toroid Fuelling System for ITER", *Nuclear Fusion*, Volume 48, September 2008



* Image provided courtesy and with permission of Professor Jordan Morelli, Queen's University, Kingston, Ontario

Figure 66: Illustration of FAT-CM (Field-Reversed Configuration Amplification via Translation – Collisional Merging) Fusion Plasma Confinement Device at Nihon University in Japan.

A.3.7 General Fusion (Burnaby, British Columbia)

General Fusion (https://generalfusion.com/) is a private-sector fusion company based in Burnaby, British Columbia, and was founded in 2002 by Dr. Michel Laberge. General Fusion now has over 75 employees, and is focused on building a practical, commercially viable alternative path to fusion energy, based on the alternative fusion concept of acoustically-driven magnetized target fusion (MTF), which is also known as magneto-inertial confinement fusion (MICF).

General Fusion has become a world leader in MTF/MICF technology. General Fusion's R&D team includes over 50 scientists, engineers, and technicians, including 12 with PhDs in physics and engineering, and trains many co-op students (up to 13 at a time). The expertise at General Fusion covers plasma physics theory and simulation, magnetized plasma experimentation and diagnostics systems, mechanical and electrical engineering, materials, control systems, pulsed power and fluid dynamics. They operate world class compact toroid sources (Figure 67), a pulsed plasma compression program, the largest pulsed power facility in Canada, a flowing lead power plant technology platform and a 256 node computer cluster. This is the second largest privately-funded fusion science research program in the world.

Since 2014, General Fusion has invested over $350,000 in university researchers and students, leveraging federal programs to result in over $500,000 in funding. Universities and institutions involved with these collaborations include the University of Saskatchewan, Simon Fraser University, McGill University, University of Sherbrooke, TRIUMF (BC), Princeton University (in NJ, U.S.A.) and Queen Mary University (London, UK). Other formal and informal research collaborations involved professors and scientists at Queen's University (General Fusion sponsored a PhD student who has since joined General Fusion as a research scientist), Los

Alamos National Laboratory (LANL, in Los Alamos, NM, U.S.A.), Defence Research and Development Canada (DRDC), Lawrence Livermore National Laboratory (LLNL in Livermore, CA, U.S.A.), the University of Washington, and Massachusetts Institute of Technology (MIT, in Cambridge, MA, U.S.A.).

In 2019, General Fusion was awarded a grant from the Government of Canada through a Strategic Innovation Fund (SIF) program under the Ministry of Innovation, Science and Economic Development (https://www.ic.gc.ca/eic/site/125.nsf/eng/home) to support the development of the General Fusion MTF/MICF prototype device, as shown in Figure 68. This project is funded to CAD $49.3 million payable over 4 years (see Figure 69). The efforts by General Fusion have caught the attention of the Federal Government of Canada, resulting in a visit by the Prime Minister of Canada in 2016 (See Figure 70).

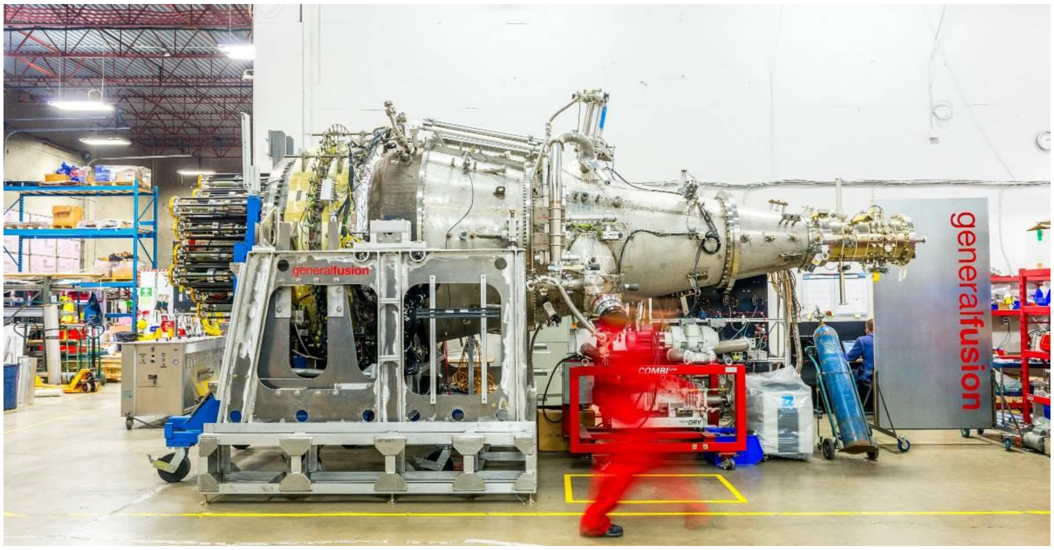


Figure 67: Plasma Injector at General Fusion for the MTF project (from References [6], [7], [99]).

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* Note: the “pink donut” is the lead-lithium blanket being used to compress the magnetized plasma target.

Figure 68: Artistic Illustration of the General Fusion Acoustically-Driven Magnetized Target Fusion Reactor Concept (from Reference [103]).

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* SDTC: Sustainable Development Technology Canada (https://www.sdtc.ca/en/)

Figure 69: The General Fusion Prototype Demonstration Program Supported by the Government of Canada's Strategic Innovation Fund (SIF) over the Period of 2019-2024 (from Reference [103]).

Figure 70: Canadian Prime Minister J.P. Trudeau visiting General Fusion in 2016 (from References [6], [7]).

A.3.8 HOPE Innovations (Mississauga, Ontario)

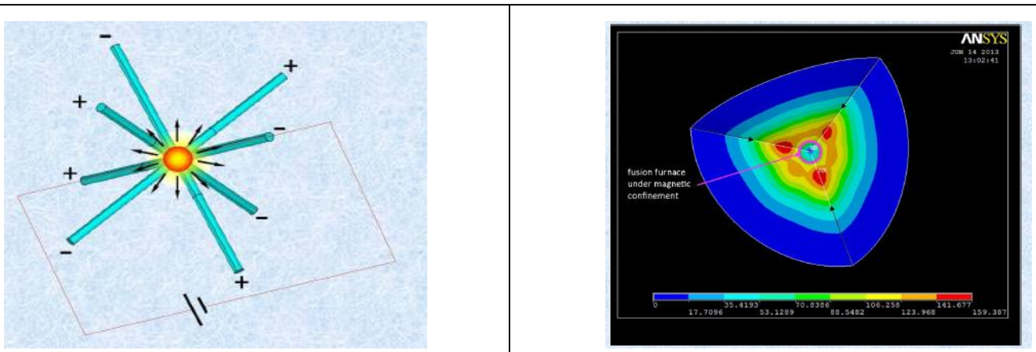
HOPE Innovations is a small, private start-up fusion company established in 2011. HOPE Innovations is investigating an alternative fusion concept based plasma confinement through the intersection of high-current discharges through a deuterium plasma. It is predicted that certain configurations could stabilize the plasma beams against the onset of certain instabilities that have historically challenged fusion plasma confinement via the use of more conventional Z-Pinch devices. Efforts to test theories and validate predictions through experimental demonstrations and measurements have been progressing at Sichuan University (SCU) in Chengdu, China with financial support from the Shanghai Hong Peng Energy Research Company. Evidence for one of the theoretical predictions, for compression and acceleration of ions, was recently reported in the following journal publication:

- X.J. Zheng, *et. al.*, 2019 *Plasma Physics Controlled Fusion* 61 105003, "A pulsed high-current plasma beam under external and self-induced magnetic confinement in a linear device", https://doi.org/10.1088/1361-6587/ab3618

Mr. Andrew Wallace joined HOPE Innovation in 2012, and is currently serving as its CEO. Mr. Wallace, who has over 30 years of experience in the Canadian nuclear industry, is engaged currently in restructuring the company. He has established a small research facility in Etobicoke, Ontario where he is producing deuterated test samples for use in the next round of experiments at SCU, as described in the following paper:

- X.J. Zheng *et. al*. 2021 *Plasma Physics Controlled Fusion* 63 035019, “Enhanced density in a stabilized high-current plasma beam”, https://dx.doi.org/10.1088/1361-6587/abd303

In the longer term, HOPE Innovations intends to establish an independent research stream in Canada and to investigate other dense plasma phenomena, and fusion plasma confinement approaches that are similar to the use of intersecting high-current plasma beams. Several Canadian and Chinese patents arising from the work have been granted or are pending.



(a) Intersection of High-Current Plasma Beams for Magnetic Confinement

(b) Simulation Prediction of Plasma Properties with Beam Intersections

* Images provided courtesy and with permission of Andrew Wallace and Henry Zheng, HOPE Innovations.

Figure 71: Illustration of the HOPE Innovations Fusion Concept Using Intersecting High-Current Plasma Beams.

A.3.9 Fuse Energy Technologies (Napierville, Quebec)

Fuse Energy Technologies (https://www.f.energy/) (FET, or “Fuse”) is a small and relatively new start-up company based in Napierville, Quebec (near Montreal), and was established in 2018. The objective of Fuse is to investigate and develop alternative plasma confinement / fusion reactor technologies based on one or more of the following fusion reactor concepts:

- Flow-through Z-pinch
- Compact Ultra Low Aspect Ratio Tokamak
- Reversed Field Pinch (RFP)
- Plasma Centrifuge Heat Engine (Rotating Magnetic Mirror)
- Magnetic Mirror/Gas Dynamic Trap (MM/GDP)
- Virtual Cathode Polywell / Magneto-Electrostatic Confinement Device

Fuse is presently evaluating the possibility of using a flow-through Z-pinch as the core for a fusion reactor. Fuse will be using a new method to sustain and control the Flow-through Z-pinch. They are presently in the construction phase of the device. This device should be operational early in 2021. It is expected that Fuse will obtain results similar to those seen at the University of Washington with a similar Z-Pinch device, and then increase the fusion reaction yields and efficiency of the device. Modified fusion reactor designs for potential alternative applications, such as medical radio-isotope production, are being investigated. An alternative fusion device concept is also in the design phase.

In terms of scientific and technical progress, FET has the following recent and upcoming milestones in relation to its Flow-Through Z-Pinch Fusion Concept:

- First plasma in device achieved by the end of 2019.
- First fusion plasma confinement experiments to be carried out in 2021, ideally using deuterium fuel, and including measurement of fusion-generated neutrons.

In terms of technological readiness level (TRL), the flow-through Z-Pinch fusion concept being investigated by Fuse is expected to have a TRL of Level 4. It is also anticipated that the components of the Z-Pinch concept should be relatively easy to manufacture.

IMAGE REMOVED / REDACTED	IMAGE REMOVED / REDACTED
a) Flow-Through Z-Pinch Experiment	b) Electron/Ion Densification in Z-Pinch

* Images provided courtesy of Fuse Technologies

Figure 72: Illustration of Flow-Through Z-Pinch Fusion Device under Investigation by Fuse Energy Technologies.

A.3.10 Plasmionique (Varennes/Montreal, Quebec)

Plasmionique (https://www.plasmionique.com/) is a small plasma technology company based outside of Montreal, in Varennes, Quebec. Plasmionique was incorporated in Quebec, Canada in 1999. A number of the current staff and many early staff of Plasmionique were members of scientists team of the Tokamak de Varennes (TdeV) fusion project in association with Hydro Quebec and the Institute National de la Recherche Scientific-Enrgie et Matériaux, INRS-EM (now INRS-EMT) during the period of 1985 to 1997, during the early phase of Canada’s national fusion program (NFP).

The mission of Plasmionique is to proliferate and commercialize plasma technology as an environmentally clean substitute for many challenging problems in Advanced Surface Engineering, Material Synthesis, and Thin Film Processing.

Plasmionique is a company driven and nurtured by extensive internal and collaborative research and development activities. The company has access to one of Canada's most advanced research infrastructures, being located on the site of INRS-EMT, including the Advanced Laser Light Source (ALLS) facility and Material Characterization laboratories.

Plasmionique's R&D is related to the development of environmentally friendly Advanced Surface Engineering Processes related to a variety of applications, including Biomaterials, Surface Modification, Hydrophobicity and Nanomaterials Synthesis. Over the last two decades, the company had maintained active collaborative research with the Plasma Fusion group in the University of Saskatchewan on topics related to Compact Toroid Injector, and study of Plasma Turbulence. The company also had consulting contracts with ENEA in Frascatti, Italy for integration of a diagnostic neutral beam injector; developed a scanning plasma edge probe for Tore-Supra Tokamak in collaboration with plasma edge group, and a scanning a retarding field analyzer for ASDEX-Upgrade Tokamak in Germany.

Since 1999, Plasmionique has designed and built customized plasma, laser, and vacuum-based systems for variety of University, governmental and industrial research groups, in Canada, US, Europe, Asia, Australia and New Zealand. These systems have utilized various methods for thin-film deposition, ion-implantation, etching, and advanced materials synthesis. Plasmionique’s internal and collaborative R&D with various national and international university research groups allows them to develop novel systems and processes.

With its expertise, Plasmionique is well positioned to provide plasma technology support for the development of new fusion reactor technologies in Canada.

A.3.11 Norax Atomics / Norax Induction Canada (Lévis, Quebec)

Norax Canada Inc. (www.noraxcanada.com) is a Canadian manufacturer of customized Resonant Switched Mode Induction Power Supplies for industrial and research applications, and has been in existence for nearly 25 years. Norax Atomics is a relatively new division of Norax Induction Canada, and it was established to leverage the knowledge and expertise of Norax Induction to develop an alternative fusion concept. Fusion-related development work at Norax Atomics / Norax Canada has been ongoing for more than 8 years.

Norax Atomics is reported to be in the final stages of assembly and testing its first prototype experimental nuclear fusion device. The Norax fusion concept and plasma confinement approach is based on forcing two counter flow plasma beams to pass through each other while being magnetically compressed at the collision/intersection point. It is estimated that the effective magnetic field at the center of collision point is approximately 0.75 Tesla. The operating frequency for plasma beams in collision is estimated to be in the GigaHertz (GHz) range. In contrast to other conventional fusion, the Norax fusion reactor concept is intended to work under atmospheric pressure. This approach eliminates problems associated with vacuum tight structure. It is also reported that the Norax fusion concept can be engineered and adapted for converting fusion energy to electrical power using a conventional steam-generator and turbo-generator, similar to what is used in existing nuclear and thermal power plants. It is also anticipated that the fusion plasma confinement system proposed by Norax may be sufficient such that it could be adapted to use other fusion fuels combinations, such as D-D, or D-^{3}He, in addition to the more conventional D-T fusion fuel combination.

A.4 OPG/OCNI: Recent and Historical Canadian Engagement with ITER Project

The following section was prepared from contributions by current and retired staff from OCNI (Organization of Canadian Nuclear Industries) and OPG (Ontario Power Generation), regarding recent and historical and efforts by members of the Canadian nuclear industry to engage with the ITER Project.

A.4.1 Background

The International Thermonuclear Experimental Reactor (ITER) Organization is a global effort to design, construct, and operate the world's largest Tokamak-type magnetic fusion reactor that will prove the scientific and technical feasibility of commercial fusion energy production. The ITER Project represents an impactful step towards a future with clean, reliable, and sustainable energy.

Canada has a rich history of nuclear research, development, and safe nuclear operations, including contributions to the ITER conceptual design. The intent of this initiative is to establish the grounds for cooperation between the Canadian nuclear community and the ITER Organization. Through involvement with the ITER Project, Canadian organizations will have the opportunity to build on our widely recognized nuclear capabilities and expand our expertise in leading edge fields such as cryogenics, materials science, and advanced robotics.

Canadian involvement in the next stages of the ITER Project will ensure future access to the operational ITER facility for continued scientific research and development. Exposure to ITER Project technology and expertise will likely lead to Canadian innovation opportunities in energy production and other related fields.

Renewed participation with the ITER Project will strengthen Canada's competitiveness in global nuclear markets, specifically in the areas of intellectual property, commercial offerings, technology innovation, and research & development.

Over the next five years (2020-2025), it is expected that collaboration between Canada and ITER will provide the following key opportunities for the Canadian nuclear industry:

- ITER is interested in securing a reliable source of tritium supply within the next two years. Tritium is a critical component of the fuel required for the ITER plasma fusion reaction. Ontario Power Generation is positioned to provide the necessary inventory in addition to the technical expertise and operating experience to support safe handling, storage, and transportation.
- Over the next three years (2021-2024), critical contracts will be awarded by ITER in areas where Canada has a strong competitive advantage. These areas include tritium handling capabilities, safety-critical technology innovation and advanced robotics,

specialized nuclear equipment manufacturing and testing, and nuclear materials and safety analysis.

- Canadian involvement with ITER will offer an opportunity to market Canadian nuclear expertise and advanced technology offerings to the multi-national, multi-year, $24B Fusion Energy Project. Canada's support to the ITER Project will also allow us to develop relationships and learn from international nuclear fusion experts.

The ITER Organization continues to actively seek Canadian industry participation as the ITER Project moves into the construction and operation stages. Involvement with ITER will position Canada to develop deep expertise in fusion technology over the next decades.

A.4.2 History: Early Canadian Participation on ITER (1985-2003)

Canada has had a long association with the ITER Project beginning with work on the early design phase of ITER from 1985 to 2000 through the Canadian Fusion Fuels Technology Project (CFFTP). CFFTP was a partnership of OPG (then Ontario Hydro), and the Ontario and Canadian Federal governments.

This work culminated in the creation of ***Iter Canada***, a consortium of public and private sector stakeholders that prepared and submitted a bid to the ITER Council on June 7, 2001 to host the multi-lateral, multi-national ITER Project in Clarington, Ontario, right beside the Darlington Nuclear Generating Station.

When the ITER Council selected Cadarache in southern France as the host site in 2005, Canada subsequently decided to discontinue its involvement with the ITER Project, following its earlier withdrawal from the site bidding process in 2003. What was unusual and conspicuous was that Canada was the only major nuclear nation that chose not to participate in this multi-national project with seven partners (United States, Russia, Japan, China, India, South Korea and the European Union) including 35 countries.

A.4.3 History: Early Contributions by CFFTP to Previous ITER Design Work

During the period of 1985 to 1997, Canada's contribution to ITER design stemmed from contributions by the Canadian Fusion Fuels Technology Project (CFFTP) to the EURATOM Design of the Next European Torus (NET). The CFFTP was a joint project lead by OPG (then Ontario Hydro), with contributions and technical support by Atomic Energy of Canada Limited (AECL). The NET project was a pre-cursor project that later evolved and merged into ITER, when multi-national cooperation between Europe, Russia and the United States was proposed in the late 1980s.

The collaboration between CFFTP and EURATOM began in the early 1980s, following a CFFTP organized "Team Visit" of its senior managers to the main European labs engaged in fusion research to discuss how Canada's efforts might complement their own. Encouraged by the results of this visit, CFFTP assigned senior technical experts with prior involvement in both the U.S. and European fusion programs to work with members of the NET team in Garching, Germany, with the objective of defining where Canada's expertise could contribute to the program goals. Subsequently, under a memorandum of understanding between Euratom and the Government of Canada, CFFTP sent specialists in tritium design, safety assessment, and robotics on multi-year assignments in Garching where the NET Team was based. These efforts were augmented by CFFTP's sending additional specialists for short periods, and launching a series of technical and R&D contracts contributing to the EURATOM Programme, aligned with the work of its assigned specialists. This formula worked very well, enhancing the productivity and recognition of these efforts both within the NET team and by senior EURATOM Management. As time went on, the assignees became fully embedded in the NET team, with EURATOM contributing to their costs of assignment and the support work being done by Canadian companies. This arrangement remained in effect from 1983-1988, when the ITER Conceptual Design Activities (CDA) began (1988-1991), and Canada's agreed to participate in them through Europe. At that point, one of the long-serving assignees, the NET Tritium and Vacuum Group Leader, was officially designated the ITER Concept Design leader for this area.

Throughout the CDA, and during the subsequent Engineering Design Activities (EDA) in the period of 1992 to 1998, and their extensions, Canadian scientific and technical staff employed directly or under contract to CFFTP continued to be involved in the design activities, initially mostly in vacuum system design, tritium plant and remote handling, and later increasingly in safety and licensing studies and reactor building design. Until 2001 Canada's contribution in design and R&D contributed to that of EURATOM. Canada, by making a site proposal in 2001, vital in maintaining the momentum of the design work until a site could finally be chosen, entered the project as a partner in its own right, directly employing staff contributing technically. After its withdrawal from the project at the end of 2003, and until the establishment of the ITER Organisation in 2007, Canadian staff continued to be involved in safety analysis and building design, with their contracts being paid directly by EURATOM.

A.4.4 History: Iter Canada bid to host the ITER Project - June 2001

A comprehensive "Plan to Host ITER in Canada", including 14 Sections, was submitted to the three ITER Council Co-Chairs from the European Commission, the Russian Federation Ministry for Atomic Energy and the Science, and Technology Agency of Japan on June 7, 2001 signed by Dr. Peter Barnard Chair and CEO of Iter Canada. The Plan covered Canadian technical scope of supply, a project schedule and organization , licensing in Canada, socio-economic benefits (for ITER) of the Clarington Site, financing arrangements, siting requirements and design assumptions, and advantages of siting the ITER Project in Clarington, as shown in Figure 73. Canadian stakeholders for ITER are shown in Figure 74, while the Board of Directors for Iter Canada are shown in Figure 75.

IMAGE REMOVED / REDACTED

Figure 73: Proposed ITER Site in Clarington, Ontario.

IMAGE REMOVED / REDACTED

Figure 74: ITER Canada Public and Private Stakeholders (2001).

IMAGE REMOVED / REDACTED

Figure 75: ITER Canada Board of Directors (2001).

A.4.5 History: Final Selection of ITER Site at Cadarache, France (2005)

The Canadian proposal submission to host the ITER Project helped stimulate international competition in hosting the project and three competing bids were also submitted in June 2002 by Spain (Vandellos Site), France (Cadarache) and Japan (Rokkasho-Mura). Ultimately, the Cadarache Site was selected for the $24B ITER Project on financial grounds, although it was recognized and Canada was advised that the Clarington site was a superior "technical site", largely due to its deep-water port access on Lake Ontario and the St. Lawrence Seaway, and its easy access to power and tritium from the adjacent Darlington Nuclear Generating Station.

A.4.6 Canadian Re-Engagement – the Canada-ITER MOU, April 17, 2018

Although the Canadian government of 2003 decided to discontinue formal participation and support of the ITER Project, a number of Canadian companies with tritium- related capabilities secured contacts to work on ITER through suppliers based in the EU and the United States.

Through the sponsorship by the Organization of Canadian Nuclear Industries (OCNI) of the 2017 Toronto Global Forum, Dr. Spencer Pitcher (a native-born Canadian) of the ITER Organization (IO) was invited to speak at the Forum in November 2017. Following the Global Forum, discussions began among representatives and stakeholders from the IO, the Ontario Government, Natural Resources Canada (NRCan), Global Affairs Canada (GAC, with Denis Trottier serving as the Canadian Trade Commissioner in France) and OCNI to develop a mechanism through which Canadian suppliers could contribute mission-critical and unique tritium-handling, robotics and materials-related capabilities as well as tritium after 2030. These discussions led to the signing of a Collaboration MOU between the Government of Canada and the ITER Organization in Paris on April 17, 2018 by the Canadian Minister of International Trade, François Champagne, and the ITER Director General, Bernard Bigot, during a Canadian AI Trade Mission to Paris led by Minister Champagne, as shown in Figure 76.

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Figure 76: MOU signing April 17, 2018: The Honourable François-Philippe Champagne, Minister of International Trade (left), ITER Director General Bernard Bigot (right) with OCNI President and CEO Ron Oberth (standing).

The following quotes are taken from the news release by Global Affairs Canada, following the signing of this Canada-ITER MOU:

"Canada's expertise in the nuclear sector is world renowned, and this MOU will launch a process to ensure that Canadian suppliers are able to export technologies and expertise on a commercial basis in support of the ITER project, which, in turn, will contribute to well-paying middle-class jobs and more sustainable energy in the future." **François-Philippe Champagne, Minister of International Trade**

"This MOU is good news for the Canadian nuclear industry and a testament to the excellence of Canadian nuclear energy expertise and technology. This arrangement will ensure that Canadian suppliers are positioned to support the ITER Project on a commercial basis, helping to advance clean, non-emitting energy for the future." - **Jim Carr, Minister of Natural Resources**

Under the auspices of the MOU, ITER Director-General Bigot and Dr. Spencer Pitcher visited Canada in August 2018 for discussions with OPG, Canadian suppliers and federal and Ontario government officials and a tour of OPG's Tritium Removal Facility, and the engineering research laboratories at Kinectrics (a member of OCNI).

A.4.7 Canadian Trade Mission to ITER Business Forum - March 2019

The Organization of Canadian Nuclear Industries (OCNI) and Ontario Power Generation (OPG) led a delegation of 10 leading Canadian nuclear suppliers along with the University Network of Excellence in Nuclear Engineering (UNENE) to the 2019 ITER Business Forum in Antibes, France from March 26 to 28, 2019, as shown in Figure 77. The bi-annual ITER Business Forum brings together more than 1000 delegates from 30 countries to hear updates on ITER construction and systems installation and to seek opportunities to collaborate in tackling ITER project challenges.

The Canadian delegation visited the ITER project, Europe's largest construction site, on March 25, 2019, and toured the Poloidal Field Coils facility, the Cryostat workshop, the massive Assembly Building and the Tokamak Complex at the heart of the site.

The following quotes from that visit are given below:

"The scale and complexity of the facilities we visited were truly impressive...this project exemplifies teamwork, offering an amazing example of what can be accomplished when the best engineer/construct talents from many nations join together to achieve a common goal," **Dean Townsend OPG's Vice President of Engineering Strategy.**

"ITER staff on site and ITER suppliers from many participating countries showed a genuine interest in learning about what the Canadian team could bring to the project based on their unique capabilities acquired in designing and operating CANDU nuclear plants for 60 years. We look forward to exploring in the coming months how Canada can best support the ITER project by complementing the diverse capabilities of the ITER partner nations". **Ron Oberth OCNI CEO**

IMAGE REMOVED / REDACTED

Photo: Canadian delegation (representing OCNI, ATS Automation, OPG, Rolls Royce, MDA, Canadian Nuclear Laboratories, Tyne Engineering, Laker Energy Products, SNC-Lavalin, Promation Nuclear and UNENE) with Trade Commissioner Denis Trottier (fifth from the left) greeted by ITER Director General Dr. Bernard Bigot (back row third from the right)

Figure 77: Canadian Delegation to ITER Business Forum, Antibes, France, March 26 to 28, 2019.

Mutually beneficial Canada-ITER collaboration ensued September 18, 2020 when OCNI hosted webinar workshop on September 18, 2020 among the ITER Hot Cell Complex project managers and Canadian project managers on "Collaborative (Alliance) Contracting" models like the one used by Canadian Nuclear Laboratories and its contractors on the new Advanced Nuclear Materials Research Centre at the Chalk River Laboratories.

A.4.8 Canada-ITER Nuclear Cooperation Agreement (NCA) -October 15, 2020

Following several months of negotiations, the Canada-ITER Nuclear Cooperation Agreement (NCA) was signed in a virtual signing ceremony on October 15, 2020 with Assistant Deputy Canadian Minister of Foreign Affairs Dan Costello and ITER Director General Bernard Bigot, as shown in Figure 78. The next step will be to establish the Canada-ITER commercial framework under which Canadian companies can provide commercial services and products to the ITER project. A model on how this will work is being developed with NRCan.

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Figure 78: Virtual Meeting and Signing of Canada-ITER Nuclear Cooperation Agreement, October 15, 2020.

The NCA will allow the transfer of nuclear materials supplied by Canada (such as tritium), as well as tritium-related equipment and technologies. Before it begins self-breeding of tritium, ITER is expected to consume most of the tritium currently available worldwide. The largest tritium reserves are in Canada because tritium is mainly produced by Canadian CANDU reactors. The ITER-Canada Nuclear Cooperation Agreement (NCA) is awaiting ratification by the Canadian Cabinet in 2021.

A.4.9 Next Steps for Canada-ITER Cooperation in 2021 and Beyond

Canadian entities, such as member companies of OCNI, and others, are awaiting formalization of a framework relationship with the ITER Organization under which they will be able to supply unique services and products to the ITER Project subject to the conditions set out in the Canada-ITER NCA.

The Canada-ITER NCA will be managed by a Coordinating Committee, co-chaired by NRCan and including representatives from AECL, CNL, OPG and OCNI on the Canadian side. It is anticipated that the NCA Coordinating Committee will set out the framework arrangement under which Canadian companies will be able to bid for ITER commercial contracts where they have unique capabilities not available from ITER member states, most likely in the areas of tritium production and handling.

To facilitate Canadian contracts on ITER projects under the Canada-ITER NCA, OCNI will work with government officials to organize Canadian participation in a virtual ITER Business Forum in Marseille in April 2021. Pending the easing of COVID travel restrictions OCNI will lead another Canadian trade mission to the ITER Business Forum in 2022.

Participation in the ITER Project at this pivotal moment will allow Canada to achieve international recognition and to solidify Canada’s status as a technologically advanced, industrial nation.

A.5 CNSC – Request for Proposals to Evaluate CNSC Regulatory Framework Readiness for Evaluating Fusion Power Plants – Annex A – Statement of Work

A.5.1 Title

Review of the Canadian Nuclear Safety Commission’s Regulatory Framework for Readiness to Regulate Fusion Technologies.

A.5.2 Objective of the Contract

The Canadian Nuclear Safety Commission (CNSC) requires a Contractor to conduct a third-party research and an evaluation of the CNSC’s Regulatory Framework‘s readiness to accept and evaluate a license application for a Fusion Power Reactor or Subcritical Nuclear Assembly (henceforth referred to as fusion or fusion technology).

A.5.3 Background

The CNSC is a Federal Government Agency that regulates the nuclear industry in Canada. By virtue of the Nuclear Safety and Control Act, the CNSC regulates the use of nuclear energy and materials to protect health, safety, security and the environment; to implement Canada’s international commitments on the peaceful use of nuclear energy; and to disseminate objective scientific, technical and regulatory information to the public.

For over a decade, the CNSC has been preparing its regulatory framework for the potential introduction of advanced reactor technologies (ARTs) such as small nuclear reactors (SMRs). Canadian provinces and industry are evaluating these technologies to possibly replace current nuclear power plants, fossil fuel electrical generation plants and for resources extraction projects and remote community energy needs.

To assist the CNSC with its work on its regulatory framework, Discussion Paper DIS-16-04 was published on the CNSC website on May 31, 2016. A consultation notice was also posted on the Government of Canada's Consulting with Canadians website. The CNSC continues to monitor fusion developments and efforts around the world and remains open to engaging with potential proponents seeking to conduct fusion activities in Canada.

A.5.4 Scope of Work

The successful Contractor will review the implementation of the CNSCN"s Regulatory Framework, provide a consistent and reliable approach to reviewing the effectiveness of the CNSC's Regulatory Framework, with respect to novel technologies is an area of broad interest and concern, and provide feedback related to general implementation issues.

A.5.5 Tasks

The Contractor must complete the following:

Task #1: Using publically available resources, the Contractor must draft three (3) hypothetical preliminary descriptions of the hazards and activities of nuclear fusion technology facilities.

- The hypothetical descriptions should provide in-depth details that will be used to evaluate the "regulatory readiness" of the CNSC regulatory framework in subsequent tasks.
- The development of the hypothetical preliminary descriptions will be informed by reviewing operating and proposed fusion technologies internationally, to aim for a representative and plausible potential licence application.
- The three descriptions should vary in plasma confinement methods and plasma thermal power. Section 4.2.2 of CNSC REGDOC-1.1.5, RFP Reference Number: 5000055100 Page 23 of 27
- Supplemental Information for Small Modular Reactors is to be used to draft the hypothetical preliminary description of activities and hazards.

Task #2: Review of existing regulatory documentation and literature

- This task would include the current license and inspection evidence related to the implementation of the CNSC Regulatory Framework as the baseline source of evidence. It also encompasses a review and comparison of comparable Regulatory Frameworks (e.g. USNRC, ONR, ITER (ASN and IRSN), and IAEA documents), conceptual and design documents for fusion technologies, academic and industry literature, comments and concerns raised by external stakeholders (including, but not limited to Civil Society organizations). Task #2 will also include a review of "regulatory readiness" methodologies to help guide and clarify further deliverables.

Task #3: Initial Assessment of the CNSC's Regulatory Readiness

- this would include the initial report to the CNSC project team on initial observations with respect to regulatory readiness, potential license and implementation challenges with a fusion technology and guidance on potential solutions.

Task #4: Interviews with internal and external stakeholders

- this task entails developing a brief presentation based on the initial Assessment Report and seeking feedback from both CNSC officials as well as industry, academic, Indigenous groups and civil society representatives. As required, CNSC staff can facilitate the implementation of this task (e.g. setting up a webinar with stakeholders).

Task #5: Overview report

- based on feedback from external stakeholders, this task entails developing a final report on readiness, which will include specific regulatory issues (e.g. restrictive guidance or requirements) and implementation issues (e.g. the clarity of the Framework with respect to compliance and inspection of novel technology).

Task #6: Outreach and communication

- this task entails providing support to CNSC staff and/or leading presentations to federal and international fora on the readiness and implementation of fusion *technology.*