Nuclear Fusion: Progress, Prospects, and Innovation Opportunities

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Slide #1 Thank you for giving me the opportunity to contribute to this meeting of Innovation Directors. As innovation experts, you identify major innovation challenges, and develop strategies to address such challenges.

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Progress, Prospects, and Innovation Opportunities

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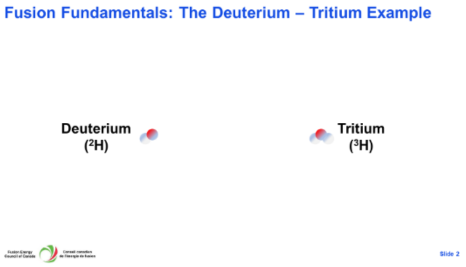
In this presentation, I will focus on *fusion energy innovations* because fusion energy has the potential of addressing a crucial, global challenge of our time: This challenge is the provision of large quantities of energy for citizens and industry alike; energy that is reliable, affordable, sustainable, decarbonized, and safe.

Some of you are familiar with fusion energy while others are not. Permit me therefore to give a brief introduction to fusion energy before I outline progress with fusion energy, its uses, and its innovation potential.

The concept of fusion energy is based on getting the nuclei of small atoms, like deuterium and tritium, to combine or 'fuse'. Slide #2 These nuclei consist of just a few protons, which have a positive charge, and a small number of neutrons which have no electrical charge. In this slide, the protons are red, and the neutrons are grey.

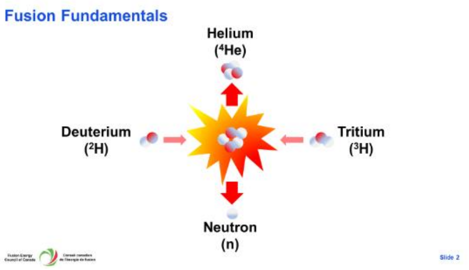


Fusion Fundamentals: The Deuterium – Tritium Example

Slide 2

Usually, we also depict electrons that surround the nuclei of atoms but let us imagine that the temperature is elevated so that the electrons and nuclei have separated, forming a state of matter that is known as the plasma state. Plasmas are similar to gases, except that their positively charged atomic nuclei and negatively charged electrons have separated and move freely and rapidly. They constantly approach each other and, by virtue of their charge, typically repel each other as they approach each other.

When we raise the temperature, the speed of the nuclei increases, the collisions occur more frequently, and the collisions take place with greater force. When the temperature reaches millions of degrees Celsius, the deuterium and tritium nuclei overcome their repulsive forces, fuse briefly and then separate into helium nuclei and neutrons. Slide #2


Fusion Fundamentals

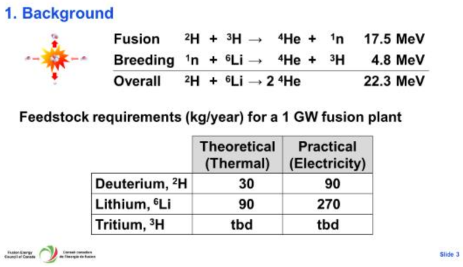
Slide 2

This process is accompanied by the release of energy because the mass of a helium nucleus plus the mass of a neutron is slightly less than the sum of the masses of a deuterium and a tritium nucleus. The decrease in mass is converted into energy, following Einstein's well-known equation, in which energy produced equals the change in mass times the square of the speed of light.

This change in mass is the essence of energy production by nuclear fusion.

It is important to recognize that nuclear fusion is a natural phenomenon, occurring in the sun and all other stars. Nuclear fusion differs from nuclear fission because the change of mass results upon small nuclei *combining*. In nuclear fission, the change in mass results from large nuclei, like the nuclei of uranium isotopes, *splitting*.

To illustrate the enormity of fusion energy production, consider the fusion of deuterium and tritium, coupled with neutrons reacting with lithium, thereby breeding more tritium. Slide #3


1. Background

Fusion	$^2H + {}^3H \rightarrow {}^4He + {}^1n$	17.5 MeV
Breeding	$^1n + {}^6Li \rightarrow {}^4He + {}^3H$	4.8 MeV
Overall	$^2H + {}^6Li \rightarrow 2\,{}^4He$	22.3 MeV

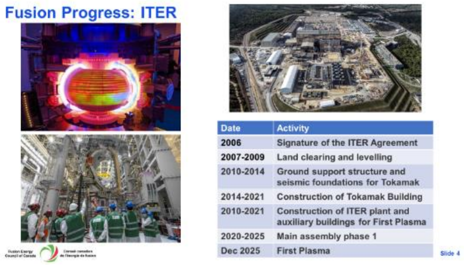
Feedstock requirements (kg/year) for a 1 GW fusion plant

	Theoretical (Thermal)	Practical (Electricity)
Deuterium, ^{2}H	30	90
Lithium, ^{6}Li	90	270
Tritium, ^{3}H	tbd	tbd

Slide 3

The equations are important but what I want you to note particularly is that only very small quantities of materials are needed to produce very large amounts of energy. Slide #3 For example, a plant producing 1 GW of electricity would theoretically require just 90 kg per year of deuterium and 270 kg per year of lithium. The amount of tritium remains to be determined. It depends on the fusion reactor technology used. However, the tritium requirement would also be small, likely just a few kilograms for plant start-up.

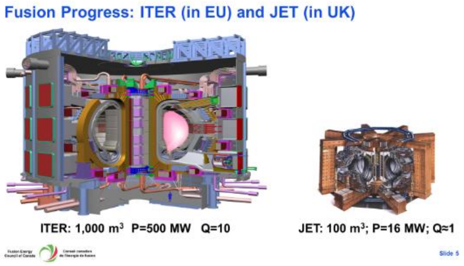
The big challenge for fusion energy developers is the creation of the extreme conditions that make fusion possible. Various efforts are currently under development. The largest effort is the ITER project in Southern France. Slide #4 It is a project costing over 25 billion euros and it is expected to start up in late 2025. ITER is an *experimental* project intended to demonstrate and investigate fusion over extended periods of time. The project is not designed to produce electricity for general use; that will come later.



Fusion Progress: ITER

Date	Activity
2006	Signature of the ITER Agreement
2007-2009	Land clearing and levelling
2010-2014	Ground support structure and seismic foundations for Tokamak
2014-2021	Construction of Tokamak Building
2010-2021	Construction of ITER plant and auxiliary buildings for First Plasma
2020-2025	Main assembly phase 1
Dec 2025	First Plasma

The ITER project is based on the principle that plasmas consisting of deuterium and tritium can be heated to extreme temperatures, temperatures of 100 million degrees Celsius or more, and can be confined to a circular torus using electromagnetic forces. ITER is a collaboration of the European Union, the United States of America, China, Russia, Japan, the Republic of Korea, and India. The United Kingdom and Switzerland are also major participants.



Fusion Progress: ITER (in EU) and JET (in UK)

ITER: 1,000 m^3 P=500 MW Q=10

JET: 100 m^3; P=16 MW; Q≈1

ITER's forerunner is the much smaller Joint European Torus (known as 'JET'). Slide #5 It is located in the United Kingdom and, last year, demonstrated nuclear fusion with a small net energy gain for about 5 seconds. While this is a very short time, it has been called the 'Kitty Hawk' moment of fusion. It proved the feasibility of man-made fusion, just like the Wright brothers demonstrated human flight near

Kitty Hawk, North Carolina in 1903.

Fusion Progress: National Ignition Facility (in USA)

Lawrence Livermore National Laboratory, California

Slide 6

Within a few weeks of the JET demonstration, the National Ignition Facility in the United States Slide #6 was also able to show near-fusion but using a different technique. This technique involves shining 192 high powered laser beams on a millimeter size encapsulated pellet of deuterium and tritium located in the centre of a large sphere that you see being hoisted into place in the middle picture. The lasers vaporize the pellet surface, thus compressing the pellet centre to high temperatures and pressures that enable deuterium and tritium fusion.

As with the first human flight, much innovation remains to be done to transform fusion into a reality so that it meets requirements of commercial energy markets. The key scientific challenges are the following: producing fusion energy with an energy output that exceeds the energy input required for fusion conditions, producing fusion energy over long periods of time (not just for a few seconds), and producing fusion energy that is competitive with other forms of energy production.

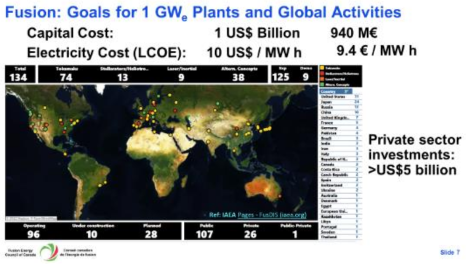
Fusion: Goals for 1 GW_e Plants and Global Activities

Capital Cost:	1 US$ Billion	940 M€
Electricity Cost (LCOE):	10 US$ / MW h	9.4 € / MW h

Slide 7

In this slide, Slide #7 I give the aspirational goals for a plant that generates 1 GW of electricity. The goals are a capital cost of about 1 billion US dollars and 10 US dollars per mega watt hour. The corresponding figures in euros are also shown. Today, these aspirational goals are far from being met, but confidence is building that they can be reached.

Slide #7 This confidence is reflected by what is occurring globally. Over 130 sites are now engaged in significant fusion work. In the past, governments have been the primary supporters of fusion development but the private sector has also recognized the potential of fusion. Over 5 billion US dollars of private funding have recently been invested into fusion development. That funding is not only for basic fusion research, but also for supporting technologies and for processes that are not based on deuterium and tritium.

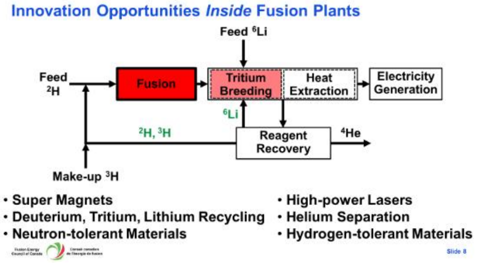

Fusion: Goals for 1 GW_e Plants and Global Activities

Capital Cost:	1 US$ Billion	940 M€
Electricity Cost (LCOE):	10 US$ / MW h	9.4 € / MW h

Private sector investments: >US$5 billion

Innovation Opportunities – Fusion Plants

Let me now turn to innovation opportunities that present themselves *inside* and *outside* fusion plants. Slide #8 To do this, I need to show first a simplified flowsheet of a fusion plant based on deuterium and tritium. This figure shows, in dark red, the facilities where the fusion reactions occur. It also shows, in pink, where tritium breeding takes place. Electricity is generated by extracting heat from both the fusion and breeding reactions.


Innovation Opportunities *Inside* Fusion Plants

- Super Magnets
- Deuterium, Tritium, Lithium Recycling
- Neutron-tolerant Materials
- High-power Lasers
- Helium Separation
- Hydrogen-tolerant Materials

It is important to understand that the fusion and breeding reactions do not go to completion and that reagents must therefore be recovered and recycled. Consequently, fusion plants need not only reagents like deuterium, tritium, and lithium but they also need technologies for recovering and recycling them. The reagents requiring recycling are shown in green in this slide. In addition, fusion plants need technologies for separating fusion products like helium.

At the bottom of the slide Slide #8, I list the innovation opportunities. Most of the technologies and materials are not well developed but will be critical for commercial fusion plants.

Innovation Opportunities - Outside Fusion Plants

In addition to innovation opportunities *inside* fusion plants, there are also opportunities *outside* fusion plants.

The most important opportunities relate to the supply of deuterium, tritium, and lithium. Slide #9 While fusion plants require only small quantities of these materials, they are nevertheless important. Let me elaborate.

Innovation Opportunities *Outside* Fusion Plants

Deuterium: ENSI, Arroyito, Argentina

Tritium: OPG, Darlington, Canada

Lithium:
^{6}Li 7.5% , ^{7}Li 92.5%

Slide 9

Good technologies already exist for the extraction of deuterium from salt and fresh water, and there are considerable stockpiles of deuterium in the form of heavy water for controlled trade from countries like Canada. The situation is, however, very different for tritium. Global tritium stockpiles are low and largely held by Canada.

CANDU reactors produce tritium as an undesirable by-product. Projections indicate that there will probably not be enough tritium to supply even experimental and first-generation demonstration plants, let alone commercial fusion plants in the decades to come. This supply gap needs addressing through innovation, starting now.

The lithium situation is again different because the global production and trade of lithium (principally in the form of lithium carbonate) are very large. However, fusion plants require the lithium 6 isotope rather than the more abundant lithium 7 isotope. Separating lithium 6 from lithium 7 is therefore also an innovation opportunity. While existing processes are adequate to meet small-scale requirements for lithium 6, they will likely be insufficient once large-scale fusion energy generation occurs.

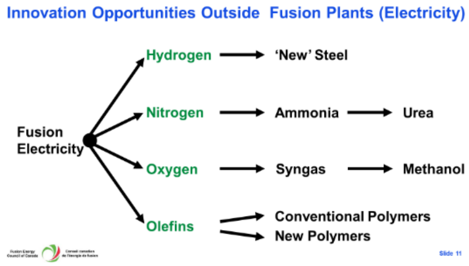
Innovation Opportunities for *Use* of Fusion Energy

I now wish to turn attention away from *producing* fusion energy and their supporting technologies, to focusing briefly on the *uses* of fusion energy. Given limited time, I will concentrate on electrical energy rather than thermal energy.

Slide #10 This slide shows some of the potential large-scale uses of fusion electricity.

Innovation Opportunities for Fusion Energy (Electricity)

The main use of electricity from fusion plants will likely be the electrical grid where demand is expected to increase substantially, driven by the electrification of transportation and, more generally, decarbonization objectives. Traditional industries, such a steel, aluminum, copper and zinc refining and the production of chlor-alkalis will also benefit from fusion electricity. Higher efficiencies and smaller carbon footprints will be the immediate benefits, but another fundamental change will occur. That change is the possibility of locating plants not just where cheap hydropower and petroleum-based electricity are available, but also close to where resources are found. An example is aluminum. If fusion electricity is available in appropriate quantities and at competitive prices, aluminum could be produced in countries with major bauxite deposits. These countries would include Australia, Guinea, and Guyana.



Innovation Opportunities Outside Fusion Plants (Electricity)

In addition to considering fusion electricity for traditional uses, we should also take the longer view and consider fusion electricity for novel uses. Slide #11 These uses include producing hydrogen, nitrogen, oxygen, and olefins. Hydrogen could be produced by electrolysis from water, nitrogen and oxygen could be produced by cryogenic air separation using electrical energy, olefins could be obtained by cracking heavier hydrocarbons using electrical energy rather than fossil fuels. Once the compounds shown in green in this slide are available, they can be used to produce conventional products such as steel, ammonia and urea, as well as syngas and methanol – all with low greenhouse gas emissions. They can also be used to produce entirely new types of polymers that are functional and biodegradable. The potential for new technologies, better conventional products, and new products is extraordinary.

Meeting the Innovation Challenge

This gets me to my last point. Slide #12 Meeting the fusion innovation challenge, i.e., making fusion energy a reality and putting that energy to good use, requires innovation. In turn, innovation requires 'ideation', namely the development of creative ideas – ideas for doing things differently and ideas for doing things better - and then translating these ideas into reality at scale and at speeds demanded by sustainability and prosperity objectives.

Meeting the Fusion Innovation Challenges

Ideation and Collaboration
- Fusion Energy Generation and Uses
- Developed and Developing Countries
- Government, Industry, Academia

Academic Programs
- Sciences, Engineering, Humanities
- Electrochemistry

Slide 12

Given the magnitude of the innovation challenge, these objectives can only be achieved by developed and developing countries working together and by government, industry and academia collaborating. Multinational organizations, like the European Union, the International Atomic Energy Agency, and the International Energy Agency have a special responsibility to foster this collaboration. I also wish to single out ITER. While its membership is already multinational, many countries are not direct participants. These countries, including Canada, have much to offer, but are not yet engaged with ITER or engaged in significant fusion development.

For members of academia who are participating in today's meeting, I encourage you to think about academic and university-based programs that address fusion energy production and uses. This means programs for science, engineering, business, and humanities. A specific subject area that not to be overlooked is electrochemistry. Electrochemistry will see a renaissance driven by opportunities created by electricity from fusion as well as from other sources.

Conclusions

Let me conclude Slide #13 by stating that fusion energy on earth is becoming a reality and we can expect large, commercial fusion plants well before mid century.

Conclusions

- Man-made fusion is near
- Creativity, innovation, and collaboration are key for fusion energy development and uses
- Opportunities for fusion innovation abound, with example areas having been given

Slide 13

In this talk, I have suggested important areas of innovation related to fusion energy production and uses, without being highly specific. I hope that I have stimulated your interest.