Fusion Power Plant Technologies / Generic and Supporting Technologies for Fusion Energy Development

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Fusion 2030: A Roadmap for Canada

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Introduction

- **Fusion Power Plant Technologies.**
- **Generic / Supporting Technologies.**
  - **Applicable to many or most fusion reactor concepts / designs.**
    - **Mainstream (such as Tokamak, Laser-ICF, and Stellarators)**
    - **Alternatives (Magnetized Target Fusion, Reversed Field Pinch, Field-Reversed Configurations, Magnetic Mirrors, Spheromaks, Z-Pinches, etc.)**
- **International Context**
  - **What are the issues?**
- **Canadian Context**
  - **Past / Current Experience**
  - **Proposed Canadian Program / Future Efforts**
    - **What can be done in the near and intermediate future.**

International Context (1/4)

- **Interaction between the fusion plasma and first wall of the surrounding structural components**
  - **Erosion of materials; contamination of plasma.**
  - **Generation of secondary X-rays.**
- **Modeling and assessment of radiation transport**
  - **High-energy neutrons (2.45-MeV, 14.1-MeV).**
  - **Photons (gamma rays, X-Rays).**
  - **Interactions outside the fusion plasma region.**
  - **Interactions with various materials and components**
  - **Interactions with coolants, breeding materials, shielding, support structures, field magnets, and others.**
  - **Damage, activation, breeding.**

International Context (2/4)

- **Performance of structural materials and components**
  - High radiation environments (neutron, gamma, X-rays).
  - Cycling of thermal heat, stress, and mechanical force loads
  - Fatigue and damage issues.
- **Production, handling and storage of fusion fuels**
  - Deuterium (D) and tritium (T)
  - Interactions of D, T with various materials.
- **Behavior of fertile and fissile nuclear materials**
  - Fertile: U-238, Th-232; Fissile: Pu-239, U-233
  - If fusion reactor used as a neutron source to drive a sub-critical fission reactor blanket.

International Context (3/4)

- **Balance-of-Plant**
  - **Design and operation of the balance-of-plant, which is used to convert the heat from the fusion plasma into electricity.**
- **Safety & Licensing Analyses**
  - **Large magnetic, electromagnetic fields.**
  - **Radiofrequency EM waves.**
  - **Cyclic forces.**
  - **High temperatures; Chemically reactive materials.**
  - **High-pressure, high-temp. coolants (liquids, gases).**
- **Environmental Assessments**
  - **High radiation fields while in operation.**
    - **High-energy neutrons, X-rays, and gamma rays.**
  - **Activation of materials by radiation fields.**
  - **Addressing risks of chemical/radioactive leaks/contamination.**

International Context (4/4)

- **Operating parameters of a fusion reactor place many of the materials under severe stress.**
- **Materials development, engineering and testing is a key necessity for the eventual implementation of fusion reactors.**
  - **Test facilities with sufficient neutron, photon and charged particle flux, and the correct mix of high-energy particles and photons do not exist today.**
    - **Plans underway for the construction of such test facilities.**
  - **Generic fusion reactor issues being studied at research facilities globally: United States, Russia, China, Korea, Japan, and Europe.**
  - **More effort required to develop materials and sub-systems for prototype demonstration fusion power plant facilities**
    - **Effort will allow more rigorous lifetime testing of the various subcomponents under real operating conditions.**

Canadian Context (1/4)

- **Historically, Canada involved at a small scale in carrying out supporting research**
  - **Mainstream and alternative fusion reactor concepts.**
    - **Tokamak, Laser ICF, Magnetic Cusps**
- **Since the early 1970s until 1997, researchers across Canada were contributing to broad-purpose fusion energy science and technology development through:**
  - **Canadian National Fusion Program**
    - **Support halted in 1997 (GoC effort to eliminate deficit)**
  - **Canadian Fusion Fuels Technology Project (CFFTP).**
    - **Cooperation between Ontario Hydro and AECL.**

Canadian Context (2/4)

- **Technologies for the production, handling and storage of deuterium and tritium**
  - **Evaluating tritium breeder blankets.**
  - **Materials/compounds containing Li-6, Li-7.**
- **Understanding how D, T interact with materials.**
  - **Chemical reactions, diffusion, crystal structures.**
- **Separating D, T from water (D_2O, DTO).**
  - **Methods of storage (metal hydrides).**
- **Current activity focused on deuterium production and tritium handling.**
  - **Ties in with Canadian nuclear industry with heavy water reactors.**

Canadian Context (3/4)

- **Evaluating fusion-driven sub-critical systems**
  - **Hybrid fusion-fission reactors for producing power and breeding fissile fuels (1970s).**
    - **Alternative to fast-breeder reactor.**
    - **Large support ratio for conventional fission reactors.**
  - **Computational neutronics studies on hybrid fusion-fission reactors (1970s-1980s).**
  - **More recent exploratory work on hybrid reactors.**
    - **Near-term, early-application of first-generation fusion.**
- **High-level economic assessments of fusion technologies.**

Past/Current Canadian Context (4/4)

- **Plasma / first wall material interactions:**
  - **Importance for the first wall lifetime in fusion reactors.**
  - **University groups in Saskatchewan, Alberta, Ontario and Quebec have studied such interactions for decades.**
    - **Continuing at small scale (University of Toronto).**
  - **Private research company in Montreal, Plasmionique (operating since 1999)**
    - **Developing/providing plasma source systems of various specifications for applications in plasma processing.**
    - **Potential to adapt for fusion research applications.**

Future Canadian Efforts (1/9)

- **New contributions, build upon current expertise.**
  - **Make use of existing facilities.**
  - **Experts in research and industry.**
- **Key areas:**
  - **Licensed facilities for handing T, DTO, T_2O.**
  - **D, T production, extraction, storage, handling.**
    - **Builds upon experience with CANDU reactor technology.**
    - **New technologies have been developed in Canada.**
    - **No current formal linkages to ITER project.**
    - **Access to potentially large market limited right now....**
    - **Opportunity for Canada to re-assume leadership role.**

Future Canadian Efforts (2/9)

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  - **Licensed facilities for handing T, DTO, T_2O.**
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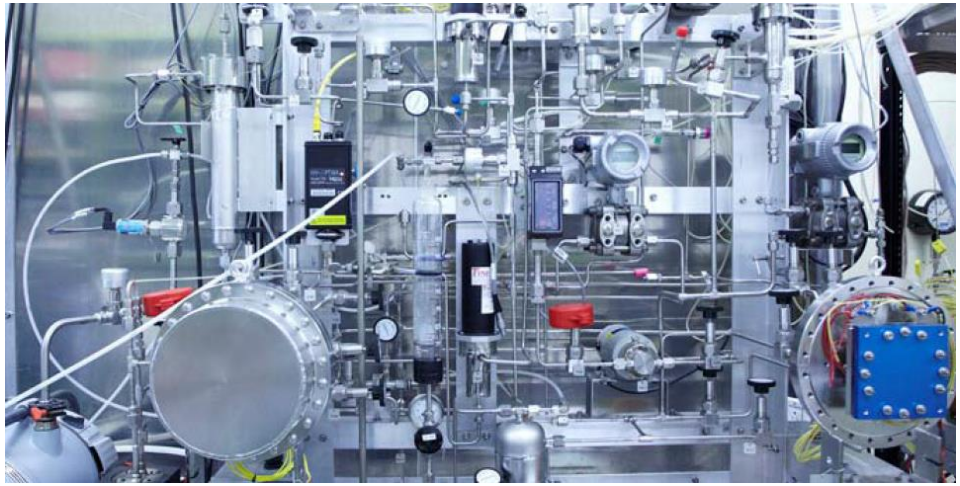
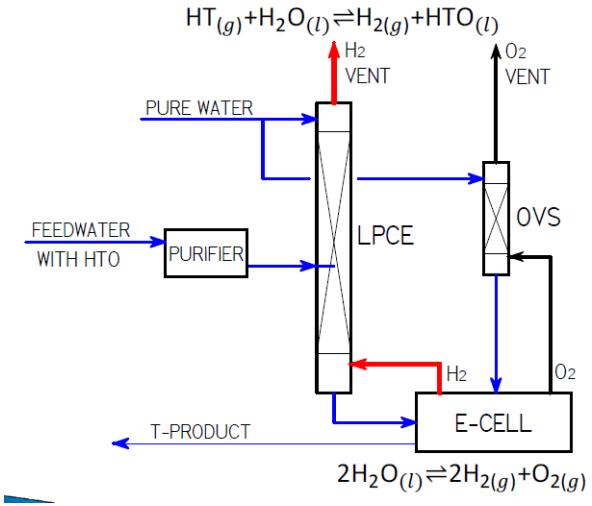
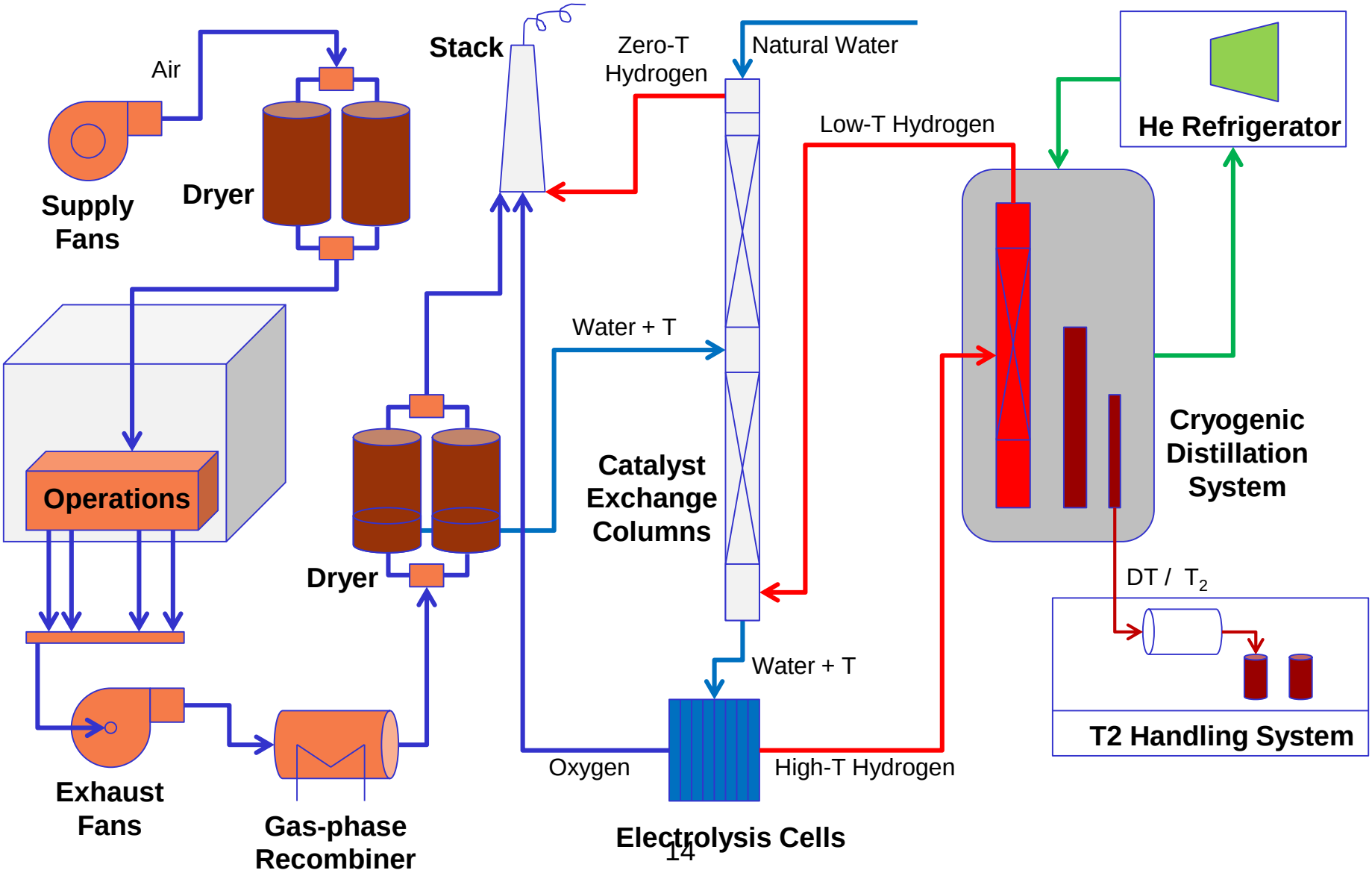




Future Canadian Efforts (3/9)

- **Tritium Handling, in water form:**
  - **Best for low concentrations (simple equipment)**
  - **Simple barriers (PPE)**
  - **Readily condensed/adsorbed (e.g. mol sieves)**

Future Canadian Efforts (4/9)

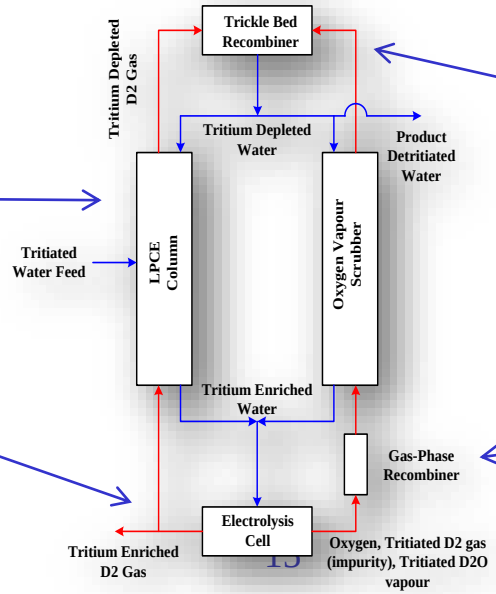


Tritium Processing System Diagram

Future Canadian Efforts (5/9)

Canadian technologies:

- Tritium power sources
- Processes for tritium removal
- Catalysts for tritium reactions and separations
- Certified tritium standards
- Tritium-resistant materials and equipment

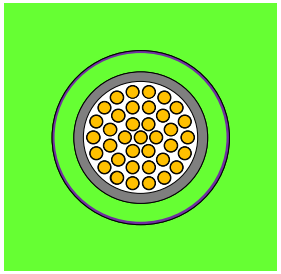


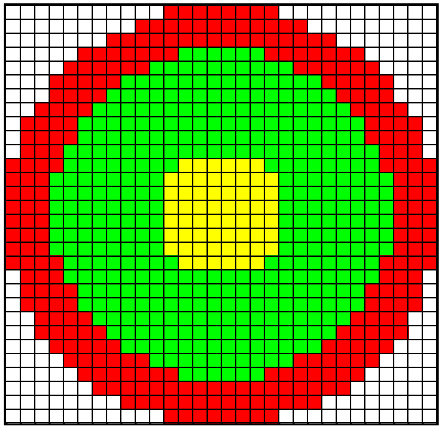
Future Canadian Efforts (6/9)

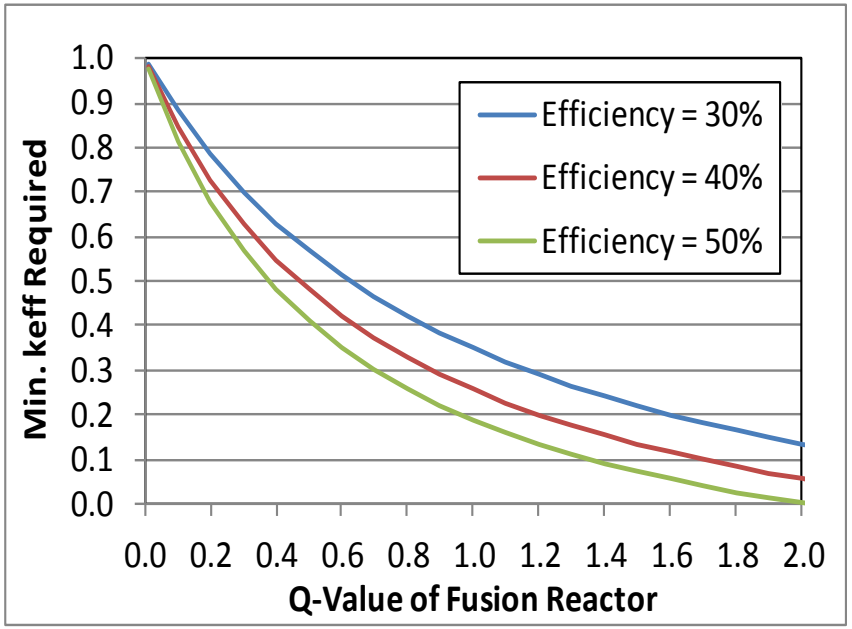
- **Key areas:**
  - **Licensed facilities for fusion blanket technology.**
    - **Materials and components (lithium-based).**
    - **Fabrication and testing.**
  - **Computational neutronics and radiation transport modeling.**
    - **Evaluate materials damage, breeding in blankets.**
    - **Design of shielding.**
  - **Thermal-hydraulics**
    - **Fluid flow and heat transfer in fusion reactor components.**
    - **Water, and alternative coolants.**
    - **Computational and experimental.**

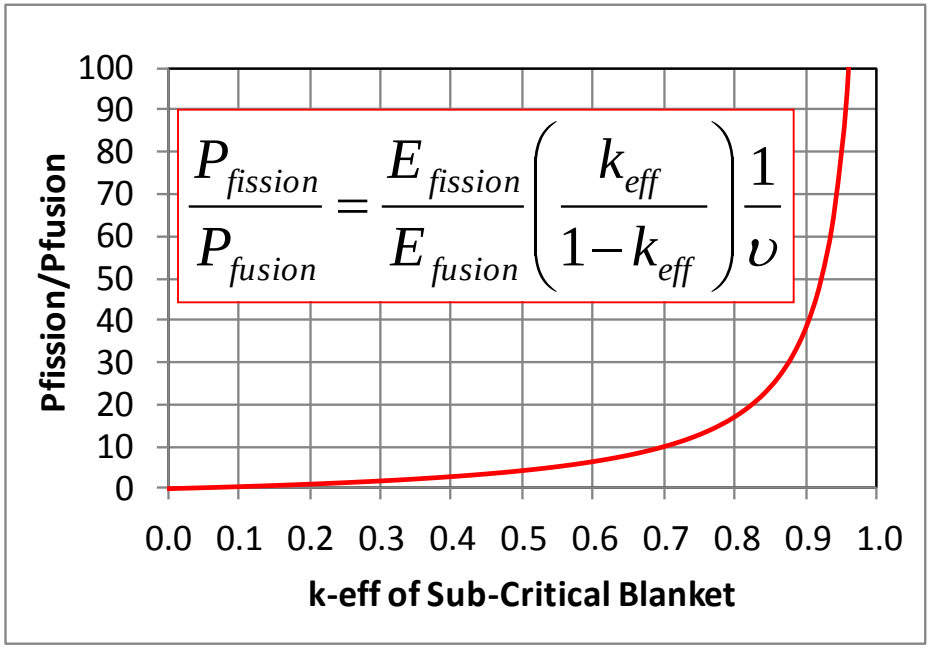
Future Canadian Efforts (7/9)

- **Hybrid fusion-fission reactor technology**
  - **Blankets made of Th-232 / U-238**
  - **Breeding U-233 and Pu-239.**
  - **Early application of fusion.**
  - **Q~1.0 fusion reactor sufficient.**
  - **Complements / supports fission reactor technology.**









Future Canadian Efforts (8/9)

- **Key areas:**
  - **Plasma-material interactions**
    - **Plasma bombardment, radiation damage of materials.**
    - **Testing of materials and components.**
    - **Use of neutron sources, proposed plasma sources, and high-energy particle sources (from accelerators) at various research and university facilities.**
      - **Plasmionique in Quebec**

Future Canadian Efforts (9/9)

- **Key areas:**
  - **Plasma-material interactions**
    - **Use of neutron sources, proposed plasma sources, and high-energy particle sources (from accelerators) at various research and university facilities.**
      - **University of Saskatchewan**
      - **University of Alberta (laser-based plasma source)**
      - **TRIUMF**
    - **Analysis of response and material changes in samples using the diagnostic and analytic tools of nanotechnology, as exists at the National Institute for Nanotechnology (NINT).**

Summary

- **Opportunity for Canada to develop fusion power plant technologies, and generic and supporting technologies for fusion energy development.**
- **Canada has experience, expertise and facilities.**
- **Key areas for Canada to take leading contributing role:**
  - **Plasma-material interactions.**
  - **Deuterium, tritium production, storage, handling.**
  - **Fusion blanket technology**
    - **Build upon past efforts with CFFTP.**
  - **Neutronics/radiation transport modeling.**
  - **Hybrid fusion-fission reactor technology.**

END

Supplementary Slides

Where Canadian Research Facilities Fit

- **Fusion-related skills development**
  - **Computational modeling, software tools.**
  - **Experiments, Instrumentation.**
- **Fusion-related technology development (Topical Areas)**
  - **Tritium, deuterium, and hydrogen production, storage and handling.**
  - **Blanket materials manufacturing and testing.**
  - **Thermal-hydraulics analyses and experiments.**
  - **Neutronics and radiation transport analyses; dose calculations.**
  - **Hybrid fusion-fission reactor concept analyses.**

What Do Various Canadian Research Facilities Offer?

- **Positions**
  - **Several Hundreds of R&D staff:**
    - **Scientists, engineers, technologists, technicians, etc.**
- **Resources**
  - **Topical areas of strength:**
    - **Experimental Physics, Computational Physics,**
    - **Fuel manufacturing and testing.**
    - **Thermal-hydraulics, fluid flow, heat transfer.**
    - **Instrumentation and Control.**
    - **Chemistry, Corrosion**
    - **Hydrogen Technologies, Energy Storage.**
    - **Materials Science, Mechanics, Solid Mechanics, Fluid Sealing,**
    - **Mechanical engineering.**
    - **Radiation damage of materials. Radiobiology.**
    - **Systems analyses, economics, social acceptance analyses.**

What do Canadian Research Facilities Need to Expand?

- **Short Term:**
  - **Staff dedicated to fusion-related research activities.**
  - **Re-deploy and re-train current scientific staff**
    - **New fusion-related projects will help enable this effort.**
  - **Acquisition of more computational software tools and hardware.**
  - **Evolutionary hiring of staff with more formal training in various aspects of fusion science and technology (post-docs).**
- **Longer Term:**
  - **Neutron source / irradiation facilities.**
    - **To test structural components and fusion blanket materials.**
  - **Updates of various experimental facilities.**
    - **Example: update of thermal-hydraulic facilities for testing components using non-water coolants, such as liquid metals and molten salts.**
  - **Construction of prototype fusion device / reactor concept.**
  - **Will become more clear as fusion-related research progresses.**

What Linkages will be Enhanced by Existing Canadian Research Facilities

- **What linkages will be enhanced - academic-industry-international?**
- **Research Contracts with Government and Industry**
  - **Preferred.**
- **Partnerships**
  - **With private industry, where a strong business case can be made.**
- **Collaborations**
  - **Strong business case, good leveraging of resources.**
  - **Domestic industry, government agencies/corporations**
    - **OCI, OPG, STDC, NRCan, and others.**
  - **International agencies and Organizations**
    - **IAEA, ITER**
  - **Other national research laboratories in international community.**
    - **LLNL, ORNL, LANL, PPPL**
    - **NFRI (Korea), JET (Culham, UK), Wendelstein (Germany), etc.**
  - **Universities – Domestic and International**
    - **UOIT, U. Toronto, McMaster U., U. Saskatchewan, U. Alberta, and others.**
    - **University of Wisconsin, and others.**

What would be Short-Term Financial Requirement? (2018-2030)

- **Canadian Research Facilities**
- **Annual Budget Request:**
  - **$4 Million to $5 Million per year for 5 years (initially).**
  - **More required for use of experimental facilities.**
  - **Will permit 10 to 15 dedicated R&D staff.**
  - **Could support 2 to 5 projects in key topical areas.**
  - **Depending on progress and knowledge gained, could grow larger.**
  - **Less budget means less can be accomplished.**
- **Projects:**
  - **In the short term, make use of existing staff and facilities.**
  - **Typically 1 to 3-year projects, with potential for update/renewal.**
  - **Monitor for progress and make course-corrections, as needed.**
  - **Discuss with stakeholders in Government of Canada (GoC) to ensure in alignment with GoC interests and priorities (both near-term and long-term).**

What can Canadian Research Facilities Contribute to Fusion 2030?

- **Highly Qualified Personnel (HQP):**
  - **Automatic by-product through work experience on technically challenging fusion-related problems in various topical areas.**
  - **Scientists, engineers, technologists and technicians.**
- **Technology Development:**
  - **Canadian nuclear research facilities could pursue fusion-related R&D in many areas, but the following could build upon historical and existing experience and expertise:**
    - **Tritium, deuterium, and hydrogen production, storage and handling.**
    - **Manufacture and testing of fusion fuel blanket materials and components.**
    - **Thermal-hydraulics analyses and testing of heat transfer components.**
    - **Neutronics and radiation transport analyses of fusion reactor systems.**
    - **Integration of fusion power systems into the hydrogen economy.**
    - **Analysis and concept development for fusion-driven sub-critical systems.**
    - **Economic and social assessments of fusion systems.**

Coherent Path Forward – Integration

- **Focus areas:**
  - **Do what other facilities and laboratories may not be able to do as easily.**
  - **Technologies that share some commonality with more traditional nuclear power industry.**
  - **Build upon past experience and expertise.**
  - **Licensed nuclear sites in Canada site could be used for construction of prototype experimental facilities.**
    - **Important if neutron source rate from DD and DT fusion reactions becomes relatively high.**

Stakeholders

- **Stakeholders in Federal Government / Agencies:**
  - **Natural Resources Canada (NRCan).**
  - **National Research Council Canada**
  - **Canadian Nuclear Safety Commission (CNSC).**
  - **Sustainable Technology Development Canada (STDC)**
  - **Environment Canada, ... and others**
  - **https://www.canada.ca/en/government/dept.html**
- **Stakeholders in Provincial Governments**
  - **Provincial utilities (such as OPG, HQ, NBPower, BC Hydro, etc.)**
    - **Ontario: Ministries of Energy, Environment, Climate Change, Natural Resources, Research, Innovation and Science, Education**
- **Stakeholders in Private Sector**
  - **Power industry (such as OCNI), and others.**

What does CNL/CRL Offer?

- **Visit: http://www.cnl.ca/en/home/facilities-and-expertise/default.aspx**

- **Facilities / Experimental Facilities (over 30):**
- **Analytical Chemistry Laboratories, Chemical and Corrosion Autoclave and Loop Test Facility**
- **Digital Radiography and Computer Tomography Facility ,**
- **Fluid Sealing Technology Metrology Facility**
- **Fuel Development Laboratories**
- **Health Physics Neutron Generator**
- **High Pressure Water Test Loop Facilities , High Temperature and Pressure Test Loop Facilities**
- **High Temperature Fuel Channel Laboratory , Impact Fretting-Wear Facility**
- **Large Scale Containment Facility , Large-Scale Vented Combustion Test Facility**
- **Laser Dimensioning , Laser Welding Facility**
- **Mechanical Testing Laboratories , Metallographic Services Laboratory**
- **Model Development Laboratory, Nuclear Fuel Fabrication Facility**
- **Nuclear Instrumentation Development Laboratory , RD-14M Experimental Facility**
- **Recycle Fuel Fabrication Laboratories, Single-Specimen Uniaxial-Stress Thermal Creep Facility**
- **Small Scale Burst Test Facility, Surface Science Laboratories**
- **Thermalhydraulics Laboratory, Transmission Electron Microscopy Laboratory**
- **Tritium Facility, Van de Graaff Accelerator Facility**
- **X-Ray Diffraction Laboratory**

Supplementary Info

- ***FYI – Govt of Canada is seeking public input on the future of science and "innovation". Feel free to contribute! These are the two links for the government consultations:***
  - ***1. Canada's Fundamental Science Review:***
    - ***http://www.examenscience.ca/eic/site/059.nsf/frm-eng/RVOT-AASJLL***
  - ***2. Innovation Agenda consultation:***
    - ***http://www.ic.gc.ca/eic/site/062.nsf/eng/home***
- ***The first one is the one that the submissions will be private (public cannot see them and has a expert panel). For the second one the submissions are public and less technical.***

CNS-FESTD

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- ***https://cns-snc.ca/home***
- ***https://cns-snc.ca/CNS/fusion/***

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