

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

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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 (1/3)

- **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 (2/3)

- **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. Engineering testing needed.
- **Production, handling and storage of fusion fuels**
 - Deuterium (D) and tritium (T)
 - Interactions of D, T with various materials.
 - Lithium-based blanket materials for producing tritium.
- **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.
 - *Strong interest in this option in China, to complement fully-fusion systems.*
 - *Only require a low performance fusion reactor ($Q \sim 1$) to generate net power.*
 - *Alternative to using fast breeder reactors.*

International Context (3/3)

➤ 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 for pulsed systems. Thermal cycling.
- High temperatures; chemically reactive materials (some cases).
- 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/tritium leaks/contamination.

Canadian Context (1/2)

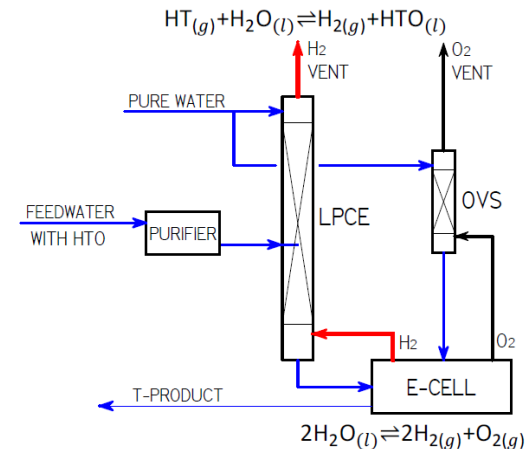
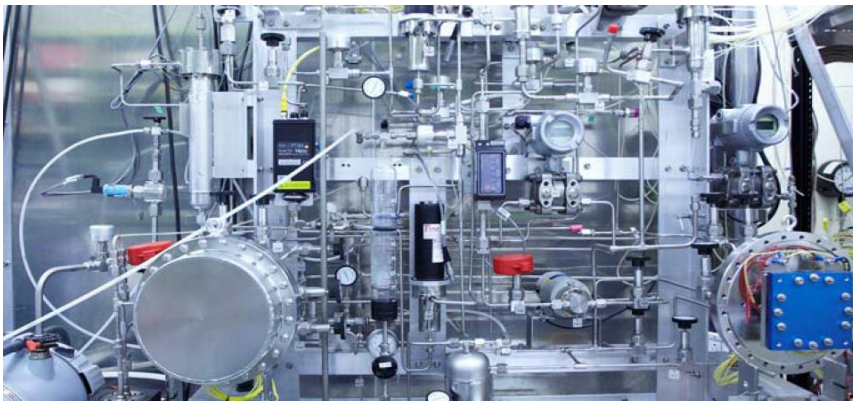
- **Historically, Canada involved at a small scale in carrying out supporting research**
 - **Mainstream and alternative fusion reactor concepts.**
 - *Tokamak, Laser ICF, Magnetic Cusps*
- **Since the early 1970s until 1997, researchers across Canada were contributing to broad-purpose fusion energy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

Canadian Context (2/2)

- **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 pressure tube heavy water reactors (such as CANDU) .

Future Canadian Efforts (1/4)

- **New contributions, build upon current expertise.**
 - **Make use of existing facilities. Experts in research and industry.**
- **Key areas:**
 - **Licensed facilities for handling T, DTO, T₂O.**
 - **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 (2/4)

- **Key Area: 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, U. Sask., U. Alberta, TRIUMF, NINT.*



Future Canadian Efforts (3/4)

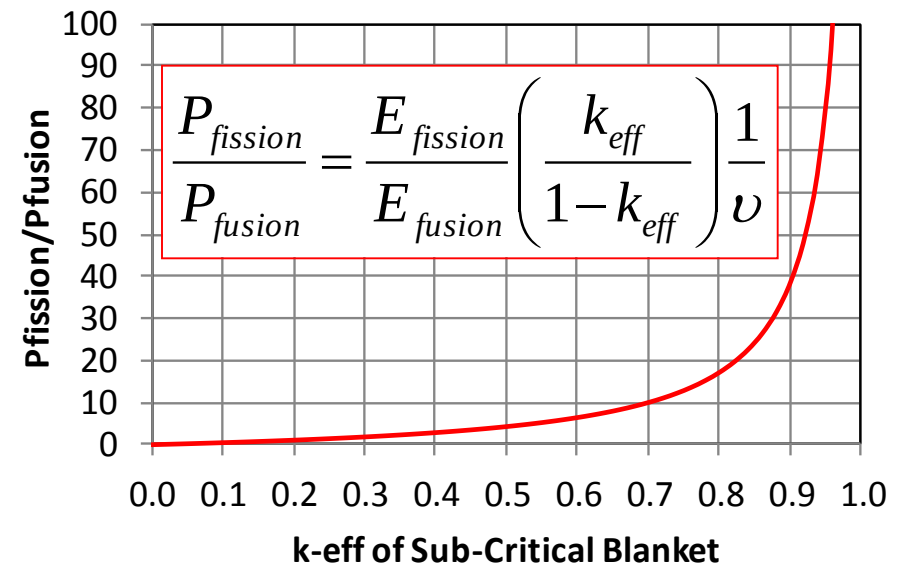
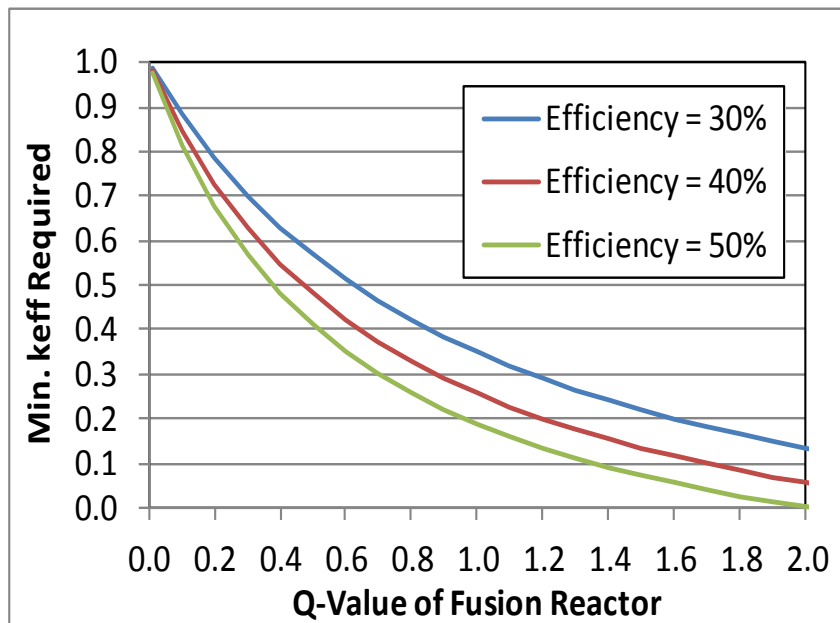
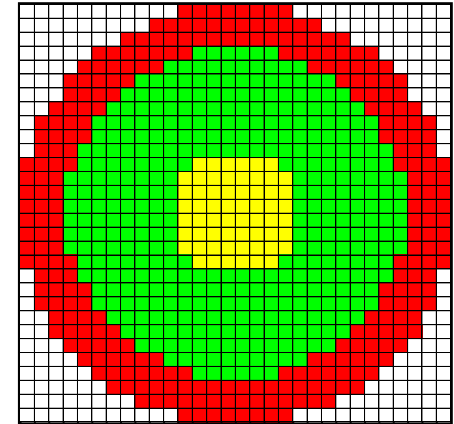
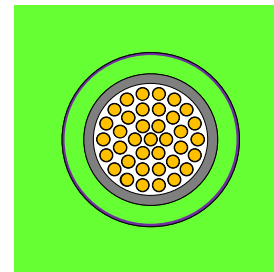
➤ Key areas:

- **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 (gas, liquid metals, molten salts).*
 - *Computational and experimental.*

Future Canadian Efforts (4/4)

➤ Hybrid fusion-fission reactor technology

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



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:
 - Deuterium, tritium production, storage, handling.
 - *Build upon expertise in Canadian nuclear industry with heavy water reactors.*
 - Plasma-material interactions.
 - Fusion blanket technology
 - *Build upon past efforts with CFFTP.*
 - Neutronics/radiation transport modeling.
 - Thermal-hydraulics / heat transfer modeling and experiments.
 - Hybrid fusion-fission reactor technology.

END

International Context (extra - 1)

- 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.*

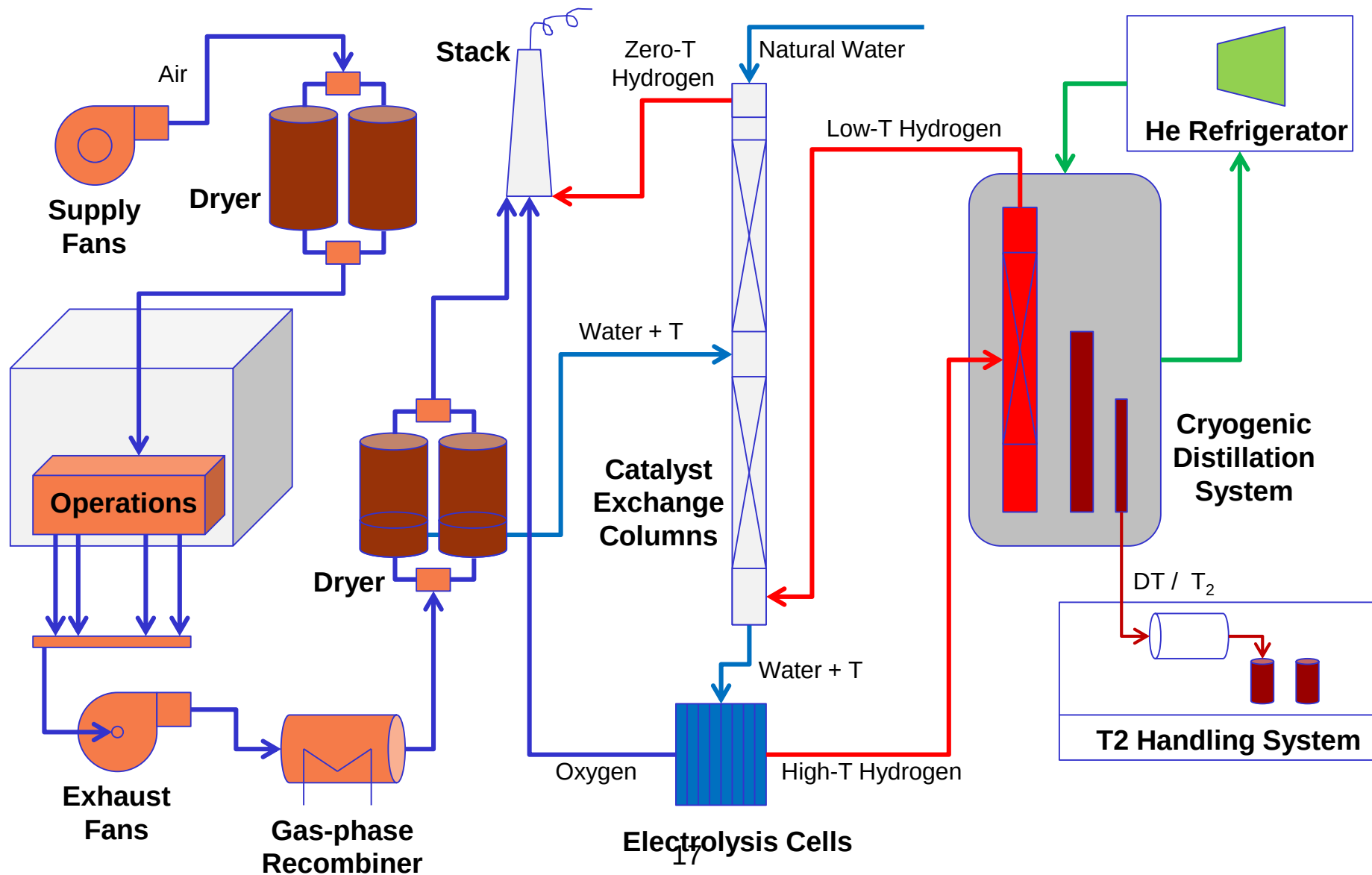
Canadian Context (extra – 1/2)

- **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.**

Canadian Context (extra – 2/2)

- **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.

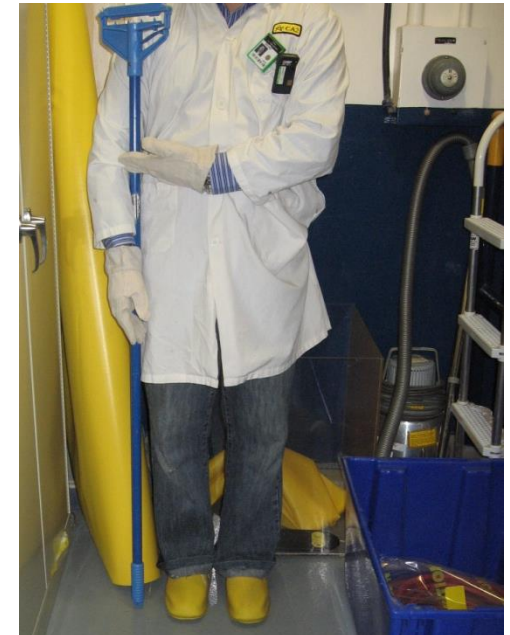
Future Canadian Efforts (extra 1/4)



Tritium Processing System Diagram

Future Canadian Efforts (extra 2/4)

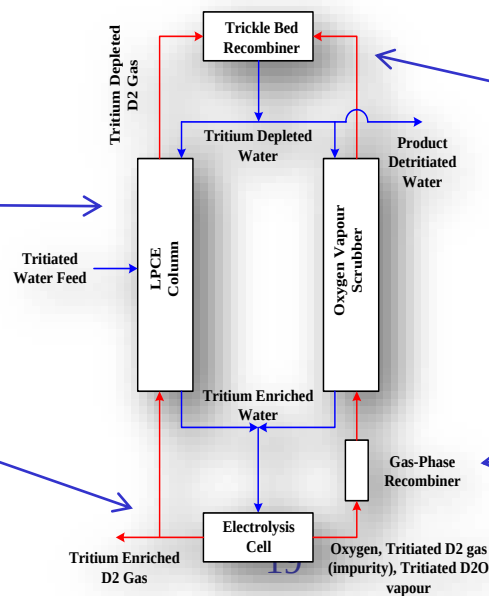
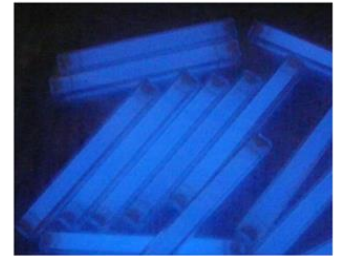
- **Tritium Handling, in water form:**
 - **Best for low concentrations (simple equipment)**
 - **Simple barriers (PPE)**
 - **Readily condensed/adsorbed (e.g. mol sieves)**



Future Canadian Efforts (extra 2/4)

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 (extra 3/4)

➤ 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).

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, which may be used in different fusion reactor design concepts.
- 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 Suggestion:

- \$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
 - OPG, HQ, NBPower, SaskPower, 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

- *Gov. of Canada has sought public input on the future of science and “innovation”. These are the two links to 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>*

CNS-FESTD

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

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