Canada’s R and D Strengths and Innovation Challenges: New Opportunities for Enabling Materials Technologies

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National Science Advisor

Peters and Co., Energy Conference
Lake Louise, Alberta
January 2008
Structure of the Presentation

1. The New Economy: Knowledge, Innovation People
2. Canada’s New S&T Strategy
3. Canada’s Strengths: A Very Strong Research Base, Infrastructure; Education & Skills
4. Weaknesses: Business Innovation and Commercialization Challenges
5. Capitalizing on Our Strengths: Public-Private Partnerships, New Models to Foster Innovation
From Old to New: The Changing Paradigm for Success – Innovation & People

OLD ECONOMY – Grow and attract capital investment in factories and physical infrastructure; sell raw materials

NEW ECONOMY – Innovation is key: enterprises must transform ideas into new products, services, business models; make business processes more productive; add value to natural resources

HUMAN CAPITAL – and the ability to attract the brightest and best gives a competitive advantage
Key Tenets

- Knowledge and innovation, driven by investments in S&T determine a nation’s productivity and international competitiveness.
- Successful nations create competitive advantage through people, skills, ideas and new technologies.
- Government’s role:
  - Create an enabling, effective policy, tax and regulatory environment to ensure a competitive marketplace for companies
  - Provide direct and indirect (eg SR & ED tax credits) support for R&D and infrastructure
  - Strengthen national and international partnerships between players (researchers, institutions, companies) to stimulate innovation and investment
The Diagnostic: Canada’s Strengths

Canada’s Strengths

- Fiscal discipline: 10 consecutive years of budgetary surplus – only country in OECD
- Politically stable, tolerant democracy
- Open market economy; a trading nation
- Best economic footing in G8: strongest job growth over last decade; lowest debt/GDP ratio
- Very strong research base in universities: leads G8 in HERD/GDP
Leading All G-7 Countries: Sound Fiscal Management

General Government Financial Balances
Surplus (+) or deficit (-) as a percent of nominal GDP

Source: OECD Economic Outlook, No. 82 (December 2007)
Building the Research Base
Recent Funding of University R&D

**Brains**
Attract & Retain Best

- Canada Research Chairs
  - 1000 Senior Chairs
  - 1000 Junior Chairs (5 years renewable)
    - $1.5B to date
- Canada Graduate Scholarships
  - 4000 New Awards ($100M/yr)

**Funding**
Provide Strong Research Support

- Grants to University Researchers
  - Basic Funding doubled from 1997-2007
  - Genome Canada: $700M endowment since 09
  - Networks of Centres of Excellence
    - 21 Networks funded - $83M/yr
  - New Centres of Excellence for Research and Commercialization - $366M in 2007

**Provide Outstanding Facilities, Equipment, Infrastructure**

- Canada Foundation for Innovation (CFI) $3.65 Billion endowment has attracted an additional $5B from partners
- CFI New Opportunities Fund – provides start-up funding for young researchers
**Canada Leads G7 in Performance of University R&D**

Higher Education Expenditures on R&D, as a % of GDP (2005)

- Sweden: 0.76
- Canada: 0.72
- Finland: 0.66
- Japan: 0.45
- United Kingdom: 0.45
- Germany: 0.42
- France: 0.41
- United States: 0.37

OECD Science and Technology Database 2007/1
Impacts of New Research Funding on University R&D Environment

- Infrastructure and equipment competitive with best laboratories in world (CFI, GC, Granting Agencies)
- Canada Research Chairs Program has attracted outstanding young and established scholars from other countries (568 Chairholders from outside Canada – Expatriate + Foreign)
- Rising Canadian stars retained
- Has enabled Faculty renewal at a critical time
- Significant growth in research capacity in universities – Faculty, MSc, PhD students, postdoctorals
Strengths

- Canada ranks #1 in OECD: share of population with post-secondary education
- In OECD Program for International Student Assessment (PISA) Canadian 15 year olds ranked #3 behind only Finland and Hong Kong-China in science – easily highest in G8
- 11 Canadian universities listed in the top 200 worldwide in Times (London) ranking (07)

Weaknesses

- Canada ranks only 20th in OECD: natural sciences and engineering degrees as a share of total degrees
- Canada ranks 18th in OECD: share of young Canadians with PhD’s
### Program For International Student Assessment (PISA)

- A triennial survey of the knowledge, skills of 15 year olds

#### RANK OF COUNTRIES ON THE SCIENCE SCALE

<table>
<thead>
<tr>
<th>Rank</th>
<th>Country</th>
<th>Science Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Finland</td>
<td>563</td>
</tr>
<tr>
<td>2</td>
<td>Hong Kong – China</td>
<td>542</td>
</tr>
<tr>
<td>3</td>
<td>Canada</td>
<td>534</td>
</tr>
<tr>
<td>4</td>
<td>Chinese Taipei</td>
<td>532</td>
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<tr>
<td>5</td>
<td>Estonia</td>
<td>531</td>
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<td>6</td>
<td>Japan</td>
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<td>7</td>
<td>New Zealand</td>
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<td>11</td>
<td>Korea</td>
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<td>25</td>
<td>France</td>
<td>495</td>
</tr>
<tr>
<td>29</td>
<td>United States</td>
<td>489</td>
</tr>
</tbody>
</table>

- Source: OECD PISA 2006
Program For International Student Assessment (PISA)

Note: The OECD average is 500 with a standard error of 0.5.
World University Rankings (4th Edition)

- Ranks the World’s Top 200 Universities
- The 10 top ranked institutions are all from USA and EU: HARVARD, CAMBRIDGE, OXFORD, YALE, IMPERIAL COLLEGE, PRINCETON, CALTECH, CHICAGO, UNIVERSITY COLLEGE LONDON, MIT
- McGILL ranks #12, UBC #33, Toronto #45
- CANADA has 11 institutions in the top 200: three above plus QUEENS (#88), MONTREAL (#93), ALBERTA (#97), McMASTER (#108), WATERLOO (#112), WESTERN ONTARIO (#126), SIMON FRASER (#139), CALGARY (#166)
- USA has 57 institutions in the top 200, UK has 32, Germany 11, Japan 11
Breakthrough Achievements

- 2005 Albert Lasker Award
  - Ernest McCullough and James Till (stem cell pioneers)
  - First single dose vaccine against Ebola-Marburg viruses (Nature Medicine 2005 Jul;11(7):786-90)
  - Collaboration between scientists from the Public Health Agency of Canada and the U.S. Army Medical Research Institute of Infectious Diseases (supported by CIHR grant)

- Breast Cancer Research
  - Stephen Narod, University of Toronto - top cited author in the last 10 years; Canada is the 3rd most cited country in the world (ISI 2005)

- Genome Sequencing
  - Robert Holt and international team sequenced the mosquito genome (Science 2002 Oct;4(298):129 – 149)
  - SARS corona virus genome sequenced in the Michael Smith Genomics Centre
Institutional Innovation

- **National Stem Cell Network**
  - Network has 83 Canadian and international principal investigators
- **Four Gates Foundation Grand Challenges grants to:**
  - Canadian labs in Manitoba (infectious diseases), Saskatchewan (vaccines), and British Columbia (antibiotic resistance)
  - Univ. of Toronto team for research on ethical, social and cultural issues
- **Genome Canada successes**
  - Discovery of hormone that controls stress tolerance in plants, potential to improve quality and increase crop yields
  - Collaboration with US DOE and Swedish Umea Plant Centre to complete DNA poplar sequence - commercially valuable tree
  - HapMap – International Consortium to map genetic variation
    - Strong Canadian leadership - McGill University & Génome Québec (Tom Hudson and colleagues)
  - Sequencing Bovine Genome: Genome Canada / USDA / Australia / NZ
  - Aquaculture & Genomics: international collaboration on atlantic salmon, sole, halibut and cod
Focusing on Areas of Research where Canada can be a World Leader

Four clusters of strengths identified

1. **Natural Resources**: Oilsands and related – major strength. Also conventional oil & gas; hydroelectric power; geology; mining; aluminium production; remote sensing

2. **Information & Communication Technologies**: broadband networks, wireless; new media, gaming, animation

3. **Health & Life Sciences**: Genetics, genomics, proteomics, cancer, neuroscience. Strong trend towards interdisciplinary research

4. **Environment**: Remote sensing, physical geography, geochemistry, geochronology, hydrology, climate science, oceanography

Other strengths: • astronomy, cosmology; • emerging areas such as quantum informatics, nanotechnology

Canada’s Innovation and Commercialization Challenges

- Productivity gap with U.S. is widening.
- 54% of R&D in Canada is performed by business, well below OECD average of 68%.
- Canada ranks only 14th in OECD in terms of GERD/GDP (2.0%).
- Canadian industry does not invest enough in R&D. BERD/GDP has been declining since 2001.
- Canada ranks 16th in OECD: high quality patents per million of population.
- Canada ranks 19th in OECD: investment in machinery and equipment as a % of GDP.
- Canada lags in capacity to commercialize results of research into new products, companies in marketplace.
BERD as a Percent of GDP: 1981 - 2006

BERD = Business Expenditures on R&D

Canada’s BERD has declined steadily since 2001

<table>
<thead>
<tr>
<th></th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
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<tr>
<td>Canada</td>
<td>1.29</td>
<td>1.17</td>
<td>1.13</td>
<td>1.12</td>
<td>1.07</td>
<td>1.03</td>
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<tr>
<td>OECD Average</td>
<td>1.57</td>
<td>1.51</td>
<td>1.51</td>
<td>1.49</td>
<td>1.53</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Source: OECD Main Science and Technology Indicators, 2007/2
Q. Why are University - Industry, Gov’t - Industry and Gov’t - University collaborations important?

- In a competitive, global, knowledge based economy, scientific and technological innovation is a key driver.
- Innovation is a ‘body contact sport’ requiring a constant exchange and transfer of knowledge, ideas, discoveries and technological developments at all stages of the innovation cycle.
- Building relationships, partnerships between players (researchers, institutions, companies, investors, customers) is crucial to effective innovation.
- Knowledge and technology transfer is a 2-way process:

  Technology push (Supply side R&D)  ➞  Technology pull (demand side Industry/user)
Benefits of Collaboration and Partnership to Industry

- Access to state of the art scientific research, new ideas, expertise, networks
- Opportunity to identify, build relationships with talented students, grads and post-docs – the work force of the future
- A window on new developments in interdisciplinary science (eg nanotechnology, computational materials science, synchrotron science). Partnering to leverage resources, access major facilities
- Opportunity for:
  - Contract research, short term problem solving
  - Developing a more strategic, longer term R&D relationship
Mobilizing R&D Excellence to Improve Innovation Performance

- Universities and national labs are the wellsprings of innovation for the 21st century
- Large companies can build strategic public-private partnerships with universities to tap the research base for new ideas and approaches to technological innovation
- There are excellent opportunities for SMEs to co-locate and for spin-offs and start-up companies to incubate in university or NRC industrial partnership facilities
- New partnership models for centres and institutes eg. MARS Discovery District (Toronto) or NINT (Edmonton) are meeting places where innovation and entrepreneurship can flourish
- Major Science Facilities such as the Canadian Light Source (CLS Inc) in Saskatoon, one of the world’s most advanced synchrotrons, provide a unique focus on interdisciplinary research and collaboration with industry on real industrial problems.
New Models for Sharing Research Infrastructure, Building Research Capacity

- Co-location of federal labs on university campuses

**National Institute for Nanotechnology**

$120M joint venture between NRC, Government of Alberta & University of Alberta. Opened June 2006

Shared facilities, staff jointly or cross appointed between NRC and the university

Multi-disciplinary institute: physics, chemistry, engineering, biology, informatics, pharmacy and medicine

Incubation facilities for start-ups will act as a catalyst for a nanotech cluster in Edmonton, accelerate commercialization of new technologies and the growth of high tech firms
National Institute for Nanotechnology (NINT): Why we are different

- University Research Culture
  - Creative
  - Free
  - Individualistic
  - Competitive

- NINT
  - Cross appointments
  - Joint projects
  - Shared IP

- Industry Collaborations

- Strategic Directed Focused Supported

Source: NRC
New Models to Foster Innovation & Commercialization: The MaRS Centre

The MaRS Centre is a convergence facility located in the heart of Toronto’s Discovery District, Canada’s largest biomedical research cluster.

- **Phase I** of the MaRS Centre (78K m² in 3 buildings) is home to over 65 organizations: leading researchers, technology transfer groups, SMEs, multinationals, service providers, venture capitalists and networking organizations.
- Private sector tenants outnumber public sector tenants 3:1.
- The **MaRS Incubator** (4K m²) houses 27 promising emerging life sciences, engineering and information technology companies.
- The **MaRS Collaboration Centre** is a conference venue.
- The **MaRS Venture Group** provides hands-on support to companies.
- Phase II space will be doubled
MaRS Discovery District

The MaRS Centre
101 College Street, Toronto

Source: MaRS Discovery District
Institute for Quantum Computing (IQC)
University of Waterloo, Ontario

- Founded in 2002 by personal donations of $33.3M from Mike Lazaridis, RIM co-CEO and wife Ophelia
- **Established Mission**: Advanced fundamental experimental and theoretical knowledge in quantum computation and information processing
- **Research Programs**: From solid state micro-electro mechanical and photonic devices to liquid NMR; mathematical algorithms for communications and computation
- 2004 Mike & Ophelia Lazaridis increase their IQC donation to $50M
- Ontario budget 2006, matched the $50M investment
- **Graduate Programs**: in quantum information science, Quantum cryptography
- 27 core faculty members – largest quantum science research group in world
Canadian Light Source (CLS)

- Third Generation 2.9 GeV Synchrotron built in Saskatoon at University of Saskatchewan – pioneering advanced accelerator design competitive with the best in the world
- Funding of $175M for project – largest ever science infrastructure investment in Canada. CFI largest partner
- Set of 7 beamlines commissioned in Phase I; 7 others under construction in Phase II and 5 in Phase III
- Spectrum of research from: materials science, nanostructures, protein x-ray crystallography, biotechnology, environmental science, molecular spectroscopy, XAFS, biomedical imaging
- National facility with a unique focus on industrial science
Canadian Light Source (CLS) cont’d

Environmental Science & Technologies
- Environmental Impact of Mine Waste
- Carbon Sequestration
- Soil Remediation
- Atmospheric Pollutants
- Biofilms

Natural Resources and Energy
- Catalysis
- Fuel Cells
- Oil and Gas Exploration
- Monitoring Pipelines
- Heavy Oil

Information and Communications Technologies
- Optoelectronics
- Memory Devices
- Quantum Materials
- High-Speed Remote Access
NEPTUNE – North-East Pacific Time-Series Undersea Networked Experiments

- A major joint project with NSF (USA) to instrument the sea floor of N.E. Pacific with fibre optic cable
- Canadian funding of $70M from CFI. USA funding projected at $200M
- Will provide an undersea laboratory to explore science on deep seafloor (new life forms), identify new mineral resources, provide early warning of earthquakes, eruptions, tsunami’s and effective communications;
- Longitudinal studies of seismic events, ecosystem changes, ocean currents, warming
All of these large domes were built by a Canadian company. Original CFHT $150k study contract has led to $150M business in astronomy for Canadian firms, including $44M for the Gemini Project alone (exceeding Canada’s $38M Gemini contribution).
Powering a Revolution in Industrial Materials Design

Computational and Data Mining Approaches to Wear and Erosion Resistant Nanocoatings

A Collaborative Industry – Government Partnership

IMT – Innovative Materials Technologies – an SME
NRC – Institute for Aerospace Research
Can modelling speed up the design of materials?
- Advances in computational power and storage (hardware)
- Advances in algorithm design (software)
- Advances in data mining and knowledge acquisition
- Advances in our understanding of materials behaviour
- Reduction in computing hardware costs

Implementation of multiscale modelling (atomistic → engineering) + experimental validation = optimize materials design

► Significant improvement in the predictive power of modelling
Progress in Computing Technology

Office of the National Science Advisor
Bureau du Conseiller national des sciences
Aerospace Industry Materials Requirements

- Gas turbine engines in modern aircraft operate in extreme conditions: high temperatures, erosive environments

- Metal alloy property requirements:
  - high strength
  - high stiffness
  - high melting temp ($T_m$)
  - ductility
  - low thermal expansion

★ Solutions
- high $T_m$/high strength INTERMETALLICS (REFRACTORY SUPERALLOYS)
- thermal barrier coatings (TBC) (CERAMICS)
- erosion resistant materials (NANOCOATINGS)

Source: Innovative Materials Inc
Materials in Gas Turbine Engines

Blue: compressor section – titanium

Red: hot combustor section: Nickel based superalloys

Yellow: steel supports

Image courtesy Michael Cervenka, Rolls-Royce (Trent engine)
Source: Innovative Materials Inc
- Gas turbines need to provide improved efficiency, operability and reduced costs.
- Current materials are being pushed to their mechanical and physical limits in terms of strength and temperature capabilities.
- High temperature materials allow for reduced cooling requirements and hence higher efficiencies.
Evolution of High Performance Gas Turbine Materials

Operational Temperatures

Schematic of Thermal Barrier System

TBC allow higher temperature of the gas inflow ➔ higher turbine efficiency, lower fuel consumption and larger economical effectiveness.

Source: Innovative Materials Inc
Erosion and Surface Protection: A Very Expensive Problem

**Erosion Damage**
- Exhaust Temperature ↑
- Vibration ↑
- Fuel Consumption ↑
- Engine Efficiency ↓
- Serviceable Life ↓
- Safety ↓
- Performance ↓
- Cost ↑

- In extreme environments (deserts, marine) erosion can reduce life cycle of compressor components by 10x
- Cost of 1 compressor blade (uncoated) = $96.00
- Cost of 1 coated blade = $420
- Number of compressor blades/engine = 700
- Total refurbishing cost for 1 engine = $1M

Source: Innovative Materials Inc
Why Nanostructured Coatings for Erosion Protection?

1. For a **nanomaterial** consisting of atoms of an element A and an element B, the properties of **AB** will differ from a simple extrapolation of the individual properties of A and B (the Law of Mixtures). **Nanocrystalline** materials often have superior properties.

2. A **superlattice** consisting of alternating layers of two nanomaterials A and B (3-10 nm thick) eg. TiN and NbN, has a high hardness.

3. A **layered nanostructure** with alternating layers of a superlattice on metal, gives hardness and toughness. The latter arises because such a layered nanostructure has ductility.

4. A particle impinging on one layer A of a superlattice will not produce a crack through a second layer B.
Nanostructured Coatings

Yields a combination of high hardness and good toughness.

Toughness → strength & ductility

Source: Innovative Materials Inc / NRC Institute for Aerospace Research
### Nitride coatings design

**TiN**

\[ \text{Nitride coatings design} \]

<table>
<thead>
<tr>
<th></th>
<th>Ti</th>
<th>V</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>51</td>
<td>54</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zr</td>
<td>49</td>
<td>Nb</td>
<td>Mo</td>
</tr>
<tr>
<td></td>
<td>53</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>Hf</td>
<td>50</td>
<td>Ta</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td>52</td>
<td>55</td>
<td></td>
</tr>
</tbody>
</table>

\[ (\text{Ti}^{\frac{1}{4}} \text{Mo}^{\frac{1}{4}} \text{Nb}^{\frac{1}{4}} \text{V}^{\frac{1}{4}}) \text{N} \rightarrow \text{R3m} \]

\[ (\text{Ti}^{\frac{1}{3}} \text{Mo}^{\frac{1}{3}} \text{Nb}^{\frac{1}{3}}) \text{N} \rightarrow \text{P3m1} \]

\[ (\text{Ti}^{\frac{1}{6}} \text{Mo}^{\frac{1}{6}} \text{Nb}^{\frac{1}{6}} \text{Zr}^{\frac{1}{6}} \text{Cr}^{\frac{1}{6}} \text{V}^{\frac{1}{6}} \text{Hf}^{\frac{1}{6}} \text{W}^{\frac{1}{6}}) \text{N} \rightarrow \text{R3m} \]

Source: Innovative Materials Inc / NRC
Designed Coating: Greater Erosion Resistance

Source: Innovative Materials Inc

1/7 the erosion rate of TiN
7x as erosion resistant
### Why do we need structure prediction?

<table>
<thead>
<tr>
<th>Material</th>
<th>Exp. Known systems</th>
<th>% known</th>
<th>Maximum number of systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements (1)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Binaries (2)</td>
<td>4,050</td>
<td>82</td>
<td>4,950</td>
</tr>
<tr>
<td>Ternaries(3)</td>
<td>8,050</td>
<td>5</td>
<td>161,700</td>
</tr>
<tr>
<td>Quaternaries(4)</td>
<td>~1,000</td>
<td>~1</td>
<td>3,921,225</td>
</tr>
<tr>
<td>Higher orders</td>
<td></td>
<td></td>
<td>~10¹⁴</td>
</tr>
</tbody>
</table>

To get reliable results from materials selection there is need to fill in the holes in property space –
- Calculations or estimations – derived data (structure and property)
- Experimental combinatorial method
- Computational combinatorial methods.

Source: Innovative Materials Inc
Illite is a major clay mineral which is a component of sedimentary basins.

Illite occurs as very fine sub-micron and nano-particles preventing laboratory determination of physical properties.

Atomic modelling allows systematic exploration of compositional ranges of stable low energy structures.

Since seismic reflection profiling is the main tool for exploring sedimentary basins; knowledge of elastic properties (of illite) provides accurate, and cost saving, determination of drilling depth and thickness.
Opportunities for New Materials in the Energy Sector

- New protective coating materials for shovels, conveyors
  - Hard, tough materials for drill bits
- Improved performance operating in harsh environments
  - Surface technology corrosion and erosion
  - Mechanisms of embrittlement, creep, fatigue
- Synthetic proppants
- Catalysts for bitumen fractionation, hydrocracking
TBC Materials

Zirconia (AO₂)

YSZ = Yttria stabilized zirconia
• Phase transition for temperature > 1200°C
• Spallation and increased thermal conductivity

Pyrochlore (A₂³⁺B₂⁴⁺O₇)

Phase stable to \(T_m \sim 2300°C\)
• Lower thermal conductivity
• Lower thermal expansion

Combinatorial Solutions

\[
\begin{array}{c|c|c|c}
A & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\
B & 0 & 0 & 0 \\
C & \frac{3}{8} & \frac{3}{8} & \frac{3}{8} \\
O & \frac{3}{8} & \frac{3}{8} & \frac{3}{8} \\
\end{array}
\]

1. Calculate structure stability.
2. Elastic tensors.
3. Physical properties – elastic modulii, Debye’s temperature, specific heat, …
4. Use screens.
5. Potential candidates – \(\text{Gd}_2\text{Zr}_2\text{O}_7\), \(\text{Sm}_2\text{Zr}_2\text{O}_7\), \(\text{Er}_2\text{Sn}_2\text{O}_7\)

Office of the National Science Advisor

Bureau du Conseiller national des sciences
Property trends - ductility


Source: Innovative Materials Inc / NRC
A combination of hardness and ductility (toughness) for coating design
Canada’s S&T Strategy: “Mobilizing S&T to Canada’s Advantage”

Science and Technology Framework

Vision to build a sustainable competitive advantage through S and T, skilled people, translating ideas, knowledge, into applications.

Entrepreneurial Advantage
Canada must translate knowledge into practical applications to improve economic, social prosperity

Knowledge Advantage
Canada must build on S&E strengths, generate new ideas & innovations to achieve global excellence

People Advantage
Canada must develop, attract and retain highly skilled people needed to thrive in the global economy
Gas Turbine Environmental Research Centre (GTERC)

- $30M jointly funded partnership between NRC and Pratt & Whitney Canada
- To develop more efficient and environmentally friendly gas turbine engines
- To provide an increase in airflow capability during the test aircraft engines which can generate exhaust temperatures of 1400°F
- Rolls Royce Canada will use a combustion test cell in their development of low-emission combustors for their gas turbine engines
### Top 15 Research Intensive Canadian Universities

<table>
<thead>
<tr>
<th>Rank</th>
<th>University</th>
<th>Sponsored Research Income FY 2006 ($000)</th>
<th>Research Intensity $ per Full-time Faculty ($000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>University of Toronto</td>
<td>$763,541</td>
<td>$323.4</td>
</tr>
<tr>
<td>2</td>
<td>Université de Montréal</td>
<td>$447,158</td>
<td>$237.0</td>
</tr>
<tr>
<td>3</td>
<td>University of British Columbia</td>
<td>$421,993</td>
<td>$198.4</td>
</tr>
<tr>
<td>4</td>
<td>McGill University</td>
<td>$397,136</td>
<td>$259.1</td>
</tr>
<tr>
<td>5</td>
<td>University of Alberta</td>
<td>$382,810</td>
<td>$252.2</td>
</tr>
<tr>
<td>6</td>
<td>McMaster University</td>
<td>$331,575</td>
<td>$290.9</td>
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<tr>
<td>7</td>
<td>University of Calgary</td>
<td>$262,215</td>
<td>$184.0</td>
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<td>8</td>
<td>Université Laval</td>
<td>$258,948</td>
<td>$191.4</td>
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<td>9</td>
<td>University of Ottawa</td>
<td>$244,003</td>
<td>$239.2</td>
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<tr>
<td>10</td>
<td>University of Western Ontario</td>
<td>$225,946</td>
<td>$173.5</td>
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<tr>
<td>11</td>
<td>Queen’s University</td>
<td>$173,696</td>
<td>$219.3</td>
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<tr>
<td>12</td>
<td>University of Guelph</td>
<td>$149,640</td>
<td>$191.1</td>
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<tr>
<td>13</td>
<td>University of Manitoba</td>
<td>$139,646</td>
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<tr>
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<td>$127,472</td>
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<td>Dalhousie University</td>
<td>$106,895</td>
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Source: RE$EARCH Infosource