CANADA'S NSERC/NRCan/AECL Generation IV Energy Technologies Program

D. Brady[1], T. Anderson[3], D. Guzonas[2], H. Khartabil[2], L. Leung[2], S. Quinn[1], W. Zheng [1]

[1] Natural Resources Canada
580 Booth Street, Ottawa
Ontario, Canada
K2M 2M5
Phone: 613-947-6066 Fax: 613 995-6164
dabrady@nrcan.gc.ca
[2] Atomic Energy Canada Limited, Chalk River Laboratories
[3] Natural Sciences and Engineering Research Council of Canada

Abstract

Of the six nuclear systems endorsed by the Generation IV International Forum, Canada is focusing on the development of the Supercritical Water-cooled Reactor (SCWR) system.

Given the fundamental nature of the research required to support the development of the SCWR, there existed a unique opportunity to establish collaboration between NSERC, NRCan, and AECL. The resulting collaboration created the NSERC/NRCan/AECL Generation IV Energy Technologies Program to fund research in three areas: materials, chemistry, and thermalhydraulics and safety for the SCWR

This paper highlights the establishment of the program with a focus on the research to be undertaken in Canadian universities.

1. Introduction

Canada is working toward achieving a secure and reliable energy supply mix that will be sustainable, environmentally friendly and clean. As concerns grow over the impact of the use of fossil fuels on the environment and the expanding global energy demand, nuclear energy is increasingly accepted as a clean, viable and secure energy source [Martyn, 2007].

Canada is uniquely positioned in the global nuclear market to capitalize on this increased need for nuclear power because it has both nuclear reactor technology and some of the world's largest and richest uranium ore deposits [Canadian Nuclear Association, 2008]. Nuclear energy will remain an integral part of Canada's future energy mix, at least in the medium-term, based on recent announcements of potential "new-builds", new feasibility studies, and decisions to refurbish existing units.

In anticipation of increased nuclear energy demand, and to address concerns associated with nuclear energy, the international community has come together in a unique endeavour to develop the next generation of reactors. The international community recognized that no single nation could overcome the technological and engineering challenges in a timely manner, afford the costs and risks, nor commit the long-term resources required. In 2001, nine countries, including Canada, initiated the Generation IV International Forum (GIF) by signing a charter to collaboratively develop the next generation of nuclear energy systems. The goal is to develop next generation systems that can be licensed, constructed and operated in a manner that will provide a competitively priced and reliable supply of energy, while addressing nuclear safety, waste, proliferation and public perception concerns by the 2030 timeframe [GIF, 2001]. In February 2005, five countries, including Canada, signed the Framework Agreement - a treaty level document that would allow participants to undertake research and development of Generation IV Nuclear systems. Today, there are eight countries, as well as Euratom, that are actively participating through the Framework Agreement.

Participating in the GIF is one means by which Canada will ensure that its strategic goals of energy prosperity, security, and environmental and social sustainability will be achieved [Brady et al., 2007]. Canada's participation in the GIF will further enable Canada and Canadian companies to remain engaged and active players in the global nuclear community.

Canada established its Generation IV National Program in 2006 to ensure that Canada will be able to meet commitments to the GIF and to support Generation IV research and development specific to Canada. From the outset, it was intended that universities would play a major role in undertaking research in support of Generation IV technology. To this end, Natural Resources Canada (NRCan), along with the Natural Sciences and Engineering Research Council of Canada (NSERC) and Atomic Energy of Canada Limited (AECL) established the NSERC/NRCan/AECL Generation IV Energy Technologies Grant Program, focusing on key areas of research for the Supercritical Water-cooled Reactor (SCWR) system.

The paper provides a general overview of the Canadian Generation IV National Program with a focus on the NSERC/NRCan/AECL grant program. Section 2 provides a description of the structure and the roles of the participants and special requirements of the program. A review of key research activities to be undertaken by Canadian universities is provided in Section 3.

2. Canada's Generation IV Program Overview

NRCan is the department in the federal government of Canada responsible for establishing policies, priorities and programs for energy science and technology (S&T). In 2006, NRCan established a national program (Generation IV National Program) to support research and development of the Generation IV reactor systems. The program was established to ensure Canada would meet its international commitments to the GIF while supporting generation IV research of specific interest to Canada. Canada's Generation IV National Program focuses on two of the six GIF nuclear energy systems, namely the SCWR and the Very-High Temperature Reactor (VHTR) systems.

Canada believes the development of a pressure-tube SCWR with heavy water moderation is the most natural evolution of existing CANDU technologies. Several technological advantages are achieved when combining supercritical water (SCW) with the CANDU pressure-tube design, including:

- building on existing knowledge and equipment established in the supercritical fossil plants;
- potential for direct steam-cycle option, which could eliminate expensive steam-generators and related secondary systems;
- pressure tube design allowing for consideration of reheat cycles with the potential for better overall reactor efficiency or combined power and heat applications;
- advanced fuel cycles, which could include the use of thorium or mixed oxide (MOX) fuels; and
- the potential for a completely passive safety system.

Research undertaken in support of the VHTR is synergistic with the needs of the SCWR, and of particular interest to Canada. Notable areas for this system include: high-temperature material development, hydrogen cogeneration, and process heat applications.

Canada's Generation IV National Program aims to include as many organizations in the private and public sectors as possible in order to ensure a truly national program. Another goal is to attract and train highly qualified professionals to work in nuclear and energy related positions within Canada, as well as position Canadian companies to benefit from, and engage in, future market opportunities.

The Gen IV program has identified the following key research priority areas:

- SCWR - Fuel and fuel cycle development
- SCWR - Material research
- SCWR - Water chemistry
- SCWR - Balance of plant
- SCWR - Physics
- SCWR - Design & Integration
- SCWR - Thermalhydraulics and Safety
- SCWR - System Integration and Assessment
- VHTR -High temperature material development
- VHTR - Hydrogen production

Of these, SCWR materials, chemistry, and thermal hydraulics and safety are considered the three areas with the most pressing issues that need to be resolved in order for the SCWR effort to advance to the next level. As such, a majority of Canada's efforts, as well as those of our international partners in the SCWR, are focused in these areas.

To achieve its objectives, the program established two main delivery mechanisms. The first is targeted calls for proposals to the national energy S&T community, which includes federal laboratories, agencies and crown corporations. The second, is targeted calls for proposals to universities though the NSERC/NRCan/AECL Generation IV Energy Technologies.

2.1 NSERC/NRCan/AECL Generation IV Energy Technologies Program

The NSERC/NRCan/AECL Generation IV Energy Technologies Program is a collaborative partnership between NSERC, NRCan and AECL to fund and coordinate nuclear energy research in Canada's universities. The research is directly linked to Canada's commitments to international nuclear energy cooperation through the GIF, and will be an integral part in achieving nuclear research and development results for Canada and our international collaborators. This Program brings to bear the best practices and expertise of each organization.

NRCan is the Government of Canada's main co-coordinator of energy S&T and a long-time funder of energy R&D. NRCan, through its existing networks, coordinates the research of federal laboratories across Canada that have the necessary expertise and capability to undertake research in support of Generation IV technologies. NRCan is also the Signatory to the GIF SCWR and VHTR System Arrangements, with its staff participating in the GIF legal, policy and technical boards and groups.

NSERC is a federal granting agency whose vision is to help make Canada a country of discoverers and innovators for the benefit of all Canadians. Part of NSERC's mandate is to financially support university-based natural sciences and engineering research. Furthermore, co-funding university research in collaboration with NRCan and AECL fits well with the goals of NSERC's Research Partnership Program to foster collaborations between university researchers, government departments and industry, in order to develop new knowledge and expertise, and to transfer this knowledge and expertise to Canadian-based organizations. It also supports the federal governments focus on combating climate change through the development of alternative energy sources and improvements to the efficiencies of existing systems such as the next generation nuclear power plants.

This grant program will also develop highly qualified personnel for the nuclear industry. Many of the engineers and scientists who will design and construct a GEN IV reactor for deployment in 2030 have not yet entered the workforce, while the majority of the current Canadian nuclear workforce will have retired by then.

AECL, as Canada's flagship nuclear energy corporation, holds significant R&D capability in terms of expertise and facilities. Therefore, Canada's participation in GIF relies on AECL resources and expertise as a performer of Gen IV R&D. Furthermore, AECL plays a key role in meeting Canada's GIF commitments and supports Canada's Generation IV National Program by providing technical leadership for the majority of Generation IV related activities, representing Canada on various GIF groups, providing in-kind contribution, and conducting R&D through its own funding and through funding received from the Canadian National Program.

Program Mandate

In 2008, a memorandum of understanding was signed between NSERC, NRCan and AECL to establish the NSERC/NRCan/AECL Generation IV Energy Technologies Grant Program to support Canadian Gen IV R&D conducted at Canadian universities.

This grant program is co-funded by NSERC and NRCan's Office of Energy Research and Development. Canadian academic researchers, in collaboration with AECL and NRCan scientists, receive grant funds to undertake specific research in support of Generation IV Energy Technologies. A targeted call for proposals from the NSERC/NRCan/AECL Generation IV Energy Technologies Program focused on the three key research priority areas highlighted in Section 2, namely; SCWR materials, chemistry, and thermalhydraulics and safety.

A two-stage review process was established, with the Generation IV Portfolio Committee performing an initial review of letters of intent to ensure that only research proposals investigating the three Canadian Gen IV research priority areas were invited to submit full applications. Thirty-four letters of intent were received, and 29 invitations to submit full applications were sent to 20 universities. The review of the full applications followed NSERC's established peer review process. Each of the funded proposals had a clear plan to direct, manage and integrate the research activities in support of Canada's Generation IV National Program and its international commitments. Each proposal demonstrated an integrated approach to the research problem so as to fully exploit the research facilities and resources available at government and industrial laboratories, and at universities.

Under GIF guidelines, participants performing Generation IV research are required to have an established quality assurance (QA) program. In order to comply with this requirement, AECL has taken the lead in establishing a QA program for Program participants (e.g., universities) that do not currently have an established and recognized QA program. The basis for the establishment of this QA program is the GIF approved Quality Management System (QMS) Guidelines. Using the GIF QMS Guidelines, AECL has developed a QA template that consists of two main elements: a) a checklist to be completed before or shortly after the work starts, ensuring the proponent understands the QA requirements prior to undertaking the research, and b) simplified procedures that contain the main compliance elements for different activities.

Further to the GIF QA requirements, participants in the program agreed to adhere to the intellectual property provisions in the GIF SCWR Project Arrangements. Under the IP provisions, the participants undertaking research in support of the GIF own the IP developed, but agree to share the IP royalty free with other GIF participants if requested. The participant requesting access to the IP must demonstrate how the IP will be used to further advance research of the SCWR system. Each researcher had to agree to abide by GIF QA requirements and the intellectual property provision in the Project Arrangements under which the research is being offered.

3. NSERC/NRCAN/AECL Program Research Activities

Canada is engaged in all research areas related to the development of the SCWR. The Program builds upon national expertise in both fossil-fired SCW power plants and pressure-tube nuclear reactor design. The main research areas are described briefly below. This section focuses key on research activities that are associated with the NSERC/NRCan/AECL Program.

3.1 CANDU-SCWR Development in Canada

The CANDU-SCWR is similar to a typical CANDU reactor but with the following major differences:

1) The spacing between the fuel channels (lattice pitch) is smaller to reduce heavy water cost and to achieve desirable neutronic characteristics (e.g., negative void coefficient).

2) The coolant is light water at supercritical conditions (system pressure of 25 MPa and outlet temperatures up to 625 ^{o}C).

3) A direct thermodynamic cycle is employed using existing supercritical turbine technology.

4) An improved fuel channel design with internal insulation [Chow and Khartabil, 2008] to accommodate the high coolant pressure and temperature.

The use of pressure tubes is expected to be less challenging than the use of a large pressure vessel operating at supercritical conditions. The use of heavy water as a separate moderator provides unique opportunities to optimise the SCWR core parameters, and to adapt the design to various advanced fuel cycles. In addition, the role of the moderator as a passive heat sink can be significantly enhanced by optimizing the heat transfer characteristics of the fuel channel [Khartabil, 2008]. Optimization of the CANDU-SCWR design is carried out under a dedicated project led by AECL where the results of the R&D are used to update the design; this project also guides and provides input to the R&D projects that are described next. These projects are key to the development of the SCWR because they address viability issues that need to be resolved before the R&D activities are expanded to cover other areas.

3.2 CANDU SCWR Material Research

The expected high thermal efficiency of the SCWR arises from high operating temperatures and pressures in the reactor core (625 ^{o}C and 25 MPa), which are much higher than the temperatures and pressures of the current CANDU designs.

These aggressive conditions render most of the current reactor materials unsuitable for use as in-core and some out-of-core components, such as the outlet feeders. The stringent requirements for nuclear materials in a nuclear system also preclude the use of many of the alloys used in fossil-fired SCW plants. For example, the high corrosivity of water at supercritical state and the associated high solubility of dissolved gases cause rapid corrosion of Grade 91/92 steel (T/P 91/92), a commonly used high-temperature ferritic-martensitic alloy for fossil SCW plants. Zr-based alloys, a work-horse materials for fuel-cladding and CANDU pressure tubes, show excessive corrosion and creep at SCWR temperatures. While the insulated fuel channel concept solves this problem for the pressure tube, Zr-based alloys will not likely be practical as a fuel cladding for an SCWR. Preliminary research findings by the international community indicate that most 3XX series stainless steels creep or crack too easily in supercritical water. Ni-based alloys have been shown to have good corrosion resistance under SCWR conditions, but their susceptibility to stress corrosion cracking and to irradiation-induced helium embrittlement is a major concern.

To improve the resistance of materials to creep, stress-corrosion cracking and neutron irradiation-related damages, the NSERC program, in conjunction with the effort at AECL-CRL, NRCan-MTL and NRC, expects to deliver innovative research results in the following topical areas:

1. Assessment of available alloys and development of new alloys for SCWR applications.
2. Development or modification of surface coating processes for producing corrosion and SCC-resistant materials
3. Assessment of Excel Zr alloy as a candidate pressure tube material
4. Mechanistic studies of the fundamental corrosion processes of alloys in this special (partially water-like and partially gas-like) state of water.

As discussed elsewhere [Zheng et al, 2008], it is likely that no single conventional material will possess all the required properties for SCWR in-core or out-core applications. Therefore, development of candidate component using dual or multiple materials is part of the effort.

In addition to corrosion and mechanical performance considerations, the Gen IV materials R&D effort must also consider the fate of the corrosion products released from the materials into the coolant, in particular the possibility that they may deposit on the fuel cladding, or become neutron activated and then transported and deposited on out-of-core surfaces, leading to high radiation fields. This concern may limit the use of some of the common alloying elements such as Al, Co, Mo and W.

A key aspect of the Canadian effort, as part of this special Gen IV program as well as other related ‘infrastructure’ development initiatives funded by the federal and provincial agencies, is to significantly expand, in a coordinated manner, the Canadian research capabilities available for Gen IV materials research. These include corrosion test facilities (engineering and bench-scale SCW loops and autoclaves, corrosion fatigue testing system), high temperature (up to 850ºC) creep and creep-fatigue testers, and specialized transmission electron and focused ion-beam microscopes for handling radioactive materials samples. As part of the funding for NRCan-MTL’s relocation to the McMaster Innovation Park, a new suite of materials processing and assessment equipment has been approved. The nuclear-materials research facilities, which are a significant part of the overall facility, can be accessed by Gen IV NSERC researcher groups through the MTL-NSERC Resource for Innovation of Engineering materials (RIEM) mechanism.

3.3 CANDU SCWR Chemistry Research

In addition to proper materials selection, the long-term viability of any SCWR design will depend on the ability of designers to predict and control water chemistry to minimize corrosion and the transport of corrosion products and radionuclides [Guzonas et al., 2008]. Meeting this goal requires an enhanced understanding of SCW chemistry, in particular, water radiolysis and corrosion product transport and deposition.

3.3.1 Radiolysis

One of the most significant water chemistry challenges for any SCWR design will be to understand and mitigate the effects of water radiolysis; preliminary studies suggest markedly different behavior than that predicted from simple extrapolations from conventional water-cooled reactor behavior. The radiolytic degradation of water leads to the formation of a variety of oxidizing species such as O_2 and H_2O_2; these species can significantly increase the rates of various corrosion processes. The strategy used in pressurized light and heavy water reactors of adding excess hydrogen at concentrations sufficient to suppress the net radiolytic production of primary oxidizing species may not be effective in an SCWR.

Because experiments at very high temperatures and pressures, and especially beyond the critical point of water, are difficult to perform, computer simulations using a combination of molecular dynamics (to generate reliable, molecularly-detailed configurations of SCW at selected temperatures and densities) and Monte Carlo simulations (to simulate the deposition of energy by the incident radiation and to model the subsequent radiolysis process to determine the yields of radiolytic species) has been initiated at the University of Sherbrooke. The goal is to develop a radiolysis model capable of predicting the concentrations of various oxidizing species in-core and immediately downstream of the core outlet. These data are required in order to specify water chemistry conditions for materials testing.

The success of the modeling effort will depend on the availability of experimental data on the reaction rate constants required as input to the model. While some of these data will become available as a result of research programs underway in other countries, the number of unknown parameters is large. Therefore, a Canadian experimental program is also being established, including radiolysis experiments in SCW using the muon[1] beam at TRIUMF. Frequent interactions between modelers and experimenters will ensure that the correct experiments are being performed.

3.3.2 Corrosion Product Transport

The release and transport of corrosion products from the surfaces of system components and their subsequent deposition has been a serious concern for all water-cooled nuclear power plants. Using a simple model of Fe transport in an SCWR and input parameters extrapolated from subcritical temperatures, Burrill (2000) predicted that, for Fe saturated coolant at the channel inlet, a peak deposit weight of 108 mg/cm^2 could be obtained. This is about 10 times that seen in Russian fossil-fired SCW plants, and 10^4 times higher than values typically found on CANDU reactor fuel sheaths. High concentrations of corrosion product transport can lead to: a) increased corrosion product deposition on fuel cladding surfaces, leading to reduced heat transfer and the possibility of fuel failures, and b) increased production of radioactive species by neutron activation, resulting in increased out-of-core radiation fields and worker dose. Very little is

[1] Muonium behaves as a light isotope of hydrogen.

known about how corrosion products may behave in an SCWR; data from fossil-fired SCW power plants suggests a significant risk of deposition of corrosion products released from out-of-core surfaces onto fuel cladding surfaces in-core, even when materials with low general corrosion rates are used [Guzonas et al., 2009].

Because the SCWR will operate at pressures of 25-30 MPa, well above the critical pressure of water (p_c = 22.1 MPa), there will be no boiling and no "steam" phase. Instead, the coolant will undergo a transition from "water-like" to "steam-like" densities (from ~0.8 to 0.1 g/cm^3) as it passes from subcritical to supercritical conditions through the critical temperature at t_c = 373ºC. This is a frontier region of hydrothermal chemistry; the SCWR will produce unique water chemistry and most quantitative studies of aqueous solutes do not extend above 300ºC. Solubility experiments at high temperatures are exceedingly difficult, and therefore, calculation of the solubility of magnetite and other metal oxides from other thermodynamic data is an attractive alternative route to predict corrosion product deposition. Therefore, as with the radiolysis program, corrosion product transport is being assessed by a combination of modeling and experiments. The modeling work includes the development of a self-consistent set of thermodynamic data. The experimental program is being performed at a number of Canadian universities using engineering-scale loop tests as well as smaller bench-scale loops and methods such as the diamond anvil cell. Key thermodynamic parameters will be obtained using methods such as conductance and various spectroscopic techniques (e.g., UV-visible, Raman, X-ray absorption and X-ray fluorescence). Tests will also be performed to study potential oxygen scavengers for use as part of the development of a chemistry control strategy.

Work is also underway to address a key requirement for SCWR chemistry control strategies: the development of suitable sensors for on-line measurement of the main chemistry parameters. On-line monitors will be required because the changes in water chemistry that occur upon cooling from supercritical to subcritical conditions will mean that samples taken after cooling will not be representative of process conditions.

3.4 CANDU Thermalhydraulics and Safety Research

Thermalhydraulics characteristics at supercritical water-flow conditions are required in support of the design and qualification of the fuel bundle and safety analyses for the SCWR. The GIF work plan lists tasks required for completing the conceptual design of the SCWR, and covers key areas such as heat transfer, critical flow, instability, development of analytical toolsets for supercritical-water applications, and preliminary safety analyses. Completing these tasks will demand a large coordinated effort between research organizations and the academic community.

The Canadian contribution to various key areas of the GIF SCWR Thermalhydraulics and Safety Project has been identified in the Project Plan. It consists of projects directly relevant to the CANDU SCWR fuel and core designs at AECL and fundamental research and development (R&D) projects related to the SCW flow and heat transfer at various Canadian universities [Boyle et al., 2009]. In addition, AECL has initiated other collaborative projects with Canadian universities (with proposed support from the Ontario Research Fund) and Chinese universities to develop the future reactor design. Information from these projects is also applicable to the Gen-IV SCWR design and will be included as part of the Canadian contribution to GIF. The

Thermalhydraulics and Safety projects in the grant program focus on improving/developing heat-transfer prediction methods for supercritical heat transfer in tubes and bundles, examining the stability and critical-flow characteristics of supercritical flow, and performing simulations of the depressurization phenomena through small breaks at supercritical conditions. The tube-data-based prediction method for supercritical heat transfer is applied in subchannel analyses, while the bundle-data-based prediction method is implemented for safety analyses.

3.4.1 Supercritical Heat-Transfer Studies

The design criterion for the CANDU-SCWR is based on the cladding temperature limit for normal operation and trip analyses. Experimental data on heat transfer are crucial in establishing this limit accurately [Pioro and Duffey, 2005]. A database on supercritical heat transfer in tubes has recently been assembled [Leung et al., 2008]. It is being applied to assess various correlations and, if necessary, to improve prediction accuracy. A project has been initiated at the University of Ottawa to develop a look-up table for heat transfer covering trans-critical conditions (i.e., both the near-critical region and the supercritical region) in tubes. Advantages of the look-up table approach include superior prediction accuracy (representing directly the database), wide-ranging applicability, and smooth transition in tabulated values between different regions.

Performing heat-transfer experiments with supercritical water flow is complex and expensive due primarily to the harsh operating environment and the high level of required heating power. Surrogate fluids (such as carbon dioxide and refrigerants) have been suggested for replacing water in heat transfer studies. These fluids were previously utilized in studies of critical heat flux and film-boiling heat transfer at subcritical conditions. Applying these fluids reduces experimental cost and schedule, reduces test-section design and operation risk, and increases testing flexibility. This arises from the fact that supercritical conditions for surrogate fluids are less severe than those for water.

A project has been established to expand a sub-critical refrigerant test facility at Carleton University for supercritical heat transfer experiments. The test facility can accommodate test sections such as tubes, annuli, and small bundle subassemblies to study various separate effects on supercritical heat transfer. A tubular test section is being designed for commissioning the facility using Refreigerant-134a. The first test series examines the effect of spacing devices on supercritical heat transfer in annuli.

Large amounts of supercritical heat transfer data are available for tubes, but there is a lack of data for bundle geometries. A heat-transfer test facility has been designed for construction at the University of Ottawa (UO) [Groeneveld et al., 2008]. It employs carbon dioxide as working fluid and is capable of testing small bundle subassemblies. Key components of this test facility have been procured. A project has been arranged to complete the construction of the facility and perform commissioning test using a tubular test section. The commissioning data will be compared against experimental data in the AECL database [Leung et al., 2008]. Another project has been established to perform heat-transfer experiments using a 3-rod bundle string in this test facility. The objective of this experiment is to generate bundle heat-transfer data in carbon dioxide flow. These data are essential for quantifying the impact of flow and enthalpy distributions in subchannels on supercritical heat transfer, and are also applicable for validating subchannel codes and computational fluid dynamic tools.

Computational fluid dynamic (CFD) tools have been widely used in support of fuel design for SCWR. These tools are based on fundamental conservation equations but depend strongly on the turbulence model selected in the calculation. Currently, there is little (or no) information on turbulence measurements in supercritical flow. A project has been awarded to the research team at the University of Ottawa to obtain turbulence measurements in a 22.9-mm tube with supercritical carbon dioxide flow. Subsequently, the measurement technique may be implemented to the 3-rod bundle.

3.4.2 Safety-Related Studies

The CANDU-SCWR may be susceptible to dynamic instability due to the sharp variation in fluid properties (such as density) at the vicinity of the critical point. This instability may lead to high cladding temperatures in the fuel, prematurely impacting on the operating and safety margins. Analytical models have been developed for predicting the onset of dynamic instability with in-phase 1D oscillations and out-of-phase 2D and 3D oscillations [Chatoorgoon et al., 2007]. A project has been approved for the University of Manitoba to perform flow-stability experiments using carbon dioxide in single and parallel channels. Test data will be applied for validation of the analytical model.

In support of the design and operation of the reactor safety (or relief) valves and the automatic depressurization system, the critical (or choked) flow characteristic must be established at supercritical conditions since current information has been obtained at subcritical conditions. This established characteristic is also required in the analysis of a postulated large-break loss-of-coolant accident event. A project has been awarded to the Ecole Polytechnique to construct a test facility for critical-flow measurements in water at supercritical conditions. Blow-down experiments from a supercritical pressure tank to a medium pressure reservoir will be performed with discharge nozzles of different shape, size and length. Direct experimental measurements of the temperature and pressure along the discharge nozzles, and of the void fraction and flow rate at the nozzle outlet will be obtained. These data will enable accurate benchmarking of existing critical-flow models and, if needed, development of new ones.

The basic thermalhydraulics phenomena during hypothetical accidents involving depressurization of the reactor coolant system at subcritical water conditions (such as critical break discharge and flashing behaviour) have been extensively analyzed within the nuclear industry. However, very little analysis is available for reactors near or above the supercritical pressure. A project has been initiated at McMaster University to examine depressurization characteristics for near critical and supercritical systems, taking into consideration the unique properties as the fluid transitions through the critical state. These systems include simple pipes and tank geometries (which have been previously studied at sub-critical conditions) and constricted flow passage through nozzles (simulating the small breaks phenomena). Simulation results will be compared against experimental data at subcritical and supercritical conditions.

4. Conclusion

The NSERC/NRCan/AECL Generation IV Energy Technologies Program funds nuclear research in Canadian universities that is directly aligned with the needs of Canada's nuclear industry. This Program is a critical means by which Canada will fulfill its obligations under the Generation IV International Forum treaty agreement. The breadth of scope and quality of R&D that is being done through this program would not otherwise be possible given the budgets available and given the multidisciplinary nature of the problems being addressed.

The success of the Program is based on utilizing the best practices and expertise in each of NSERC, AECL and NRCan to deliver a cost-effective and innovative program. It is founded on the sharing and integration of facilities, knowledge and expertise. Indeed it is expected that this Program will help to ensure that Canada is well positioned in the long term to benefit from the coming nuclear renaissance.

5. References

Brady, D., Duffey, R., Khartabil, H., Sadhankar, R. and Suppiah, S., "Generation IV Reactor Development In Canada", 3rd Int. Symposium on SCWR, Shanghai, China, March 12-15 2007.

Burrill, K.A., [2000] "Water Chemistries and Corrosion Product Transport in Supercritical Water in Reactor Heat Transport Systems", 8th BNES Conference on Water Chemistry of Nuclear Reactor Systems, Bournemouth, U.K., 22-26 October 2000.

Canadian Nuclear Association, "Canada's Nuclear Energy: Reliable, affordable and clean electricity", 2008. As cited on January 3, 2009 from the World Wide Web site: http://www.cna.ca/english/pdf/NuclearFacts/2008/CNA_Nuclear_Energy_Booklet08.pdf.

Chatoorgoon, V., Shah, M., Duffey, R., "Linear Predictions of Supercritical Flow Stability in Parallel Channels", Proc. 3rd Int. Symposium on SCWR – Design and Technology, Shanghai, China, March 12-15, 2007.

Chow, C.K. and Khartabil, H.F., "Conceptual fuel channel designs for CANDU-SCWR", Nuclear Engineering and Technology, V. 40, No. 2, 2008.

Generation IV International Forum, "Generation IV International Forum Charter", 2001. As cited on January 13, 2009 from the World Wide Web site: http://www.gen-.org/GIF/Governance/charter.htm.

Groeneveld, D.C, Tavoularis, S., Gudla, P.R.S.S. , Yang, S.K.. and Leung, L.K.H. , "Analytical and Experimental Program of Supercritical Heat Transfer Research at the University of Ottawa," Nucl. Eng. Techn., Vol. 40, No. 2, pp. 107-116, 2008.

Guzonas, D., Tremaine, P., Jay-Gerin, J.-P., "Chemistry Control Challenges in a Supercritical Water Cooled Reactor", NPC '08, Int. Conf. on Water Chemistry of Nuclear Reactor Systems, Sept. 15-18, 2008, Berlin.

Khartabil, H.F., "Review and status of the Gen-IV CANDU-SCWR passive moderator core cooling system", Proc. 16th Int. Conf. on Nuclear Eng. (ICONE-16), Orlando, FL, USA, May 11–15, 2008.

Leung, L.K.H., Groeneveld, D.C., Gudla, P.R.S.S. and Tavoularis, S., "An Expanded Database on Supercritical Heat Transfer for Water, Carbon Dioxide and Other Fluids", Proc. 7th International Topical Meeting on Nuclear Reactor Thermalhydraulics, Operation and Safety (NUTHOS-7), Seoul, Korea, October 5-9, 2008.

Martyn, C., "Getting real – How do Canadians view the environment and energy?", Ipsos Reid, March 2007. As cited on January 10, 2009 on World Wide Web site: http://www.cna.ca/english/articles.asp#research.

Pioro, I.L. and Duffey, R.B., "Experimental Heat Transfer to Supercritical Water Flowing inside Channels (Survey)," Nucl. Eng. Des. Vol. 235, No. 22, pp. 2407-2420, 2005.

Zheng, W., Guzonas, D., Wills, J., Li, J., "Novel Approach to the Development of In-Core Materials for a Supercritical Water Cooled Reactor", 16th Pacific Basin Nuclear Conference (16PBNC), Aomori, Japan, Oct. 13-18, 2008, Paper ID P16P1413.