

Royal Military College of Canada – Brent J. Lewis IRC

NSERC/UNENE/COG Industrial Research Chair
in Nuclear Fuel



Overview

Prof. Brent Lewis was appointed the NSERC/UNENE/COG Industrial Research Chair (IRC) in Nuclear Fuel in the Department of Chemistry and Chemical Engineering at the Royal Military College of Canada (RMC) in September 1, 2007. The main objectives of the research chair are to better understand nuclear fuel performance during normal and reactor accident conditions, including the behaviour of advanced and next generation fuel designs. This research program developed from a previous partnership with the CANDU Owners Group (COG) and NSERC through a four-year Collaborative Research and Development (CRD) Grant in defective fuel behaviour from September 2004 to August 2008.

Research Program

Nuclear fuel is at the heart of any improved design for the CANDU reactor and is a key enabling technology for enhancement of reactor safety, performance and economics, as well as continued sales of Canadian nuclear technology worldwide. This research is of particular importance in light of the need for increased generation capacity and the realization of next generation reactors. The specific areas of research for this chair are: nuclear fuel chemistry; nuclear fuel and fission product release behaviour during normal and reactor accident conditions; fuel-failure monitoring techniques; and fuel performance prediction to improve operation and safety margins in present, advanced and future reactor designs.

Research Facilities

The research made use of gamma spectrometry and neutron activation analysis capability at the SLOWPOKE-2 nuclear reactor facility at RMC. A high-temperature Thermal Gravimetric Analyzer/Differential Scanning Calorimeter has also been installed to support fuel studies. In addition, work involved the use of software for Gibbs-energy minimization with the Facility for the Analysis of Chemical Thermodynamics and finite element modelling with COMSOL multiphysics and ANSYS. The research group also collaborates with other groups at the national laboratory and international institutes.

Research Team

Both the COG/NSERC CRD and NSERC/UNENE/COG IRC involved collaboration with Prof. W. T. Thompson also at RMC in the area of fuel thermochemistry. From September 2007 to September 2009, the NSERC/UNENE/COG IRC research team was comprised of one research associate and two research assistants, as well as twenty-one graduate students (8 PhD, 13 MASc). Three PhD projects were carried over from the CRD investigation and involved research in fuel thermochemistry modelling of Advanced CANDU Reactor (ACR) fuel, fuel-failure monitoring and the development of a phase-field model for fuel melting. These three students graduated in the spring of 2009; two of these students are now employed at the Institute of Transuranium Elements and the Canadian Nuclear Safety Commission; Dr. Corcoran has joined the RMC as an Assistant Professor in support of this IRC activity. Two MASc students, who also graduated in the Spring of 2008 and 2009, were involved in a gamma spectrometry analysis of coolant activity at a commercial Nuclear Generating Station, and leaching studies of Low Void Reactivity Fuel (LVRf), and are now working in the Department of National Defence (DND). Four ongoing PhD projects involve the development of a defective fuel performance code, stand-alone Gibbs Energy Minimization tool for fuel thermochemistry computation, and development of an on-line fuel failure monitoring tool and design of an instrumented out-reactor test for defective fuel studies both in collaboration with Atomic Energy of Canada Limited (AECL). Seven on-going MASc projects involve the development of a hydriding model for defective fuel analysis, fuel-bundle modelling, fuel thermochemistry model for the SOURCE-2 industry standard toolset (in collaboration with AECL), noble gas tagging methods for demonstration irradiations, development of ultrasonic testing instrumentation for discharged CANDU fuel bundles, stress corrosion cracking model for the ACR, and a dissolution study of ACR fuel. In addition, one PhD student and four MASc students joined our research group in September 2009 in fuel-related projects including: actinide burning in multi-spectral CANDU reactors, high-temperature fuel-behaviour modelling, Be-brazing reduction in CANDU fuel manufacturing (in collaboration with Cameco Fuel Manufacturing), isotope identification in support of non-proliferation treaty (NPT) monitoring (in collaboration with Health Canada), and delayed-neutron monitoring techniques for defective fuel location in CANDU reactors (in collaboration with Candesco).

Two other MASc students and three PhD students are supervised by faculty also involved with this IRC that are further funded by NSERC Discovery grants as well as other government departments including the DND and Canadian Space Agency.

Interaction with Industry, University and Other Organizations

This chair program supplements research and development activities in nuclear fuel technology being carried out by the COG, which benefit the national laboratory, reactor designer and commercial utilities. In particular, the university research contributes directly to three COG work packages (WP) on fuel oxidation behaviour modelling (WP 22324), fuel-failure monitoring (WP 22303) and fuel thermochemistry (WP-22326).

The university research has involved strong collaboration with Atomic Energy of Canada Limited (AECL) – Chalk River Laboratories (CRL) and Sheridan Park (SP) on fuel development studies for the ACR, which have included X-ray diffraction studies at the university, fuel thermochemistry modelling of irradiated CANDU fuel and ACR burnable

neutron absorber material and use of coulometric titration (CT) equipment at the CRL for validation of the fuel thermochemistry model as part of COG WP-22326. The university has also worked closely with Bruce Power and other commercial utilities on gamma spectrometry analysis of gaseous fission product (GFP) and Chemistry Environmental Management (CEM) data in support of the development of fuel-failure monitoring tools for Nuclear Generating Stations (i.e., Visual DETECT and STAR). Additional collaboration with Bruce Power has also been carried out in which Cameco has provided fuel samples in support of LVRF defective fuel identification. In addition, neutron beam time was awarded and experiments carried out in December 2007 at the Los Alamos Neutron Science Centre (LANSCE) for scoping tests using neutron diffraction at very high temperature on doped CANDU fuel in support of the New Fuel Project for Bruce Power. This project was terminated with the announcement that Bruce Power was not pursuing LVRF development. The research group has also collaborated internationally with the Institute for Transuranium Elements, Commissariat à l'Énergie Atomique and Oak Ridge National Laboratory. The Chair holder collaborates with other professors within RMC (i.e., Profs. T. Krause, D. Kelly and H. Bonin as co-supervisors of thesis projects), the Industrial Materials Institute of the National Research Council of Canada (NRC), and UOIT. In addition, Prof. Lewis has provided assistance for COG and AECL with the development of state-of-the-art reports on defective fuel behaviour, a strategic plan for fuel and fuel channel codes, an expert panel on fuel deformation, as well as reviewing activities for AECL, Journal of Nuclear Materials, Applied Radiation and Isotopes, Health Physics Journal, Nuclear Technology, NSERC, Chemical, Biological, Radiological-Nuclear & Explosives Research and Technology Initiative (CRTI) and the US National Institute for Occupational Safety and Health (NIOSH). The Chair holder is also a member of the Fuel Normal Operating Committee for the COG R&D Safety and Licensing Program.

Research Results

Published research findings from September 2007 to September 2009 are detailed below:

Journal Papers

1. J.D. Higgs, B.J. Lewis, W.T. Thompson and Z. He, "A conceptual model for the fuel oxidation of defective fuel," *J. Nucl. Mater.* 366 (2007) 99-128.
2. B.J. Lewis, A. El-Jaby, J. Higgs, W.T. Thompson, F.C. Iglesias, R. Laidler, J. Armstrong, R. Stone and R. Oduntan, "A model for predicting coolant activity behaviour for fuel-failure monitoring analysis," *J. Nucl. Mater.* 366 (2007) 37-51.
3. M.H. Kaye, B.J. Lewis and W.T. Thompson, "Thermodynamic treatment of noble metal fission products in nuclear fuel," *J. Nucl. Mater.* 366 (2007) 8-27.
4. J.D. Higgs, W.T. Thompson, B.J. Lewis and S.C. Vogel, "Kinetics of precipitation of U_4O_9 from hyperstoichiometric UO_{2+x} ," *J. Nucl. Mater.* 366 (2007) 297-305.
5. W.T. Thompson, B.J. Lewis, E.C. Corcoran, M.K. Kaye, S.J. White, F. Akbari, Z. He, R. Verrall, J.D. Higgs, D.M. Thompson, T.M. Besmann and S.C. Vogel, "Thermodynamic treatment of uranium dioxide based nuclear fuel," *Int. J. Mat. Res.* 98 (2007) 10 1004-1011.
6. M.J. Welland, B.J. Lewis, and W.T. Thompson "A comparison of stefan and phase field modeling techniques for the simulation of melting nuclear fuel," *J. Nucl. Mater.* 376 (2008) 229-239.

7. B.J. Lewis, R. Dickson, F.C. Iglesias, G. Ducros and T. Kudo, "Overview of experimental programs on core melt progression and fission product release behaviour," J. Nucl. Mater. 380 (2008) 126-143.
8. M. J. Welland, W. T. Thompson, B. J. Lewis, D. Manara, "Computer simulations of non-congruent melting of UO_{2+x} ," J. Nucl. Mater. 385 (2009) 358-363.
9. E. Corcoran, B. Lewis, W. Thompson, J. Hood, F. Akbari, Z. He, P. Reid, "Computed phase equilibria for burnable neutron absorbing materials for advanced pressurized heavy water reactors", J. Nucl. Mater. 385 (2009) 424-430.
10. B.J. Lewis, F.C. Iglesias, R.S. Dickson and A. Williams, "Overview of high temperature fuel behaviour with relevance to CANDU fuel," J. Nucl. Mater. 294 (2009) 67-86.
11. B.J. Lewis, W.T. Thompson and F.C. Iglesias, Book Chapter prepared "Fission product chemistry in oxide fuels" in "Comprehensive Nuclear Materials," Editor-in-Chief, R. Konings, Elsevier (submitted, to be published 2011).

Conference Papers

1. B.J. Lewis, A. El-Jaby, J. Higgs and W.T. Thompson, "A model for predicting coolant activity behaviour for fuel-failure monitoring analysis," Proc. 2007 Int. LWR Fuel Perf. Conf., San Francisco, California, September 30 to October 3, 2007.
2. M.J. Welland, W.T. Thompson and B.J. Lewis, "Computer simulation of non-congruent melting of non-stoichiometric uranium dioxide fuel," Proc. 2007 Int. LWR Fuel Perf. Conf., San Francisco, California, September 30 to October 3, 2007.
3. E.C. Corcoran, M.H. Kaye, F. Akbari, J.D. Higgs, B.J. Lewis, W.T. Thompson, R.A. Verrall, Z. He and J.F. Mouris, "First principles CANDU fuel model and validation experimentation," Proc. 2007 Int. LWR Fuel Perf. Conf., San Francisco, California, September 30 to October 3, 2007.
4. M.J. Welland, W.T. Thompson, B.J. Lewis, and D. Manara, "Computer simulations of non-congruent melting of UO_{2+x} ," Eur. Mat. Res. Soc., Strasbourg, France, May 26-30, 2008.
5. E. C. Corcoran, B. J. Lewis and W. T. Thompson, J. Hood, F. Akbari, Z. He and P. Reid, "Computed phase equilibria for burnable neutron absorbing materials for the advanced CANDU reactor design," Eur. Mat. Res. Soc., Strasbourg, France, May 26-30, 2008.
6. F.C. Iglesias, B.J. Lewis, A. Oliva and P. Purdy, "Fission product release mechanisms: research in Canada," Can. Nucl. Soc. Conf., Toronto, Ontario, June 1-4, 2008.
7. E. C. Corcoran, B. J. Lewis, W. T. Thompson, "Thermochemical model for irradiated advanced CANDU fuel materials," 10th Int. Conf. CANDU Fuel, Ottawa, Ontario, October 5-8, 2008.
8. A. El-Jaby, B.J. Lewis, W.T. Thompson, M. Ip, F.C. Iglesias, "A model for predicting coolant activity behaviour for fuel-failure monitoring analysis," 10th Int. Conf. CANDU Fuel, Ottawa, Ontario, October 5-8, 2008.
9. M.H.A. Piro, D.R. Morgan, B.J. Lewis and W.T. Thompson, "Performance modelling of CANDU nuclear fuel," 10th Int. Conf. CANDU Fuel, Ottawa, Ontario, October 5-8, 2008.

10. M.H.A. Piro, W.T. Thompson and B.J. Lewis, "A self standing Gibbs energy minimization procedure to solve chemical equilibrium in multielement multiphase nuclear materials," 10th Int. Conf. CANDU Fuel, Ottawa, Ontario, October 5-8, 2008.
11. K. Shaheen and B.J. Lewis, "Development of a simplified fuel oxidation model for defective nuclear fuel," 10th Int. Conf. CANDU Fuel, Ottawa, Ontario, October 5-8, 2008.
12. J.D. Swann, B.J. Lewis and M. Ip, "Spectral analysis of coolant activity from a commercial nuclear generating station," 10th Int. Conf. CANDU Fuel, Ottawa, Ontario, October 5-8, 2008.
13. S. Livingstone and B.J. Lewis, "On-line defected fuel monitoring using GFP data," 10th Int. Conf. CANDU Fuel, Ottawa, Ontario, October 5-8, 2008.
14. M. Kleczek, B.J. Lewis, W.T. Thompson, "Dysprosia doped uranium dioxide fuel and the lambda transition," 33rd Annual CNS/CNA Student Conf., Calgary, May 31-June 3, 2009.
15. G. Bruni, B.J. Lewis and W.T. Thompson, "Sheath hydriding model for defective fuel," 33rd Annual CNS/CNA Student Conf., Calgary, May 31-June 3, 2009.
16. M.J. Welland, M.H. Piro, W.T. Thompson and B.J. Lewis, D. Manara, R.J.M. Konings, "Reassessment of UO_{2+x} melting by combined consideration of experimental and theoretical work," Top Fuel Light Water Reactor Fuel Perf. Conf., Paris, France, September 6-10, 2009.
17. M.H. Piro, M.J. Welland, B.J. Lewis, W.T. Thompson, D.R. Olander, "Development of a self-standing numerical tool to compute chemical equilibria in nuclear materials," Top Fuel, Light Water Reactor Fuel Perf. Conf., Paris, France, September 6-10, 2009.
18. A. El-Jaby, B.J. Lewis, W.T. Thompson, F. Iglesias and M. Ip, "An improved model for predicting coolant activity behaviour for fuel-failure monitoring analysis," Top Fuel, Light Water Reactor Fuel Perf. Conf., Paris, France, September 6-10, 2009.

Technical Reports

1. B.J. Lewis, W.T. Thompson, A. El-Jaby, M.H. Kaye and J. Serdula, "Fission product release model for defective fuel analysis and monitoring," CANDU Owners Group report, COG-06-2030, March 2007.
2. B.J. Lewis, W.T. Thompson, K. Shaheen, M. Welland and E. Corcoran, "Simplified fuel oxidation model for defective fuel," CANDU Owners Group report, COG-07-2047, July 2008.
3. E.C. Corcoran, M.H. Piro, W.T. Thompson and B.J. Lewis, "Fuel thermodynamic model advancement," CANDU Owners Group report, TN-08-2076, March 2009.
4. A. Oliva, F. Iglesias, B. Lewis, R. Rock, A. Williams and A. Fitchett, "Strategic planning considerations for CANDU fuel and fuel channel code development," CANDU Owners Group report, ISTO-08-5090, January 2009.
5. A. Oliva, F. Iglesias, B. Lewis, R. Rock, D. Caswell and A. Fitchett, "Strategic planning recommendations for CANDU fuel and fuel channel code development," CANDU Owners Group report, ISTO-08-5091, April 2009.
6. C. Thiriet, E. Corcoran, A. Quastel, B. Lewis and G. Hadaller, "Test plan for out-reactor instrumented defective fuel experiment," CANDU Owners Group report, OP-09-2043, August 2009.

Presentations

1. B.J. Lewis and W.T. Thompson, "Advances in fuel behaviour modelling," CANDU Owners Group, Safety and Licensing Workshop, Fuel Normal Operating Conditions Working Group, September 25, 2007.
2. B.J. Lewis, R. Dickson and F.C. Iglesias, "Overview of experimental programs on core melt progression and fission product release behaviour," Int. VERCORS Seminar, Gréoux le bains, France, October 15-16, 2007.
3. F. Iglesias, B.J. Lewis, A.F. Olivia and P. Purdy, "Fission product release research in Canada," Int. VERCORS Seminar, Gréoux le bains, France, October 15-16, 2007.
4. W. Welland, W.T. Thompson and B.J. Lewis, "Modelling the melting behaviour of hyperstoichiometric uranium dioxide fuel," Int. VERCORS Seminar, Gréoux le bains, France, October 15-16, 2007.
5. W. Welland, W.T. Thompson and B.J. Lewis, "Modelling the melting behaviour of hyperstoichiometric uranium dioxide fuel," JRC – European Commission, Institute for Transuranium Elements, Karlsruhe, Germany, October 18, 2007.
6. M. J. Welland, W.T. Thompson and B.J. Lewis, "Simulation of high temperature phase transitions in UO_{2+x} ," Mat. Models and Simulations for Nucl. Fuels (MMSNF-6), Tokyo, Japan, December 13-14, 2007.
7. E. C. Corcoran, B.J. Lewis and W.T. Thompson, "Computed phase equilibrium and material studies for burnable neutron absorbing materials for the advanced CANDU reactor design," Mat. Models and Simulations for Nucl. Fuels (MMSNF-6), Tokyo, Japan, December 13-14, 2007.
8. K. Shaheen, B.J. Lewis, "A semi-empirical oxidation model for defective nuclear fuel", Gordon Res. Conf. on High Temperature Mat., Waterville, ME, USA, July 20-25, 2008.
9. A. El-Jaby, B.J. Lewis, and W.T. Thompson, "A model for predicting coolant activity behaviour for nuclear fuel-failure monitoring analysis", Gordon Res. Conf. on High Temperature Mat., Waterville, ME, USA, July 20-25, 2008.
10. M. J. Welland, W. T. Thompson, B. J. Lewis, "Simulation techniques of non-congruent melting of UO_{2+x} ", Gordon Res. Conf. on High Temperature Mat., Waterville, ME, USA, July 20-25, 2008.
11. M.H.A. Piro, W.T. Thompson, B.J. Lewis, "A stand-alone Gibbs energy minimization tool to solve chemical equilibrium in multielement-multiphase systems," Gordon Res. Conf. on High Temperature Mat., Waterville, ME, USA, July 20-25, 2008.
12. M.H.A. Piro, W.T. Thompson and B.J. Lewis, "A stand-alone Gibbs energy minimization tool to solve chemical equilibrium in multielement-multiphase systems," Mat. Modelling and Simulation for Nucl. Fuels Workshop - 7, Karlsruhe, Germany, September 30, 2008.
13. M.H.A. Piro, D.R. Morgan, B.J. Lewis and W.T. Thompson, "Performance modelling of CANDU nuclear fuel," Mat. Modelling and Simulation for Nucl. Fuels Workshop - 7, Karlsruhe, Germany, September 30, 2008.
14. K. Shaheen and B.J. Lewis, "Modelling of UO_2 oxidation phenomena in defective nuclear fuel," Mat. Modelling and Simulation for Nucl. Fuels Workshop - 7, Karlsruhe, Germany, September 30, 2008.
15. M. J. Welland, W. T. Thompson and B. J. Lewis, "Simulation of centreline melting in operational, defective nuclear fuel", Mat. Modelling and Simulation for Nucl. Fuels Workshop - 7, Karlsruhe, Germany September 30, 2008.
16. D. Manara, M. J. Welland, B. J. Lewis, R. Konnings, W.T. Thompson, "Studies on phase diagrams of nuclear materials by laser heating and experiment

- simulation”, 12th Symposium on Thermo-chemistry and Thermo-physics of Nucl. Mat., Pörtlach, Austria, September 30, 2008.
17. B.J. Lewis, W.T. Thompson and F.C. Iglesias, “Emerging issues for nuclear fuel,” 21st Canadian Mat. Science Conf. - Nucl. Mat. Workshop, Kingston, Ontario, June 9-11, 2009.
 18. M. Piro, B.J. Lewis and W.T. Thompson, “Development of a self-standing numerical tool to compute equilibria in nuclear materials,” 21st Canadian Mat. Science Conf., Kingston, Ontario, June 9-11, 2009.
 19. M.J. Welland, W.T. Thompson and B.J. Lewis, “Simulation of the non-congruent melting of nuclear fuel,” 21st Canadian Mat. Science Conf., Kingston, Ontario, June 9-11, 2009.
 20. K. Shaheen and B.J. Lewis, “A platform-based model for intact nuclear fuel performance,” 21st Canadian Mat. Science Conf., Kingston, Ontario, June 9-11, 2009.
 21. B.J. Lewis, K. Shaheen and M.J. Welland, “Nuclear fuel behaviour modelling at the RMC using COMSOL multiphysics,” Multiphysics workshop for nuclear applications, Toronto, Ontario, Canada, June 24, 2009.
 22. M.H. Piro, B.J. Lewis, T.M. Besmann, W.T. Thompson, “Development of a Gibbs Energy Minimizer for integration into nuclear fuel performance codes,” Mat. Modelling and Simulation for Nucl. Fuels Workshop - 8, Albuquerque, New Mexico, October 19-21, 2009.
 23. K. Shaheen, G. Bruni, A. El-Jaby, M.J. Welland, B.J. Lewis, and W.T. Thompson, “Nuclear fuel element behaviour modelling,” Mat. Modelling and Simulation for Nucl. Fuels Workshop - 8, Albuquerque, New Mexico, October 19-21, 2009.

Teaching

An undergraduate course was taught by Profs. B.J. Lewis and L.G.I. Bennett, “Physics of Nuclear Reactors” at Queen’s University, September to December 2007 as an RMC outreach course. This course has led to two Queen’s students joining AECL and OPG. An undergraduate course, “Nuclear Science,” was also taught by Profs. Bonin and Corcoran in the fall term of 2008-2009. The Chair holder and Profs. Bonin and Bennett also taught graduate courses: “Nuclear Reactor Engineering”, “Nuclear and Radiochemistry” and “Nuclear Waste Management” in September 2007 to March 2008; and “Health Physics and Radiation Protection”, “Nuclear Fuel Engineering”, “Nuclear Fuel Management” and “Nuclear Detection and Measurement,” in September 2008 to March 2009.

Awards

Recognition of the research work in 2007 include: (i) a best PhD paper award at the CNS Student Conf. for Dr. E. Corcoran, (ii) CF Lucks Award for the 29th Int. Conf. in Thermal Conductivity for Dr. J. Higgs, and (iii) RMC research prize for Prof. B.J. Lewis. Awards for 2008 include: (i) 'Best Paper in the Nucl. Symposium' at the Eur. Mat. Res. Soc. Conf. in Strasbourg, France for Dr. E. Corcoran; (ii) Jervis Award from the CNS for Dr. E. Corcoran; (iii) best paper (PhD) for M. Piro at the student session of the CNS; (iv) "Outstanding Poster Presentation" at the Gordon Conf. for Dr. M. Welland; and (v) Governor General's Gold medal for D. Morgan for his MASc thesis on fuel performance code development.

M. Welland (PhD candidate)
at the Los Alamos National
Laboratory in December
2007.

