Cooperative Action Plan

between

the Department of Energy of the United States of America,

the Department of Natural Resources of Canada and

Atomic Energy of Canada Limited

on Nuclear Energy Research and Development

1. Introduction

The Department of Energy of the United States of America (**DOE**), the Department of Natural Resources of Canada (**NRCan**), and Atomic Energy of Canada Limited (**AECL**), hereinafter the "Participants",

Recognizing the important role civilian nuclear energy serves now, and the role it will serve in the future, to meet the ever increasing global demands for energy;

Noting the entry into force on 23 July 2007 of the *Agreement Among the Government of Canada, the Government of the United Mexican States and the Government of the United States of America for Cooperation in Energy Science and Technology* (**"Trilateral Agreement"**);

Noting that on 13 January 2015, acting pursuant to Article 6 of the Trilateral Agreement, then-U.S. Energy Secretary Dr. Ernest Moniz and then-Canadian Minister of Natural Resources Greg Rickford signed an *Implementing Arrangement for collaboration in the area of nuclear energy research and development* (R&D) (**"Implementing Arrangement"**) on a spectrum of advanced technologies in the fields of nuclear safety, reactor lifetime management, advanced reactor technologies, nuclear materials and fuels, modeling and simulation, and used fuel recycling and disposition technologies;

Recognizing the value of bilateral cooperation between Canada and the United States of America in the area of nuclear energy research;

Desiring to develop a Cooperative Action Plan (**"Action Plan"**) between them in order to facilitate cooperation in R&D of advanced civilian nuclear energy technologies and to create a substantive near-term engagement with positive impacts for the nuclear energy visions of each country, while at the same time laying the groundwork for long-term cooperation;

Understanding that AECL delivers its mandate through a Government-owned Contractor-operated model whereby the operation of its nuclear laboratories, including science and technology is delivered by the Canadian Nuclear Laboratories (CNL);

Intend to cooperate as follows:

2. Organization and Implementation

(a) This Action Plan is organized into four Working Groups that will focus on:

(i) Reactor Technologies;

(ii) Light Water and Heavy Water Reactor (LWR and HWR) Sustainability;

(iii) Advanced Fuels and Fuel Cycles; and,

(iv) Modeling and Simulation.

(b) Each Working Group is to be co-chaired by a lead representative from the U.S. and Canada.

(c) This Action Plan is to be guided by a committee consisting of one co-chair from each Participant ("**Steering Committee**"). The DOE Assistant Secretary for Nuclear Energy (NE), or its designee is to represent the DOE, the Energy Sector Assistant Deputy Minister, or its designee is to represent NRCan, and the Science and Technology Vice President, or its designee is to represent AECL.

(d) The Steering Committee intends to meet annually, or as deemed necessary, to review the activities, progress, and plans of each Working Group and establish priorities for Working Groups' technical activities.

(e) Each Participant intends to designate an Action Plan Manager whose roles are to:

(i) Disseminate to the Working Groups general guidance from the Steering Committee on priorities of R&D objectives;

(ii) Summarize for the Steering Committee, when necessary, the status of Working Group activities and any issues requiring resolution by the Steering Committee;

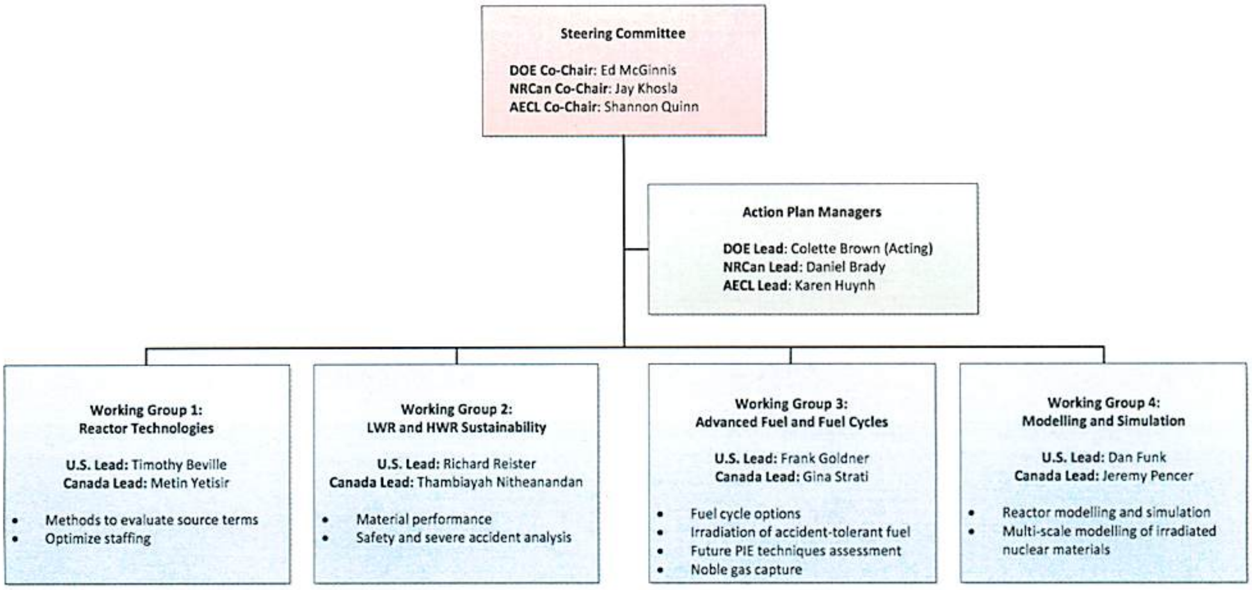
(iii) Give appropriate guidance and direction to the Working Group leads for the activities carried out under each Working Group; and

(iv) Coordinate with the Working Group leads to ensure consistency in the preparation of deliverables for the Steering Committee.

(f) An organization chart for the conduct of activities under this Action Plan is presented in Figure 1 below.

Figure 1

Organizational Chart



3. LEGAL FRAMEWORK

(a) The Participants note the importance of carrying out activities under this Action Plan in accordance with the international obligations relating to non-proliferation, safeguards, security, safety and liability.

(b) The Participants note that all activities carried out under this Action Plan are undertaken pursuant to the Implementing Arrangement and subject to the provisions of the Trilateral Agreement. The provisions of the Trilateral Agreement apply to all such activities, except as otherwise specifically agreed by the Participants, in writing.

(c) For each activity carried out under this Action Plan, the Participants and/or the entities participating in such an activity may enter into a separate legally binding instrument setting out, among other things:

(i) the general terms and conditions relating to the activity;

(ii) the terms and conditions relating to the use and handling of confidential data and information disclosed by the Participants and/or the other participating entities; and

(iii) the rights and obligations of the Participants and participating entities with respect to intellectual property.

4. Cooperative R&D Activities

(a) The Participants intend to carry out collaborative R&D activities to explore advanced civilian nuclear energy technologies in a safe, secure and proliferation-resistant manner. Joint activities under this Action Plan may take several forms, including joint studies, experiments, and analyses of advanced nuclear reactor and fuel cycle concepts and technologies, use of each other's nuclear facilities for experimental purposes, exchanges of information and research results, and collaborative personnel training.

(b) The Participants understand that the milestones reflect a 1 June 2017 start date.

(c) All areas of potential collaboration are subject to availability of funding and will be reassessed annually.

4.1. Working Group 1 – Reactor Technologies

(a) The leads for this Working Group are as follows:

(i) For the U.S.: Timothy Beville (Timothy.Beville@nuclear.energy.gov); 301 903-8251

(ii) For Canada: Metin Yetisir (metin.yetisir@cnl.ca); 613-584-3311 ext. 46577

(b) Working Group 1 will provide a forum for cooperation and collaboration on general reactor technology development. However, the initial focus of cooperation in this plan will concentrate on the development of Small Modular Reactors (SMRs). The focus on SMRs in both countries has increased in recent years as potential benefits are explored related to enhanced safety and security, reduced capital cost, shorter construction schedules, and improved quality due to the ability to fabricate modules in controlled factory environments. In the United States, attention has been directed at units with a nominal output of 300 MWe or less with a focus on large components or modules fabricated remotely and transported to the site for assembly of components and operation. In Canada, attention has been focused on units with output of 2-10 MWe or <1 MWe (Very Small Modular Reactors [VSMRs]) for off-grid remote communities, mining, and resource development, and 50-300 MWe for small grid applications and replacement of fossil plants.

4.1.1. EXPERIMENTS, MODELING AND ANALYSIS TO EVALUATE SMR SOURCE TERMS

(a) The U.S. is currently focused on SMR designs that are primarily integral pressurized water reactors. Integral designs incorporate most of the primary system components within the reactor pressure vessel resulting in a compact size with different accident response characteristics than larger reactors. A unique integral SMR design feature that can significantly affect radiological source terms in design basis and beyond design basis accidents is its relatively small containment volume with passive cooling attributes. The significantly different integral SMR containment volumes, surface areas, aerosol flow velocities, drop heights, and other physical features will result in different aerosol natural deposition characteristics. In addition, these designs rely on natural removal mechanisms instead of active components such as containment spray systems. Extrapolation of current natural containment aerosol models to integral SMR conditions results in significantly reduced accident source terms. However, direct aerosol deposition measurements under simulated integral SMR accident conditions have not been conducted to date.

(b) Through a cooperative agreement with the Electric Power Research Institute (EPRI), DOE is supporting scaled experiments to quantify aerosol behaviors within integral SMRs, with a goal of impacting the regulatory treatment of SMR source terms, and establishing a regulatory basis for reducing emergency preparedness zones (EPZs) to the site boundary for appropriate SMRs. This will ultimately provide a basis for more siting flexibility for SMRs, as well as improving their economics by reducing the staffing and operations required to support current regulatory requirements for 10–mile EPZs.

(c) The DOE proposes to share data and analytical tools that will be used to evaluate the potential for reduced source terms from SMRs based on differences in SMR geometries and aerosol behavior in these configurations.

In Canada, several SMR vendors have applied to the Canadian regulator's (Canadian Nuclear Safety Commission) pre-licencing vendor review process. Most of these SMRs are based on non-water cooled technologies. As a result, R&D efforts at CNL are currently focussed on non-water cooled SMR technologies. Some of these SMRs are proposed for off-grid applications to produce steam as well as electricity. For the effective use of steam, they need to be located close to population centers and, as a result, require very small EPZs. Accident source terms and radiological dose consequences for non-water-cooled SMRs may be quite different than for water-cooled SMRs. CNL's work, funded by the Government of Canada's Federal Nuclear Science and Technology Work Plan, includes source and consequence evaluation of various non-water cooled SMRs. This data can be used to understand the EPZs around SMRs.

(d) CNL is performing a high level source term evaluation and dose consequence analysis for limiting accidents in various non-water cooled and water-cooled VSMR technologies for a comprehensive study with applicability to the Canadian landscape. For this study, meteorological data recorded at the Chalk River site will be used. Canada proposes to share the results of this study with the United States.

(e) Canada proposes to independently model the aforementioned scaled aerosol experiments performed by DOE and EPRI using industry standard computer codes for containment and aerosol behavior. This will demonstrate that these codes correctly represent the observed phenomena in SMRs. This modelling study will provide additional confidence in the other analytical tools and models being shared by the United States under this collaboration. These tools and models can then be used as part of CNL's SMR research projects.

MILESTONES

July 2017	Develop a plan for aerosol deposition experiments to determine integral PWR correlations that can provide a technical basis for relief of regulatory treatment of SMR accident source terms, and provide experimental plan to Canadian representatives.	DOE/EPRI
December 2017	Provide access to final SMR-specific aerosol experimental data sets to Canadian representatives.	DOE/EPRI
December 2017	Conduct assessment of the radiological consequences due to a limiting reactor accident scenario for various VSMRs using meteorological data at the Chalk River site. Provide access to the report on radiological consequences.	CNL
March 2018	Conduct benchmark exercise of GOTHIC and MAAP against the SMR-specific aerosol experimental data sets (subject to data availability); share results with the U.S.	CNL

4.1.2. SHARING INFORMATION ON POTENTIAL TECHNOLOGIES, SYSTEMS OR METHODOLOGIES TO OPTIMIZE SMR STAFFING AND REDUCE COSTS

(a) A key need for SMR economic viability is the ability to safely operate and maintain the plant with an optimized staff. Existing requirements, codes, and laws require staffing based on the current fleet of reactors. In addition, current site staffing functions, tasks, and resource levels are based upon the operating experience of existing large LWR technology plants. SMR plants are designed with a smaller site size, smaller physical plants, and potentially increased use of automation technologies. These unique characteristics will change the role, responsibilities, functions and tasks of typical site staffing positions and provide an opportunity for optimization and possible cost reductions in operations, maintenance and security functions. While many of the current U.S. SMR designs are still in the design phase, it is prudent to examine where innovative technologies might be applied to reduce the cost of electricity that will be produced by the plant. The U.S. is currently performing a systematic technical gap analysis of several typical nuclear plant functional areas to determine technologies and plant design insights that can be applied to those areas to safely optimize the number of people needed to operate an SMR plant. The gap analysis research is being conducted to provide technical justification for use of technology and regulation changes to optimize staff and where needed, and define additional R&D work to develop needed technology. Related areas of specific interest to Canada are concepts for remote operation of plants, and capabilities to do remote monitoring of the health of components. The U.S. proposes to collaborate with Canada by sharing the results of the ongoing SMR staffing optimization study and to considering areas such as remote monitoring as a potential next step for technology development and application to existing SMR designs.

(b) Most SMRs are proposed to be built underground and include integral steam generators (located inside the reactor vessel). Canada is working on the development of inspection strategies and techniques for remote health monitoring of components and systems, in particular the underground structures and internal steam generators. Canada proposes to share the recommended inspection and monitoring strategies for these components that would support the justification of fitness-for-service, and lead to reduced maintenance activities and reduced staffing levels.

Milestones

June 2017	Provide access to EPRI Advanced Nuclear Technology report "Using Technology for Small Modular Reactor Staff Optimization, Improved Effectiveness, and Cost Containment."	DOE/EPRI
August 2017	Support CNL attendance at EPRI Advanced Nuclear Technology meetings.	DOE/EPRI
June 2017	Conduct analysis of degradation mechanisms of underground enclosure structures for SMRs and share reported results.	CNL
November 2017	Conduct analysis of degradation mechanisms of internal steam generators used in integral SMRs and share reported results.	CNL
March 2018	Share reported results on the study of buried structure monitoring for environmentally induced degradation.	CNL

4.2 Working Group 2 – Light Water and Heavy Water Reactor (LWR and HWR) Sustainability

(a) The leads for this Working Group are as follows:

(i) For the U.S.: Richard Reister (Richard.Reister@nuclear.energy.gov); 301 903-0234

(ii) For Canada : Thambiayah Nitheanandan (Nithy) (thambiayah.nitheanandan@cnl.ca); 613-584-3311 ext. 44954

(b) Long-term safe operation of existing LWRs and HWRs and their long term economic viability requires on-going attention to the fundamental scientific basis in areas related to materials aging and degradation, risk informed safety margin characterization, and reactor safety technology.

4.2.1 Material Performance in Nuclear Reactor Systems

(a) Knowing the condition of the plant and having the ability to predict the evolution of material properties are required for licensing applications, inspection planning, capital asset life-cycle management and refurbishment projects. Irradiation changes the microstructure of the material (via atom displacements) and defines the environment (radiolytic production of oxidizing species in reactor coolant) in which the material is exposed. The microchemistry of the material is affected by both transmutation and chemical reactions. These phenomena are studied in experimental programs where individual variables are isolated and tested, and then benchmarked through characterization and analysis of ex-service reactor components. The results of these experimental and post-service studies are used in formulating predictive models used in condition assessments and mitigating technologies aimed at extending the useful life of the plant. These studies can be complex and costly. Therefore, they are ideal candidates for collaborative ventures where knowledge and access to facilities can be exchanged.

(b) Potential areas for collaboration may include:

(i) Post-irradiation examination of ex-service reactor materials for benchmarking of predictive models on radiation and or thermally induced changes to stainless steel, concrete and cables;

(ii) Evaluation of weld repair techniques on irradiated materials of common interest;

(iii) Environmental fatigue of reactor materials; and

(iv) Research partnerships.

4.2.1.1. Exchange technical information regarding DOE LWR Sustainability Program and AECL/CNL activities involving decommissioning or long term plant operation research. Conduct in-person meeting between DOE and AECL/CNL to develop potential collaborative opportunities.

Milestones

October 2017	Develop a memorandum summarizing the potential collaborative opportunities from which further research plans can be generated.	ORNL/CNL

4.2.2. Safety and Severe Accident Analysis

This area focuses on developing advanced approaches to support the management of uncertainty in safety margins quantification to improve decision-making for nuclear power plants that can help support their long-term viability. This includes (1) development of risk-assessment methods tied to safety margins quantification, and (2) creating advanced tools for safety assessment that enable more accurate representation of nuclear power plant safety margins and their associated influence on operations and economics. This research can be used to produce state-of-the-art nuclear power plant safety analysis information that yields new insights on actual plant safety/operational margins and permits cost effective management of these margins during periods of extended operation.

4.2.2.1. Perform an Assessment of Knowledge Gaps in Severe Accident Analysis:

Collaborate to identify knowledge gaps related to severe accident analysis that are common to both LWR and HWR reactor types.

In the wake of the reactor accidents at Fukushima Daiichi, knowledge gaps related to severe accident progression were identified that could impact reactor safety evaluations and accident management strategies. Some of these gaps are based on phenomenology that is applicable to both LWR and HWR types. The objective of this task is to identify these common knowledge gaps as a basis for formulating joint research addressing the gaps.

Milestones

August 2017	Meet and discuss knowledge gaps in severe accident analysis common to LWR and HWR systems.	ANL/CNL
March 2018	Publish a joint CNL/ANL conference paper summarizing knowledge gaps in severe accident analysis.	CNL

4.2.2.2. Compare Methodologies for Quantifying Uncertainties in Severe Accident Analysis:

Compare methods used to quantify uncertainties in severe accident progression to improve plant safety assessments and inform severe accident management guideline development.

There are uncertainties related to severe accident progression in both LWR and HWR plant designs that can impact predicted plant response during a severe accident, as well as strategies for accident mitigation that are derived in part from these response predictions. The objective of this task is to compare methodologies used for characterizing the impact of these uncertainties to better inform reactor safety assessments and accident management planning.

Milestones

January 2018	Meet and discuss uncertainty quantification in severe accident analysis for improvement of plant safety assessments and severe accident management guidelines.	ANL/CNL
October 2018	Publish a joint ANL/CNL conference paper on severe accident uncertainty quantification for plant safety assessments and severe accident management guidelines in LWR and HWR applications.	CNL

4.2.2.3. **Perform an Assessment of Accident Tolerant Components to Identify Data and Knowledge Gaps:** Collaborate to identify knowledge and data gaps related to accident tolerant equipment performance under beyond design basis accident conditions common to both LWR and HWR plant types.

Much like the uncertainties in severe accident progression described in Section 4.2.2.1, knowledge gaps have been identified related to accident tolerant equipment performance under beyond design basis accident conditions. Successful operation of such components under these conditions can reduce the potential for core damage and significantly extend the time interval for operators to cope with the accident, as evidenced by the plant response at Fukushima Unit 2. The objective of this task is to identify common knowledge gaps related to accident tolerant equipment performance as a basis for formulating joint research to address these gaps.

Milestones

April 2018	Meet and discuss accident tolerant components to identify data and knowledge gaps.	ANL/CNL
March 2019	Publish a joint CNL/ANL position paper identifying data and knowledge gaps on accident tolerant reactor components common to HWR and LWR systems.	CNL

4.2.2.4. REDUCE UNCERTAINTIES IN REACTOR PRESSURE VESSEL/CALANDRIA VESSEL PENETRATION FAILURE MODELS: Collaborate to reduce uncertainties in vessel penetration failure models based on proposed reactor material tests to be conducted at CNL.

Uncertainty related to the potential for vessel penetrations to fail during a severe accident was identified as one of the highest ranked knowledge gaps during a recent U.S. LWR gap analysis activity. This same topic has also been identified as an important knowledge gap for HWRs, where failure of the calandria vessel penetrations would compromise the in-vessel retention phenomenon. CNL is proposing to conduct reactor material tests to investigate the potential for penetrations failures in a geometry that is applicable to both LWR and HWR configurations. The objective of this task is to compare existing models to the test data to reduce uncertainties in their ability to predict conditions under which penetrations would fail during a severe accident.

MILESTONES

June 2018	Meet and discuss methods for predicting vessel penetration failures to support planning for CNL penetration failure testing.	ANL/CNL
December 2019	Publish a joint CNL/ANL conference paper on uncertainties in head penetration failure models based on proposed CNL's penetration failure testing with molten core material.	CNL

4.3. WORKING GROUP 3 – ADVANCED FUELS AND FUEL CYCLES

(a) The leads for this Working Group are as follows:

(i) For the U.S.: Frank Goldner (Frank.Goldner@nuclear.energy.gov); 301 903-3346

(ii) For Canada: Rosaura Ham-Su (rosaura.ham-su@cnl.ca); 613 584-3311 ext. 44485

(b) The Participants understand that the following items are potential areas for collaboration in the area of advanced fuel and fuel cycles.

4.3.1. FUEL CYCLE OPTIONS

(a) The options for current and future nuclear fuel cycles are important topics in the U.S. and Canada. Future fuel cycles depend greatly on available resources and technologies, as well as the political and social priorities of a country. Significant resources have been dedicated to the study of options for the nuclear fuel cycle in both the U.S. and Canada. This area of cooperative research will facilitate a common understanding of the decisions made in the respective nations with the potential for developing future fuel cycle strategies. Initially, this topic will focus on communication of the latest research in the field followed by discussion of topics of mutual interest and in the long term planning for possible synergistic and cooperative studies.

(b) Both countries have an interest in performing transitional fuel cycle scenario analyses. These scenario analyses pose different and additional challenges to steady state cases. It is proposed that Canada and the U.S. collaborate to analyze cases involving synergies between LWR and HWR reactors. Scenarios involving thorium-based fuels may be of interest to Canada.

(c) The U.S. and Canada are both using the VISION (Verifiable Fuel Cycle Simulation) simulation model to perform fuel cycle analyses. There are some limitations with the VISION model, which make it unsuitable for use for some transition scenarios. For example, all reactor physics calculations are performed outside of VISION, with the fuel recipes supplied as input. This makes the model somewhat restrictive; it is unable to adjust to changes in fuel composition over the course of the fuel cycle. Other codes exist that perform reactor physics calculations as part of the fuel cycle simulation, providing higher fidelity solutions. The U.S. also has experience with ORION, a UK tool, and CYCLUS.

(d) This collaboration will also explore the evaluation and testing of other fuel cycle analyses tools, or modifying the VISION model.

(e) Potential areas for collaboration may include:

(i) Define the gaps and limitations of the current fuel cycle systems analysis tools;

(ii) Review available tools;

(iii) Suggestions on acquiring and/modifying tools;

(iv) Identify fuel cycles of common interest for study;

(v) Discuss possible scope of work for each organization for fuel cycle scenario studies and for tool development; and,

(vi) Share results.

(f) The United States and Canada will each consider:

(a) Fuel cycle toolset needs and gaps, and

(b) Fuel cycle scenarios of interest involving LWRs and HWRs (SCWR can also be considered).

(g) A meeting will then be held in which both countries present on the fuel cycle toolset needs and gaps and fuel cycle scenarios of interest. This meeting will include a workshop session to discuss possible collaboration on these two topics.

MILESTONES

July 2017	Hold a meeting between the U.S. and Canada to discuss collaboration on fuel cycle scenarios and tool sets	DOE/CNL
October 2017	Draft a plan for fuel cycle scenario analyses and fuel cycle simulation tool development	DOE/CNL

4.3.2. IRRADIATION OF ACCIDENT-TOLERANT FUEL

DOE-NE has established a robust R&D program on accident-tolerant fuels for LWRs. Irradiations are currently underway and will continue through 2022 in the DOE's Advanced Test Reactor (ATR) and the High Flux Isotope Reactor (HFIR). These irradiation programs are flexible and allow for the possibility of testing new and emergent technologies. The DOE-NE proposes to make available some in-pile test positions for Canadian R&D programs on accident-tolerant fuel technologies. It is expected that near-term activities can be focused on inclusion of Canadian technology in the ATR ATF-1 irradiation series or in rabbit capsule tests in HFIR. Future longer-term activities can explore the development of more complex irradiation experiments and coordination of mutually beneficial experiments and test reactor experiments. An additional topic that can be explored is the coordination of future need and strategy of demonstration and test reactor technologies in the U.S. and Canada.

MILESTONES

July 2017	Conduct a meeting of technical experts to discuss collaboration in this area	INL/CNL

4.3.3. Fuel Post Irradiation Examination (PIE) Techniques Assessment

(a) Post irradiation examination for traditional nuclear fuel and materials requires specialized facilities and equipment. In the past, the generation of PIE data has been intimately tied to a specific development program so that the data can be used to inform a specific fuel performance simulation code. Therefore the data generated has typically been empirical in nature and collected in bulk samples.

(b) Advanced modeling and simulation of material performance has driven the need for PIE data at the microstructural scale, however. New PIE techniques are being developed and the initial data is being used for new multi-scale, multi-physics fuel performance codes like the MBM framework. The purpose of this technical work area will be to connect the experimental PIE experts working on development of new and innovative experimental techniques. The use of these types of techniques might allow for better comparison of data generated at multiple institutions; for example, coordination of "round robin" types of experiments on irradiated nuclear fuels and materials. It is expected that initial work will focus on connecting researchers in similar topical fields together in synergistic projects and be followed in the longer term by the development of more complex R&D activities coordinated between specific institutions.

Milestones

September 2017	Initiate discussions on: Capability Development of Thermal Properties of Unirradiated and Irradiated Fuel.	INL/CNL
September 2017	CNL visit to INL: Development of thermal properties measurement capabilities for irradiated and non-irradiated fuel.	INL/CNL
October 2017	Draft Plan to develop collaboration in the PIE area.	INL/CNL

4.3.4. Noble Gas Capture

DOE-NE and CNL have a common interest in short-lived xenon emissions and control. DOE-NE's interest essentially lies on molten salt reactor emissions control purposes. This interest overlaps within Mo-99 production from short-cooled nuclear reactor targets. CNL and DOE-NE will conduct joint R&D on noble gas trapping with the testing of: advanced noble gas sorbents that are under development at DOE' National Laboratories, and silver nanoparticle coated titanosilicate molecular sieve "Ag-ETS-10" currently used at CNL's Mo-99 production facility. Other advanced adsorbents may be included.

MILESTONES

July 2017	Exchange of Xe specific sorbent materials for comparative testing.	ORNL/CNL
December 2017	Test plans development and results from comparative testing.	DOE/CNL
January 2018	Recovery of Xe/Kr loaded 5A MS (Molecular Sieve) samples from Mo-99 decay beds. Collection and Analysis of the samples.	ORNL/CNL
June 2018	Analysis plans and sharing of the test results.	DOE/CNL

4.4 WORKING GROUP 4 - MODELING AND SIMULATION

(a) The leads for this Working Group are as follows:

(i) For the U.S.: Dan Funk (Dan.Funk@nuclear.energy.gov); 301 903-3845

(ii) For Canada: Jeremy Pencer (jeremy.pencer@cnl.ca); 613 584 8811 ext. 46267

(b) The Participants understand that the following items are potential areas for collaboration in the area of modeling and simulation.

4.4.1. REACTOR CODE BENCHMARKING AND SIMULATION

(a) Internationally, there is significant interest in developing multi-physics toolsets for the purpose of simulating nuclear reactors. Improvements in computing power have increased the number of potential approaches. There is a constant need to validate the codes against experiments and benchmarks, as well as to understand the origins and impact of code uncertainties. Collaboration will fall into two areas: 1) high-priority reactor code-to-code comparisons; and 2) activities to reduce the computational cost of performing forward-propagation sensitivity/uncertainty quantification (UQ) studies of the impact of nuclear data uncertainties on reactor simulations.

(b) Performance and publication of code-to-code comparisons of experimental or benchmark data, will address several technical areas, including, but not limited to: thermal-hydraulics, reactor physics, fuel performance, and severe accidents. Additionally, efforts must identify the sources of data and the codes being compared, and should cover two classes of comparisons:

(i) Single effect comparisons: comparing the performance of a single type of code, e.g. sub-channel coolant flow, against a common benchmark or experiment;

(ii) Multiphysics comparisons: comparing the performance of multi-physics toolsets against data representative of more than one physical phenomenon.

Reducing the computational cost of performing forward-propagation sensitivity/ UQ studies of the impact of nuclear data uncertainties on reactor simulations will help us explore more fully how to address the effect of simulation design on prediction accuracy. Understanding this effect on prediction requires a systematic comparative analysis of the UQ problem, which presents the challenge of how to limit the total computing cost of the effort. Collaborative efforts will focus on identification of a benchmark problem, a comparative UQ framework, and a means of controlling computing costs. Longer term goals could include publishing a comparative analysis that can help improve simulation design employed in reactor performance and design tools.

MILESTONES

July 2017	Identify methods for reducing the computational costs of proposed sensitivity/UQ studies, with input from DOE	CNL
August 2017	Evaluate proposed reactor code comparison activities and associated experiment/benchmark cases; select initial codes and cases considered most vital to broader use and deployment, along with comparison criteria and objectives; initial focus areas: - Benchmarking for time dependent experiments (such as SPERT and/or ZED-2, available in the open literature) - Benchmarking relevant to thermalhydraulics modelling (such as IAEA Numerical Benchmarking exercise)	DOE/CNL

August 2017	Identify an initial framework that would be used to test selected sensitivity/UQ method options, and determine the numerical benchmark problems that would be used to assess their respective cost and benefit.	DOE
September 2017	Draft reactor code comparison collaboration plan.	DOE
November 2017	Meeting to discuss collaboration relevant to sensitivity/UQ study computational cost reduction options.	CNL

4.4.2. Multi-Scale Modeling of Irradiated Nuclear Materials

(a) Predictions of ageing effects and estimation of in-core component lifetimes are typically based on empirical methods and rely heavily on experiments. As computing power and computer simulation methods improve, there is growing interest in their use to better interpret and design experimental materials ageing studies to minimize unnecessary experiments, which ultimately reduces costs, risk associated with safety, and environment effects. Development of effective and accurate materials simulations codes and methods requires both experimental benchmarking and code-to-code comparisons. Collaboration will be pursued to identify problem areas of mutual interest related to in-core materials ageing. Such areas could include 1) long-time microstructural evolution; 2) Understanding and mitigating stress corrosion cracking in zirconium alloys; and 3) Understanding and mitigating stress corrosion cracking in stainless steels.

(b) Changes in material properties associated with ageing can be observed and modeled empirically based on experiments. Simulation methods ranging from density functional theory to finite element analysis have been shown to accurately predict particular aspects of materials ageing, ranging from defect migration energies to corrosion and crack initiation. Despite the success of these and other simulations techniques, additional work is needed to link these simulations across different time and length scales following a multi-physics-like approach. Collaboration will be pursued to identify multi-scale frameworks and methods of mutual interest for application of lower-length-scale and mesoscopic (mesoscale) techniques. Longer term goals could be joint development and application of such methods.

MILESTONES

July 2017	Identify multi-scale frameworks and methods for application of lower-length-scale and mesoscopic (mesoscale) techniques for modelling of materials of interest to DOE and CNL.	DOE
November 2017	Draft a collaboration plan for using selected multi-scale frameworks and methods for material modelling of joint interest.	CNL
November 2017	Conduct a workshop to discuss how computational tools could be used to develop relevant models for material problems of interest to DOE and CNL.	CNL

4.4.3. FUEL MODELING AND SIMULATION

(a) DOE has been investing extensively over the past few years in development of new multi-physics, multi-scale computational tools. In the area of fuel performance modeling, the fuel performance modeling and simulation tool under development is the Moose-Bison-Marmot [MBM] code framework. There are many U.S. universities currently engaged in the development of specific models, which simulate separate effects or a subset of multiscale/multiphysics phenomena, which may be incorporated into the MBM framework. Collaborations on fuel models and simulations of this sort, as well as the overall development and testing of MBM could be established as mutually beneficial.

(b) Collaborative development of fuel models is already underway between the DOE's Idaho National Laboratory (INL) and a selection of universities in Canada and CNL. It is desired to foster this type of relationship through expanded collaboration between already existing relationships as well as expansion of relations between other collaborative institutions in both the U.S. and Canada. Near term activities will focus on expansion of the existing INL-CNL collaborative efforts through the following:

(i) Identify fuel materials modeling methods and framework(s) of mutual interest to facilitate better representation of the underlying physics phenomena that contribute to higher length scale fuel behaviour; and,

(ii) Extend INL fuel performance code, BISON, to the simulation of MOX fuels, and assess it against CNL experimental data for MOX fuel concepts (available in open literature).

MILESTONES

August 2017	Identify CNL experimental data (available in open literature) and INL computational capabilities to be used in collaboration to extend BISON to simulation of MOX fuels.	CNL/DOE
September 2017	Meeting between CNL, LANL and INL to discuss how existing and new lower-length scale work could be combined with mesoscale models to produce output usable in higher length (engineering) scale fuel models, such as finite element mechanical models.	DOE
October 2017	Draft collaboration plan to improve modelling capabilities for fuels including MOX	CNL

5. FINAL DISPOSITIONS

(a) This Action Plan is expected to come into effect on the last day of signature by the Participants.

(b) This Action Plan represents a programmatic commitment and does not constitute a legally binding agreement.

(c) This Action Plan complements, but does not replace, consultations and collaboration under existing agreements or the implementation of other international cooperation and programmatic activities of either Participant.

(d) This Action Plan may be amended by mutual consent of the Participants.

(e) This Action Plan may be terminated by either Participant by providing thirty (30) days' written notice to the other Participants.

FOR THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA

[signature] 6/2/17

(Acting) Assistant Secretary of Nuclear Energy | **Date**

FOR THE DEPARTMENT OF NATURAL RESOURCES OF CANADA

______________________________ May 30/2017

Assistant Deputy Minister **Date**

Energy Sector

FOR ATOMIC ENERGY OF CANADA LIMITED

May 31, 2017

Vice-President Science, Technology and Commercial Oversight

Date