A Plan for the Pre-Application Review of the Advanced CANDU Reactor (ACR) (September 26, 2002)

by

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Acronyms and Abbreviations

ACR	Advanced CANDU Reactor
AECL	Atomic Energy of Canada Limited
ALARA	As Low As Reasonably Achievable
ASME	American Society of Mechanical Engineers
CANDU	Canadian Deuterium Uranium
CFR	Code of Federal Regulations
CHF	Critical Heat Flux
CNSC	Canadian Nuclear Safety Commission
COL	Combined License
CSA	Canadian Standards Association
ECCS	Emergency Core Cooling System
ESP	Early Site Permit
ESBWR	European Simplified Boiling Water Reactor
ITAAC	Inspections, Tests, Analyses and Acceptance Criteria
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MW(e)	Megawatt (electric)
NRC	Nuclear Regulatory Commission (U.S.)
NII	Nuclear Installations Inspectorate
R&D	Research and Development
RCS	Reactor Coolant System
SDC	Standard Design Certification
SDS1	Shutdown System One
SDS2	Shutdown System Two
SRP	Standard Review Plan
USD	U.S. Dollars

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1. Introduction

This plan describes the scope, schedule and organizational responsibilities for a pre-application review of the Advanced CANDU Reactor (ACR) and proposes the processes that would be followed to support the NRC's review. Successful completion of this pre-application review by the NRC will help to facilitate AECL Technologies to obtain a Standard Design Certification (SDC) for the ACR, and a utility to obtain a Combined License (COL).

2. Objective

AECL Technologies' overall objective of the pre-application review of the ACR is to obtain an understanding, from interactions with the NRC, of the scope of the review work, the cost and effort required to complete that work, and the schedule to ultimately obtain a SDC for the ACR. Therefore, during the course of the pre-application review, any major NRC concerns with the ACR design will be identified early in the licensing process and the scope of the work, required to address these concerns, along with associated completion schedules, will be formulated and ultimately agreed upon with the NRC.

It is expected that the results of the NRC staff's pre-application review of the ACR design will be documented in a Safety Evaluation Report which will:

- state whether there are any impediments to licensing the ACR in the United States, and in particular:
    - provide confirmation of the licensing criteria applicable to the ACR;
    - provide an assessment of the completeness of AECL's Research and Development (R&D) programs that exist or are proposed/planned in support of the ACR;
    - provide an assessment of the suitability for purpose of the computer codes used in the safety analysis of the ACR; and
- provide estimates of the cost and schedule for the scope of the NRC's efforts for a Design Certification review for the ACR.

3. Background

AECL Technologies' ACR design is a light-water-cooled reactor that incorporates the proven features of both CANDU and Light-Water Reactor (LWR) technologies. It uses a conventional CANDU reactor cooling system, with two steam generators and four main coolant pumps. The design uses slightly enriched uranium dioxide fuel, light water coolant, a separate heavy water moderator, computer-controlled operation, and on-power refueling with the simple, robust CANFLEX fuel design. The reactor has horizontal pressure tubes supported in a tank filled with the low-pressure, low-temperature heavy water moderator. The tank also supports the reactivity regulating and safety devices, which are located within the low pressure moderator.

The ACR is an evolutionary development of existing CANDU reactors, which have operated safely and cost-effectively for many years in Canada and other countries. As such, the ACR incorporates the Defense-in-Depth characteristics of CANDU technology, including a long prompt neutron lifetime; small reactivity holdup; a control system capable of terminating many design basis accidents; two fast, totally independent, dedicated safety shutdown systems each capable of terminating all design basis accidents; an emergency core cooling system; a steel-lined, pre-stressed concrete containment; and a heavy water moderator which provides an additional, passive, large heat sink that can further mitigate core heat-up during potential severe accident scenarios. The ACR design incorporates further enhancements, such as a highly stable core design, large operating margins, and longer times available for operator action. The use of slightly enriched uranium fuel allows the reduction of the coolant void reactivity coefficient to a small, negative value.

The ACR preserves and enhances the CANDU features that make it resistant to terrorist attack and to sabotage. In addition to the high pressure, low leakage containment, other ACR Defense-in-Depth design features, such as redundancy and separation of systems and fail-safe safety system action, will help to safely mitigate the potential consequences of the actions of hostile intruders.

The ACR is designed to be the lowest-cost of the new generation of reactor designs. Using proven construction techniques from AECL’s current 700 MWe CANDU 6 design in China, AECL has been able to significantly reduce construction time and cost. The use of light water coolant and slightly enriched fuel also provides significant reductions in capital cost, due to the greatly reduced heavy-water inventory and the reduction in reactor core size. All ACR systems and components, including the fuel, can be fully manufactured in North America.

Pre-licensing work with the Canadian Nuclear Safety Commission (CNSC) has commenced on a reference ACR design in Canada. It is anticipated that the Canadian licensing requirements for the ACR will evolve from the CNSC’s extensive experience with the operating CANDU 6s, and the previously completed, in-depth licensability assessment of the CANDU 9 design. In the mid-1990s the NRC docketed the CANDU 3 reactor for the design certification process. Since that time further CANDU-specific research and development has been performed, formal validation of the computer codes used in the design and safety analysis of CANDU reactors has been completed and many safety improvements have been made to the ACR design, which will address most, if not all, of the issues raised by the NRC staff during the review of the CANDU 3 design. As well, familiarization of NRC staff with the underlying technology of CANDU reactors obtained from the CANDU 3 review (e.g., on-power refueling, pressure tubes, etc.), should contribute to the timely completion of the current NRC pre-application review for the ACR.

Currently the near-term market in the United States, and a number of other countries, looks very promising for a design as commercially competitive as the ACR. To clearly establish the attractiveness of the ACR in world markets, AECL is committed to deliver on a capital cost of 1000 USD per kW for a two-unit station and a construction schedule of 36 months. Ensuring that the licensing requirements for the ACR in the United States are well understood and can be met is an essential factor in confirming to US utilities that these cost and schedule targets can be met. The completion of a pre-application review by the NRC for the ACR will help to ensure that any major safety issues that could adversely affect cost and/or schedule are identified and allow AECL Technologies, through interactions with the NRC, to develop resolution strategies. Currently the ACR is one of the reactor designs being considered in the Early Site Permit (ESP) application process of the U.S. utilities Dominion, Entergy and Exelon.

4. Technical Summary

The ACR design is based on the CANDU 6 and CANDU 9 designs. The ACR has a single-unit containment in a twin-unit configuration. The ACR incorporates specific changes to the design of the reactor core and coolant system, which result in major reductions in capital cost while at the same time enabling increased safety margins.

The basic CANDU features that have been retained in the ACR include:

- horizontal pressure tubes;
- on-power fueling and the fuel handling system; and
- a separate low-pressure, low-temperature heavy water moderator.

The evolved characteristics of the ACR include:

- the CANFLEX fuel design with slightly enriched UO_2 fuel;
- light-water coolant;
- a negative full-core coolant-void reactivity;
- a more compact core configuration;
- increased steam pressure and temperature to the turbine; and

- a more compact plant layout.

The ACR design consists of horizontal fuel channels (i.e., each comprised of a pressure tube surrounded by a calandria tube), in a conventional heavy-water-moderated calandria vessel. The pressure tubes are similar to those of current CANDUs albeit slightly stronger due to the increased operating pressure. Also, the calandria tubes are larger diameter and stronger. The stronger calandria tube design will substantially reduce the risk of channel failure in the event of a spontaneous pressure tube rupture. The fuel is slightly enriched (i.e., 2 wt% U-235) CANFLEX fuel. The light water Reactor Coolant System (RCS) is a conventional figure-eight layout with two steam generators and four pumps.

The ACR's safety systems are similar to current generation CANDUs. Two fully independent, testable, capable and diverse shutdown systems are provided. Shutdown System one (SDS1) uses mechanical shutoff rods, with modified dimensions to accommodate the reduced lattice pitch. Shutdown System two (SDS2) injects liquid gadolinium nitrate into the moderator. The Emergency Core Cooling System (ECCS) is similar to current generation CANDUs in that it uses light water and has a high-pressure injection stage and a recovery stage. The single-unit containment building is a steel-lined, pre-stressed concrete building. It includes hydrogen control devices for severe accidents such as a Loss of Coolant Accident (LOCA) coincident with failure of the ECCS (i.e., for which the moderator acts as a passive backup heat sink to prevent loss of core geometry). Severe accidents which progress to loss of core geometry (i.e., extremely low probability) are also explicitly addressed in the design. An elevated water system provides backup passive decay heat removal for severe core damage accidents.

The ACR design is based largely on standard components from the CANDU 6 and CANDU 9 designs. The reactor core uses calandria and fuel channel design features adapted from CANDU 6. Fuel channel external end fittings, with connections to the external coolant system piping, and the fuel channel closure plug are new components that are undergoing qualification testing at AECL's laboratories. Reactor coolant pumps, steam generators, and the RCS piping, are based on the CANDU 6 and CANDU 9 designs. The turbine-steam-feedwater system is adapted from the current CANDU 6 design being built in China.

5. Overview of the Pre-Application Review Scope

Pre-application review interactions are intended to follow the guidance of NRC's Advanced Reactor Policy. The current review plan provides for early interaction between AECL Technologies, the NRC and other government agencies to provide all interested parties, including the public, with a timely, independent assessment of the safety characteristics of the ACR.

As an evolutionary water-cooled reactor, the ACR has many common features with LWR designs. As such the ACR will generally meet the safety intent of the current regulatory requirements for LWRs. However, the enhanced safety features of the ACR also enable it to be considered an advanced reactor. In addition the channel design and successful licensing of CANDUs in Canada and other countries introduce aspects not covered by LWR requirements. Therefore, this pre-application review will also follow the intent of NUREG-1226, "Development and Utilization of the NRC Policy Statement on the Regulation of Advanced Nuclear Power Plants". Advanced reactors are defined in NUREG-1226 as "those reactors that are significantly different from current generation light water reactors under construction or in operation and to include reactors that provide enhanced margins of safety or utilize simplified inherent or other innovative means to accomplish their safety functions".

NUREG-1226 provides the following guidance on the performance of pre-application reviews for advanced reactors.

1. "In performing this review, use will be made of the existing licensing guidance for LWRs, where practical, and supplemented, as necessary, with additional criteria to address the unique characteristics of the advanced designs."
2. "While the Final Policy Statement encourages innovative reactor designs and safety criteria, the review of advanced reactor designs will still require satisfactory consideration of the Commission's regulations, regulatory guides and other guidelines, such established and developing criteria as the defense-in-depth philosophy, standardization, the Commission's safety goal and severe accident policies, and applicable industry codes and standards."
3. "The Commission and the staff expect the licensability of advanced reactor designs to be supported by technology through a suitable combination of operating experience, the existing technology base, planned technology development, probabilistic risk assessment, applicable information and data from foreign countries, and plant testing. Prototype testing is encouraged."
4. "The use of less prescriptive, non-prescriptive, or performance related licensing criteria will be considered. Designers are encouraged to propose those criteria they believe are applicable to their designs and to address how such criteria will enhance safety and what changes or benefits in the traditional NRC process of regulation are expected from the use of such criteria."

With respect to the first guidance element, it is proposed that the ACR design be reviewed against the safety intent of the existing regulations for LWRs along with due consideration of the safety and licensing aspects of pressure tube reactors in Canada. Where differences in the ACR approach to design and/or safety analysis arise, these differences will be explained, and justified from a safety perspective giving due consideration for the basis for the LWR requirements.

With respect to the second guidance element, the ACR design will reflect appropriate consideration of defense-in-depth, standardization, the Commission's safety goal and severe accident policies, and applicable industry codes and standards (i.e., ISO, ASME).

With respect to the third guidance element, the technology base for the ACR is extensive, with some further focused R&D planned/in progress to address the more evolutionary technical aspects of the ACR. It is currently anticipated that the differences between the ACR design and the operating CANDU 6s will not result in a requirement for prototype testing beyond testing already planned at AECL's laboratories.

With respect to the final guidance element, in the context of LWR regulation there will be some different design and safety criteria associated with the ACR. Where possible, these new criteria will be explained and justified from a safety perspective against the closest "equivalent" LWR criteria. ACR criteria without an obvious LWR counterpart will be fully described and the safety requirement that their application addresses discussed in-depth.

The NRC's "Statement of Policy for the Regulation of Advanced Nuclear Power Plants," dated July 8, 1986, encourages early discussions between the NRC and reactor designers as a mechanism for providing licensing guidance. NUREG-1226 provides guidance on the implementation of this policy and describes the NRC's approach in reviewing advanced reactor designs. The NRC conducts pre-application reviews of advanced reactor designs to identify: (1) major safety issues that could require Commission policy guidance to the staff; (2) major technical issues that the staff could resolve under existing regulations or NRC policy; and (3) the research needed to resolve identified issues.

Regarding item (2), world experience with the CANDU design series coupled with certain factors associated with the ACR design should enable ready resolution of technical issues by the NRC staff. These factors include the successful licensing of CANDU technology in multiple regulatory jurisdictions around the world, a well-supported technical base for the design, extensive operational experience with CANDU reactors, the evolutionary nature of the ACR design relative to existing CANDU designs and numerous similarities between the ACR and other LWRs.

Regarding item (3), the extensive research base already created through decades of analysis, development, qualification, testing, and operation of CANDU materials, components, fuel (including enriched fuel), systems, and reactors worldwide; together with additional ACR-specific testing being undertaken by AECL, should be sufficient to allow assessment of the adequacy of the ACR design, with possibly some limited confirmatory R&D directed by the NRC.

6. Pre-Application Review Tasks

It is proposed to conduct the pre-application review in two phases. During Phase 1, it is expected that the NRC will familiarize themselves with the ACR design and the scope of the available and planned analysis, testing and operational experience in support of the design. In addition to identifying issues that may require further testing, the NRC would also determine and document their resource and schedule requirements for completion of Phase 2. It is recognized that it is very important, given the long lead times associated with testing, to identify with the NRC, as soon as possible, any technical issues for which they may require further testing. In Phase 2, it is expected that the NRC will perform an assessment of the technology base for the design, identify any major technical issues and provide an estimate of the resources and schedule required for Design Certification. It is expected that both phases would be completed in 24 months total, though a better estimate of schedule will emerge from early and ongoing discussions with the NRC.

The broad scope of the tasks associated with of Phase 1 of the pre-application review for the ACR is as follows.

1. To familiarize the NRC with:
    a. the ACR design, including:
        i. core physics,
        ii. core design,
        iii. control system design
        iv. fuel channels and on-power fueling,
        v. reactor coolant and moderator systems,
        vi. safety systems,
        vii. redundancy, safety classification of systems and components and external hazards,
        viii. codes (e.g., ASME) and standards (e.g., CSA) used for design,
        ix. fires, seismic, loss of offsite power, station blackout and other external event considerations, and
        x. severe accident considerations.
    b. the methodology used in accident analysis (i.e., bases, acceptance criteria), including the computer codes used in CANDU safety analysis and their validation;
    c. the key phenomena in ACR safety analysis;
    d. the technology base for CANDU reactors and the ACR (i.e., the R&D available, and planned, in support of the claimed safety performance of the ACR);
    e. CANFLEX fuel;
    f. experience with the operation and maintenance of CANDU reactors; and
    g. ACR security and safeguards features.
2. Preliminary identification of any safety issues of concern to the NRC that need to be addressed further in Phase 2 of the pre-application review.

3. Preliminary identification of any further confirmatory testing required by the NRC that need to be further assessed in Phase 2 of the pre-application review.
4. To establish the detailed scope and schedule for Phase 2 of the pre-application review, including estimates of the NRC resources required in order to complete Phase 2.

The broad scope of the tasks associated with Phase 2 of the pre-application review for the ACR is as follows.

1. For NRC to perform a more in-depth assessment of the technology base for the ACR design, with a particular focus on the safety issues identified in Phase 1.
2. Finalize the requirements for further confirmatory testing that will be required in order to obtain a Design Certification for the ACR.
3. Finalize the scope of the work on safety issues of concern to the NRC, which must be completed in order to obtain a Design Certification for the ACR.
4. To establish action plans, including estimates of the NRC resources required, their cost and the schedule to be followed, to attain a Design Certification for the ACR.

ACR-specific technical areas that will require early introduction and focused discussion with the NRC staff include the following.

1. The design of the ACR RCS pressure boundary (i.e., the use of Zr-2.5wt%Nb pressure tubes, unique fuel channel design considerations and the role of the fueling machines as components of a Class 1 pressure boundary).
2. The definition of design basis accidents and ACR safety acceptance criteria.
3. The computer codes used in ACR safety analysis.
4. The definition of severe accidents for the ACR and the nature and extent of R&D support required.
5. The ACR treatment of safety-related systems, including seismic considerations.
6. The use of Canadian design codes and standards to address unique ACR features.
7. The use of distributed digital control systems and safety critical software.
8. The safeguards aspects of on-power refueling.

7. Information Requirements for NRC Pre-Application Review of the ACR

In support of the pre-application review of the ACR, AECL Technologies will provide the NRC with the following information, by the dates shown.

Information to be provided in Phase 1 (June 2002 to June 2003)
of the pre-application review for the ACR

Familiarization workshops/seminars:

- Overview of the ACR (Sept. 25-26, 2002)
  - ACR Design
  - ACR Technology Base

- The ACR Core (November 2002)
  - Core physics
  - Fuel channels
- ACR Design Basis Accident Scenarios and Key Behavioral Phenomena (December 30, 2002)
- ACR Thermal hydraulics (January 2003)
  - RCS, moderator and Critical Heat Flux (CHF)
  - Typical safety analysis phenomenology
  - The CATHENA computer code
- ACR Safety Design Philosophy (January 2003)
- Shutdown System Design (January 2003)
  - Including safety critical software methodology
- ECCS and Containment Design (March 2003)
- Control System Design (March 2003)
- CANFLEX Fuel and On-Power Refueling (April 2003)
- Safety Analysis Methodology and Computer Codes (May 2003)
  - Including severe accident considerations

A report on the generic CANDU Probabilistic Risk Assessment (PRA) methodology and results (October 15, 2002)

Information on selected safety analysis computer codes (e.g., CATHENA, WIMS/RFSP) (November 30, 2002).

- Reports (i.e., theory manuals, validation matrices, validation reports), which describe the computer codes that will be modified for use in the safety analysis of the ACR and the extent to which these codes have been validated prior to the required modifications.

AECL Technologies' plan for anticipatory R&D in support of ACR safety (January 31, 2003).

A report on ACR safety analysis (Mar. 31, 2003).

- Design basis accidents.
- A description of the initial conditions, assumptions, acceptance criteria, methodology and computer codes used in ACR safety analysis.
- A description of the PRA scope and methodology.
- A description of the severe accident analysis program.

A report on the proposed licensing approach for the ACR in the U.S. (Mar. 31, 2003). The report will provide discussions in the following areas.

- The safety design criteria and philosophy for the ACR.
- The role of the ALARA principle.
- The overall QA program for the ACR.
- The safety margins in the ACR design.
- The application of the defense-in-depth philosophy to the ACR.

- On-power refueling.
- On-power containment access.
- The treatment of severe accidents and source terms for the ACR.

A report which identifies those Unresolved Safety Issues and medium- and high-priority Generic Safety Issues in the current version of NUREG-0933 (i.e., including updates identified in SECY-02-0148) that may be applicable to the ACR design. (March 31, 2003).

A preliminary report on the safeguards and security concepts for the ACR (April 30, 2003).

A report describing the major safety-related systems and safety systems (April 30, 2003).

A report on the design assist PRA (June 30, 2003).

Information to be provided in Phase 2 (July 2003 to June 2004) of the pre-application review for the ACR

A report on the technology of CANDU fuel channels (July 01, 2003)

A report on the technology of on-power fueling (July 01, 2003)

A report describing the R&D in support of understanding the progression of severe accidents in the ACR (September 30, 2003).

A report on the codes and standards used in the ACR design (October 31, 2003).

A report describing the details of the ACR design (December 31, 2003).

A report on how tritium safety is addressed in the ACR design (December 31, 2003).

A report on the formal validation approach applied to the computer codes used in the safety analysis for the ACR (December 31, 2003).

A report on the CANFLEX fuel design (December 31, 2003).

A report which describes the resolution or the resolution strategies for those Unresolved Safety Issues and medium- and high-priority Generic Safety Issues, identified in the current version of NUREG-0933 that are applicable to the ACR design. (March 31, 2004).

A report on the security and safeguards aspects of the ACR design (March 31, 2004).

- The report will describe the aspects of the ACR design which provide protection from insider and outsider sabotage.

A report on the waste management approach for the ACR (March 31, 2004).

A report on ACR's proposed approach to Inspections, Tests, Analyses and Acceptance Criteria (ITAAC) for the ACR (May 31, 2004).

8. Schedule

An overview of the proposed schedule for the NRC's pre-application review of the ACR design is shown in the following table.

Item	Date
Formal request to NRC for Pre-application review of ACR	June 19, 2002
Phase 1 – ACR Pre-application review	June 2002 to June 2003
First public meeting with NRC on ACR	July 24, 2002
ACR Technical Workshop • The ACR Design • The Technology Basis for the ACR	Sept. 25, 26, 2002
Submit proposed plan for pre-application review to NRC for discussion	Sept. 26, 2002
Phase 1 technical information on ACR sent to NRC	Oct. 2002 to April 2003
NRC review of technical information	Oct. 2002 to June 2003
NRC estimates of cost and schedule for completion of Phase 2	June 30, 2003
Phase 2 – ACR Pre-application review	July 2003 to June 2004
Phase 2 technical information on ACR sent to NRC	July 2003 to May 2004
NRC review of technical information	July 2003 to June 2004
NRC Safety Evaluation Report on ACR Pre-Application review	**July 2004**