ACR Technology for CANDU® Enhancements

By

Stephen Yu, Ranjit Singh and Mike Soulard

Atomic Energy of Canada Limited

Abstract

The ACR-1000® design retains many essential features of the original CANDU plant design. As well as further-enhanced safety, the design also focuses on operability and maintainability, drawing on valuable customer input and OPEX. The engineering development of the ACR-1000 design has been accompanied by a research and confirmatory testing program. This program has extended the database of knowledge on the CANDU design. .

The ACR-1000 design has been reviewed by the Canadian regulator, the Canadian Nuclear Safety Commission (CNSC) which concluded that there are no fundamental barriers to licensing the ACR-1000 design in Canada after completing three phases of the pre-project design review. The generic PSAR for the ACR-1000 design was completed in September 2009. The PSAR contains the ACR-1000 design details, the safety and design methodology, and the safety analysis that demonstrate the ACR-1000 safety case and compliance with Canadian and international regulatory requirements and expectations.

The ACR technology developed during the ACR-1000 Engineering Program and the supporting development testing has had a major impact beyond the ACR program itself:

- Improved CANDU components and systems;
- Enhanced engineering processes and engineering tools, which lead to better product quality, and better project efficiency; and
- Improved operational performance

This paper provides a summary of technology arising from the ACR program that has been incorporated into new CANDU designs such as the EC6®, or can be applied for servicing operating CANDU reactors.

1. INTRODUCTION

Atomic Energy of Canada Limited (AECL) has two CANDU® reactor products matched to markets: the Enhanced CANDU 6® (EC6)a modern 700 MWe class PHWR design, and the Advanced CANDU Reactor® (ACR-1000), a 1200 MWe class Gen III+ design. Both reactor types are designed to meet both market-, and customer-driven needs. The ACR-1000 [1] design is 90% complete and market-ready, while current domestic and off-shore market attention is focussed on the EC6 [2] because of its attractive size and provenness.

2. ACR-1000 TECHNOLOGY APPLICATIONS

In the last 8 years AECL has completed a comprehensive R&D program in support of new features that has been incorporated in ACR-1000 and EC6. In addition, a large number of confirmatory testing were completed to demonstrate the robustness of the design, to verify the computer tools and methodology used in the engineering program and to demonstrate the performance of the design improvements incorporated. For the current year, the ACR program evolves from the managed completion of Basic Engineering Program priorities, to a long-term Technology Management program. This is primarily to transfer ACR technology to EC6 and advanced fuel cycle programs and to provide a platform for longer-term development.

The continuing generic development and confirmatory test program are in two parts:

- Completion of those ACR-1000-based tasks required to support EC6 licensing and project readiness.
- Carrying out tasks following up ACR-1000 R&D required to support CANDU fuel cycle applications [3]. For example, fuel power ramp testing is directly applicable to high burn-up fuels.

2.1 ACR R&D Technologies for EC6 Design

Reactor Containment

AECL has been a funding participant in an International program on testing and analysis of aircraft crash impact. This collaboration is continuing in support of the EC6 containment design.

Work is in progress to develop high performance concrete material for mitigation of ex-vessel retention of reactor core material under severe accident events. This work was started and ACR and is being completed to support the design of EC6 containment.

Reactor Core Components

Several material tests of ACR pressure tubes, including characterization of microstructure, fracture toughness tests, delayed hydride cracking, tensile tests and fabrication of prototype tubes were successfully completed. The experience and techniques perfected for these tests are being applied to the qualification of the EC6 thicker pressure tubes.

A development and qualification test program to demonstrate the integrity of the pressure tube to end fitting rolled joint for ACR was carried out and the initial tests were successful. The test facility built for ACR tests is being adapted to perform similar tests for the EC6 thicker pressure tubes.

A development and qualification test program to demonstrate the integrity of the calandria tube to calandria tubesheet rolled joint using and insert for ACR was successfully completed. The test experience gained from ACR tests is being used to perform similar tests for the EC6 thicker calandria tubes.

A test program to confirm the design of a new positioning assembly for ACR was completed successfully. The test facility used for these tests were modified and used successfully for completing testing of a modified positioning assembly for EC6.

Modification and upgrades to a test facility and procurement of the rod drive assembly for performing ACR Shutdown System 1 testing was completed. The facility and drive assembly is being adapted to perform testing of the redesigned EC6 Shutdown System 1. Testing will include drop tests to demonstrate endurance, performance tests to demonstrate reliability, seismic and environmental testing. The test facility simulates the full height of the rod and drive assembly.

Computer Code Development and Validation

Validation of CATHENA (Canadian Algorithm for THErmal Network Analysis) and MODTURC_CLAS (Moderator Turbulent Circulation — Collocated Advanced Solution) codes for ACR application were completed using the RD-14M test facility. The RD-14M facility was design as a scaled representation of the CANDU 6 reactor possesses most of the key components CANDU heat transport system. The facility was upgraded to meet the power requirements for achieving ACR temperatures and configuration. The facility is being modified to return it to EC6 configuration and testing is planned to verify EC6 Emergency Core Coolant safety analysis under accident conditions.

Validation of the IST safety analysis code TUBRUPT (TUBe RUPTure) for ACR was completed using a small scale burst facility built specifically for ACR.

Development and validation of reactor physics (WIMS, RFSP, MCNP) codes for ACR application were done against ZED-2 (Zero Energy Discharge) measurements and against external facilities measurements such as the FUGEN Reactor, Japan.

Validation of fuel codes; BOW, LONGER, ELESTRES, FEAT, FEAST, BEAM, FEET , were partially completed for ACR application. Completion of the validation of these is being undertaken to support the development of the EC6 fuel design manual.

Severe Accident Analysis and Methodology

A detailed review of severe accident phenomena in CANDU 6 reactors and ACR was completed under the ACR Development Program. A R&D strategic plan using the Phenomena Identification Tanking Table methodology was used to identify and prioritize severe accident phenomena in order of importance. This plan is being used in conjunction with PSA, analytical techniques and design changes to EC6 to address severe accident conditions to identify the R&D required to support EC6 safety analysis of severe accidents.

2.2 ACR R&D Technology Spin Off to Advanced Fuel Cycle Development

More than forty MOX fuel bundles was fabricated and used in ZED-2 to produce experimental data for the validation of physics codes. These bundles will be modified to incorporate Thorium fuel for use in ZED-2 to produce experimental data for validation of physics for a Thorium fuelled reactor.

A demountable element fuel bundle fabricated to the ACR design has been completed and is ready for in-reactor testing. This bundle will be irradiated in the NRU Loops 1 and 2 to undergo power ramp tests generating valuable.

3.0 Application of ACR Technology

The following are examples of where ACR technology developed through ACR-1000 Development are used in EC6:

3.1 EC6 Design Improvements and Changes

The EC6 has leveraged a significant amount, approximately 80%, of design changes using the results from the ACR-1000 product engineering. This up-front adoption has been critical in enhancing the CANDU 6 design to ensure the EC6 meets current regulations and standards, customer expectations of today including application of modern technology, and international security requirements. Applicable philosophies and design changes have been carried over to the EC6 design.

For environmental protection and fire protection, the review of current regulations including CNSC RD-337 and MISA regulations and the determination of requirements have been leveraged from ACR-1000. A significant amount of work was done on ACR-1000 to align safety goals, safety classification, environmental qualification, and single failure criteria with the latest requirements of RD-337. Incorporation of the Human Factors Program into EC6 was accomplished through development in ACR-1000 program. The same methodology and approach has been carried over to the EC6 design.

Another key area where ACR-1000 work has been leveraged in the EC6 design is the physics assessments. Although the two reactors have different cores, the EC6's physics assessments for core optimization and LOCA improvements are based on updated Industry Standard Toolset (IST) physics codes developed for ACR-1000. Extensive Licensing progress achieved with the ACR-1000 has also been built on through the establishment along with endorsement from the CNSC of the Preliminary Safety Analysis Report (PSAR) structure and content. Successful completion of the CNSC Phase 1, 2, and 3 reviews supported by the ACR-1000 Generic Safety Case Report and subsequent PSAR allow EC6 a more efficient licensing approach through to Construction License.

Major plant design changes brought over to EC6 from ACR-1000, particularly regarding containment and I&C include:

- Use of a steel-lined pre-stressed concrete containment structure
- Use of a distributed control system
- Incorporation of a computerized safety parameter display system
- Computerized safety system testing
- Use of equipment health monitoring
- Software work practices

For Instrumentation & Control (I&C), the methodology and toolsets have also been leveraged from ACR-1000, in particular, the technology selection, design concepts, and qualifications processes adopted.

Other key design changes adopted by EC6 include:

- Updates to the reactor (for example, improvements to the spacer design, positioning assembly, the use of fission chambers, the seamless calandria tubes, and enhanced flow paths between the end shields and calandria vault);
- Optimization of moderator inlet and outlet nozzle configuration on the calandria for increased moderator sub-cooling;
- Use of ultrasonic feedwater flow measurement for reducing uncertainties; and
- Use of feeder pipe material with a higher Chromium content.

3.2 Operational improvements

The EC6 performance targets are nearly as high as for ACR-1000 which is substantially higher than for CANDU 6. In the case of the forced loss rate, the EC6 performance targets are even higher than for ACR-1000. Therefore the respective operations-oriented changes on ACR-1000 to meet the higher performance targets are being adapted to EC6. The processes and experience used for ACR-1000 will be used for the EC6 to the extent possible:

- Design documents are reviewed by the same Operations & Maintenance (O&M) group for design and layout improvements to improve operability and maintainability.
- OPEX (Operating Experience) used for ACR-1000 is being applied to EC6.
- The maintenance-based design process for ACR-1000 is being applied to EC6.
  - Identification of single points of vulnerability and critical components.
  - Application of O&M checklists for the designers to follow.
  - Use of modern equipment status monitoring and equipment health monitoring tools – use of remote monitoring and collection of data via computers.
- Modern engineering tools used for ACR-1000, such as the site LAN and master equipment database will be used for EC6.
- The process to minimise length of ACR-1000 outage will be applied to reduce EC6 outage length.
- The process followed to achieve planned outages every three years for ACR-1000 will be applied to EC6, and will be available on-site to support plant operations and maintenance.
- The computerization of the ACR-1000 controls, such as the safety systems, will be applied to EC6 improving operational testing.
- The manpower required to run the ACR-1000 is less then for other CANDU plants. Applying the changes made to the ACR-1000, such as computerized equipment monitoring for more equipment, with greater details, will be applied to EC6 to allow a reduction in EC6 manpower requirements.
- ACR-1000 design changes to reduce collective staff dose will be applied to EC6.

- Work done to meet the Ontario RFP in the O&M as well as other areas will be applicable to EC6, as it is expected that any Ontario EC6 RFP will have the same requirements.
- The work done on the ACR-1000 Technical Specifications for operations will be utilized for EC6.

3.3 Project Engineering Processes and Tools

The QA Program as developed for ACR-1000 is being rolled-out essentially in its entirety to support the EC6 program. This is possible as both ACR-1000 and EC6 work is of the same type (new build design), utilizing the same project organization and execution methodology. The processes and tools being adopted on EC6 were developed, tested/debugged/implemented, and firmly established in the ACR department culture. The ACR program was reviewed by CNSC and audited by OPG and found by both as satisfactory. By transferring these as well as ACR staff directly to EC6, we give EC6 the advantage of avoiding the learning curve typical for mobilization of any project making it possible for effort to be immediately and solidly focussed on carrying out the scheduled work activities.

Examples of some specific program practices that were developed during ACR, found to be very successful in project execution, and that have been transferred to EC6, are:

- Management Review Meeting (for oversight of NCR – Non Conformance Reports)
- Processes facilitating Safety Culture initiatives in a design organization, like Event Free Day Reset
- Establishing of Nuclear Safety Review Board for design organization
- Methodology for execution of Self-assessments
- Action Tracking (including Licensing, Configuration Management, and QA actions)
- QA Orientation training for staff joining the project
- Processes facilitating the use of SmartPlant 3D in design
- Processes related to module development and integration work
- Risk Management program with methodology of mitigation of the risk during design

The use of advanced electronic tools on Qinshan is estimated to have resulted in a cost avoidance of over $100M. With the additional advances made through ACR, EC6's adoption of ACR-1000's data-centric approach sets the project up for far greater savings in plant design, construction, commissioning, and operation costs. Examples of advances in ACR data-centric toolset include:

- 3-D CADD for system, equipment, civil and instrumentation design;
- Project Control for schedule and cost controls; and
- Requirements Compliance (mandated by the regulator and customer) through electronic requirement management system.

4.0 Conclusions

The ACR-1000 Basic Engineering Program (BEP) encompasses more than the designing of a reactor or nuclear steam plant. It introduces opportunities for product development and R&D testing – resulting in better CANDU components and systems; better engineering processes and engineering tools which leads to better product quality and project efficiency; and better design features or improved operational performance that can be incorporated into new designs such as EC6 or can be used for servicing operating reactors.

4.0 References

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[3] J.Hopwood, S.Kuran & I.Hastings, "Fuel Cycles in CANDU: Security of Supply and Reduced Used Fuel Management", 32nd Annual Canadian Nuclear Society Conference, Niagara Falls, Canada, Jun5-8, 2011.