Technology Spin-offs from a CANDU Development Program

Stephen Yu
Atomic Energy of Canada Limited, Mississauga, Ontario, Canada

Abstract

Both Enhanced CANDU 6 (EC6) and ACR-1000 design retain many essential features of the operating CANDU 6 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. The ACR technology developed during the ACR-1000 Basic Engineering Program and the supporting development testing has extended the database of knowledge on the CANDU design.

This paper provides a summary of technology arising from the ACR program that has been incorporated into new CANDU designs such as the Enhanced CANDU 6 (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 HWR 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 design [1] is 90% complete and market-ready, while current domestic and off-shore market attention is focussed on the EC6 because of its attractive size and proven operational performance.

The ACR-1000 design retains many essential features of the original CANDU plant design. As well as further-enhanced safety [2], 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 a 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 in the Phase 2 pre-project design review that there are no fundamental barriers to licensing the ACR-1000 design in Canada. 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.

2. Applicability of ACR-1000 technology

The Enhanced CANDU 6 (EC6) design (see Figure 1) design change engineering program has been in progress following closely to the successful completion of the pre-project design review of the ACR-1000 design. The EC6 product definition and design planning was completed in 2010 September and the Phase 2 of the pre-project design review by CNSC is currently underway.

The EC6 design engineering has leveraged a significant amount, approximately 80%, of design changes using the results from the ACR-1000 product engineering. The ACR-1000 basic engineering program includes design concept development, licensing compliance review, confirmatory testing and design documentation. This up-front adoption has been critical in enhancing the CANDU 6 design to ensure the EC6 meets current regulations and standards, and international security requirements. Applicable philosophies and design changes have been carried over to the EC6 design.

The EC6 design features make full use of the ACR technology developed and the supporting development testing completed during the ACR-1000 Engineering Program will result in:

- Compliance with new licensing and regulatory requirements
- improved EC6 components and systems;
- enhanced engineering processes and engineering tools, which lead to better product quality, and better project efficiency; and
- improved operational performance

Figure 1 2 unit Enhanced CANDU 6 Design

The following sections provide further details of where ACR technology developed through ACR-1000 Development are used in EC6:

3. EC6 Design improvements and changes

Design changes to the reference plant to achieve the safety goals stated in CNSC RD-337 are incorporated in the EC6 design based on the technology developed in the ACR program. The changes are to enhance robustness, design margin and reliability of the design.

- Robust Steel lined containment:
  - Design for main steam line break (MSLB) as a design basis accident (DBA) event.
  - Consider the effects of severe accidents and introduce design features to provide design robustness to mitigate severe accidents.
  - Consider beyond design basis threats such as a large commercial aircraft crash.
  - Design for regulatory release limits.
  - Design for a design basis earthquake (DBE) PGA of 0.3g to improve the marketability of the product as it would meet all potential sites in Eastern North America.
  - Meet a lower leak rate and an exclusion zone of 500 meters which is the requirement of most utilities.
  - Addition of passive auto-catalytic recombiners (PARs) to deal with hydrogen behaviour in containment.
- Design Enhancement for Beyond Design Basis Events BDBA prevention and mitigation
  - Optimization of moderator inlet and outlet nozzle configuration on the calandria for increased moderator sub-cooling;
  - Stronger fuel channel position assembly when fuelling machine is attached
  - Provide flow paths (interconnection) between end shields and calandria vault
  - Increase pressure relief capacity in the calandria vault
  - Design emergency heat removal system (EHRS) as a safety system.
  - Dual train heat sinks independence for RSW and RCW systems.
  - Automatic actuation of the EPS diesel generators (DGs), ECC, and reserve water tank make-up to steam generators on a loss of all Group 1 systems
  - Seismically qualify the steam generator automatic depressurization logic .
  - Battery supply for 24 hours for components required for station blackout events .
  - Severe accident recovery and heat removal system (SARHRS).

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. Feedback from the successful completion of the CNSC Phase 1, 2, and 3 reviews of the ACR-1000 product using the concept of an interim Safety Case

Report allows EC6 a more efficient licensing approach from pre-project design review through to Construction License Application review by CNSC.

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);

- Use of ultrasonic feedwater flow measurement to reduce power measurement uncertainties and hence permit higher output without exceeding design limits.

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. The following EC6 design changes address current federal and provincial regulations which outline the as low as reasonably achievable (ALARA) principles to protect the environment, and to reduce emissions of non-radiological substances:

- Liquid Waste Management System
    - Collect detergent wastes separately from active wastes to prevent mixing of detergent wastes with active liquid wastes and extend the life of the ion exchange resin.
    - Add a treatment circuit to comply with Municipal/Industrial Strategy for Abatement requirements for oils, organics and toxicity.
- Steam Generator Blowdown System
    - Add a wet lay-up loop to the steam generator blowdown system to reduce the release of hydrazine to the environment.
    - Increase steam generator blowdown flow from 0.1% to 1% of feedwater flow to extend the life of the steam generators to 60 years.
- Vapour Recovery System
    - Add a new dryer in the service building for the moderator auxiliary areas and D_2O management systems to reduce airborne tritium emissions.
    - Reroute the vent connections from the moderator auxiliary systems to the moderator enclosure vapour recovery system to reduce airborne tritium emissions.
- Solid Spent Resin Handling System
    - Segregation of spent resin storage tanks to ensure the moderator resins holding large amounts of carbon-14 from other resins.
    - Use spent resin tank water for spent resin slurry operations to reduce liquid tritium emissions.
- Moderator Cover-Gas System
    - Circulate moderator cover gas through reactivity mechanism thimbles to reduce the possibility of hydrogen (D_2) deflagration.
- Moderator Purification System
    - Install filters downstream of the moderator ion exchange columns to capture resin fines and reduce carbon-14 emissions.

- Off-Gas Management System
  - Addition of two off-gas streams from the fuelling machine D_2O supply system to the off-gas management system to reduce emissions of noble gases to the environment.

4. Operational improvements

Design changes have been identified to address a number of modern plant expectations (i.e., Generation III/III$^+$) as identified in Utility Requirements Document by Electric Power Research Institute (EPRI), World Association of Nuclear Operators (WANO) and European Union and as specified by owner requirements, such as modern instrumentation and control, maintenance based design and operational support systems.

Modern instrumentation and control (I&C)

Major plant design changes brought over to EC6 from ACR-1000 for I&C include:

- Use of a modern distributed control system (DCS) [3] to address the obsolencence of digital control computers (DCCs)
- Incorporation of a computerized safety parameter display system
- Computerized safety system testing

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

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.

Maintenance based design and O&M improvements

The EC6 plant lifetime capacity factor target is 92%, with less than 1% forced outage rate and a 30-day outage on a 3 year frequency. The EC6 performance targets are comparable to ACR-1000 which is substantially higher than for operating 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 planned 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.
- The work done on the ACR-1000 Technical Specifications for operations will be utilized for EC6.

Operational Support Systems

Several new operational support systems developed for ACR and for Operating CANDU to support plant performance improvements have also been added to EC6:

a) Augmented and/or improved equipment health monitoring system for a selection of critical components:

   Increased and improved diagnostic health monitoring and associated analysis software packages are provided to detect the degradation of important systems/equipment prior to failure. The data analysis and visualization software includes AECL's SMART CANDU software suite of ChemAND (Chemistry ANalysis and Diagnostic), ThermAND (Thermal ANalysis and Diagnostic), FCMAT (Fuel Channel Monitoring and Assessment Tool), FDMAT (Feeder Monitoring and Assessment Tool), and FPMAT (Fuel Performance Monitoring and Assessment Tool).

b) Online risk monitor:

   An online risk monitor is provided to promote a risk-informed optimization of maintenance. The online risk monitor is implemented using EPRI's Equipment-Out-Of-Service (EOOS) software, and evaluates risk in terms of core damage frequency and large release frequency using AECL's EC6 probabilistic safety assessment models adapted for use with EOOS. This serves to enable increased maintenance on-power and improve the scheduling of maintenance both on-power and during shutdown to keep risk below acceptable levels.

c) Equipment status monitor:

   An information system is provided to manage plant status control. This system acts as a central repository for equipment status, managing the processes used to control and track equipment state or availability (e.g., work permits, lock-outs/tag-outs, alignments, temporary changes, jumpers, position assurance checks, turnovers, operator rounds, etc.).

5. 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 model 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 for the EC6 Design Change Engineering Program and to support Phase 2 of the EC6 Pre-project design review by CNSC.

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 on progress of Non-Conformance Reports (NCR)
- 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 for document production and design data management from 3D design models using integrated design tools
- 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 for document control, material management, integrated wiring and 3D plant design 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:

- Integrated 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.

6. Conclusion

The ACR technology developed during the ACR-1000 Basic Engineering Program and the supporting development testing has extended the database of knowledge on the CANDU design. The EC6 design has leveraged a significant amount of design changes using the results from the ACR-1000 product engineering program – resulting in:

- enhancements of safety and compliance with current regulatory requirements
- better and more robust CANDU components and systems in compliance to current regulations and meeting modern plant expectations;
- better engineering processes and engineering tools which leads to better product quality and project efficiency; and
- better design features or improved operational performance**.**

7. References

[1] N.Popov, S.Doerffer, R.Ion & S.Yu, “ACR-1000 – Advanced CANDU Reactor Design”, Proceeding of European Nuclear Conference, Barcelona, Spain, May 30 –Jun22, 2010.

[2] S.Yu, Z. Bilanovic, P.Reid, P. Santamaura & M. Soulard, “ACR-1000 Design and Safety Performance”, Proceedings of the 18th International Conference of Nuclear Engineering, Xian, China, May 17-21, 2010.

[3] V.Gomez et al, “Application of DCS to New Build CANDU Designs using the G-HIACS ήSAFE Platform”, Proceedings of the 23rd Annual Conference of the Canadian Nuclear Society, Niagara Falls, Ontario, Canada, 2011 June 5-8.