Advanced CANDU Reactor Design for Operability

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This paper outlines design features and engineering processes in the ACR\textsuperscript{TM} development program which contribute to excellence in performance and low operating cost.  AECL recognizes that future plant owners will place a high priority in these operational characteristics.  A successful next generation plant will have a best-in-class capability, both in its design characteristics, in the engineering philosophy and program adopted during the product development, and in the vendor's approach to operating station support.  The ACR program addresses each of these drivers.  Operability considerations are built-in to the design at an overall, plant wide level.  For example, based on the strong CANDU\textsuperscript{®} 6 operating record, targets for standard outage duration, time between outages and component durability are set, while the design engineering is managed to achieve these targets.  The ultimate maintenance target for the ACR, once initial operating experience has been gained, is to operate with a 21-day standard maintenance outage at an interval of once every three years.  At the detailed design level, close attention is paid to space allocation, to enable good maintenance access.  Selection of components also places emphasis on maintainability based on the extensive and current experience with CANDU projects.

KEYWORDS: CANDU, ACR, Maintenance

1. Introduction

The ten member countries of the Generation IV International Forum (GIF), with the help of leading international experts, have recognized a number of nearer term advanced reactor systems under development around the world.  All are expected to be deployable by 2015, and are designed to meet or exceed the performance of current light water reactors.  The Advanced CANDU Reactor (ACR)\textsuperscript{TM} is included in this grouping.

Generating stations employing heavy water reactors have now firmly established an enviable record for reliable, economic electricity generation.  There are several reasons for this, including the use of on-power refuelling, high quality engineering, manufacturing and construction, and the ability of the fuel and plant systems to permit rapid plant start-ups and loading rates.

The consistently high capacity factors achieved by different utilities (at different experience levels) in different countries, show the effectiveness of the common underlying technology, the CANDU\textsuperscript{®} 6 design.

ACR-700 is the first CANDU nuclear plant that has been designed to a target cost for Operation and Maintenance (O&M).  There are several aspects involved in the design to realize a low cost electricity generator:

- The plant must run for a minimum of 40 years, and should have no known design limitations up to 60 years.
- High average annual output.  Forced outage rates under 2%.
- Year after year dependability, with no major equipment performance that could result in extended shutdowns.
- Extended full power runs of at least 2 years between planned outages.
- Short planned outages, with predictable start up dates.
- Low staff numbers needed to operate the plant.

From the above it is clear that the major focus for the designer must be capacity factor.  Not only does it affect the bottom line directly, but also a plant that runs in the 90 \% range is cheaper to operate as long outages cost money and unreliable equipment costs more to maintain.  Poor plant performance is a detractor for management who then have little time to improve organization efficiencies.
II. Design Life

The design life for current CANDU 6 plants is 40 years. However, the high degree of conservatism in the design (assumed frequency for various transients, etc.) and the high quality of station operation and maintenance has combined to assure substantially longer station life. Recent reviews of operating CANDU 6 plants, including assessments of actual transients, equipment condition, and degradation mechanisms, indicate that operating in excess of 60 years is probable.

The 60 or more year plant operating life for the ACR-700 is possible in part due to the unique CANDU pressure tube reactor concept, which enables pressure tube replacement and avoids life limiting pressure vessel embrittlement problems. A single plant shutdown is required for 12 months or less to replace pressure tubes and perform mid-life modernization and retrofits.

III. Planned Outage Improvements

The ACR design has made significant improvements to the way outages are performed in order to achieve the capacity factors required for a lower overall energy cost. Through the ACR design process, historical reactor constraints are being removed to reduce outage duration from 40-60 days to 21 days. Critical path activities have been examined to determine which areas needed improved accessibility such that equipment can be easily and quickly maintained during outages.

Reduction in the number, and duration, of forced outages has also been examined. This will require the redesign of unreliable equipment. In addition, the ACR plans to deliver a plant wide integrated maintenance program complete with tooling, a component bill of materials, up-to-date and easily maintainable configuration management databases, and adequate spares at the day of turnover. It is, therefore, realistic to substantially reduce the historical forced outage frequency and duration.

With the improvements to capacity factors as discussed above, the redesign of plant equipment that has historically been a maintenance burden, and the improved access to design information, it is possible to significantly reduce station staff levels. Key targets for ACR-700 O&M are as follows:

- A year-to-year capacity factor 93% to 95% is feasible.
- Planned outage duration of 21 days every 2 to 4 years. The design target is 3 years.
- Significantly lower staff levels than previous CANDU reactors.

An incremental design effort at all phases of the project is being undertaken to ensure the targets given above are achieved within the operating station.

On-power refuelling is one of the ACR’s performance enhancing assets. The reactor is refuelled during full-power operation. Fuel is continuously replenished at a rate of a few bundles per week. There is no requirement to shutdown the unit for refuelling of the reactor, as is the case with PWRs and BWRs. What determines the outage frequency and duration is the need to access equipment for preventive maintenance and inspections.

The ACR-700 design outage frequency is once every 3 years, with an outage duration of 21 days. Newer CANDU plants in Canada traditionally have used an outage frequency of 2 years. One major utility has begun the process of extending this to 3 years, with a cautious first step outage frequency of 30 months.

ACR systems are being designed such that no off-power maintenance or testing is required for a minimum of 3 years. The design approach is to provide standby safety related equipment that allows both testing and maintenance at power to the maximum extent practical. A Probabilistic Safety Assessment (PSA) is performed to support the test interval of any safety critical component. If the few items that cannot be tested at power contribute unacceptably to safety targets, then additional redundancy is provided to assure 3-year operation.

1. Scheduling Constraints

Scheduling constraints during planned outages, which exist in some existing CANDU plants, can be eliminated at a reasonable cost through improved design. Key improvements are as follows:

- Two 100% long-term cooling trains have been provided to provide more flexibility in scheduling maintenance.
- Modifications to the fuelling machines to speed up the defuelling of fuel channels for pressure tube in service inspection.
- The application and removal of the Reactor Shutdown Guarantee (high gadolinium concentrations in the Moderator) has been simplified such that it can be applied and removed in a single shift.
- Computerized testing of major safety systems to reduce both on line testing and startup testing time.

2. Outage Maintenance Reduction

The ACR-700 concept reduces outage maintenance as compared to previous CANDU designs:

- The use of light water in the Heat Transport systems reduces the amount of work in plastic suits.
- The elimination of the Liquid Zone Control System from the ACR-700 removes a significant workload from the outage.
- The ACR-700 has fewer fuel channels, and feeders, to inspect.
- The ACR-700 has two boilers, versus four on the CANDU 6, to inspect, which is a significant saving in both required inspection equipment and manpower to open, close, and set up.
3. Outage Maintenance Efficiency

An ideal critical path for an outage is when all work paths are within a day of each other. This means that any single critical path duration has been improved to be in line with other durations. The result is that a large volume of work must be done in a short period. The designer must focus on improving the flow of people and materials to the job site. Scaffold erection and dismantling must be kept to a minimum:

- Specifying the ISI inspection requirements at an early stage of the design ensures platforms are designed to permit access at all locations. F/M bridge platforms and insulating panels are designed for quick access.
- Fuel channel inspection equipment is designed to be set-up in a single shift.
- A service elevator is included within the reactor building for tool carts and equipment.
- The ventilation is designed to allow main airlock doors to be open during an outage. The airlock frame design accommodates a single aluminum conventional door, thus allowing a much faster movement of personnel without risk of airborne contamination flowing out of the reactor building.
- Adequate inspection provisions are provided for major equipment (e.g., Standby Generators, major HX's, etc.) to facilitate comprehensive inspection.
- A large reduction in scaffolds or additional hoists will simplify maintenance. A maintenance specialist reviews all systems during layout. Normal shutdown maintenance provisions, such as temporary electrical, water, and air supplies are built into the design.
- Piping analyses of the HTS includes provisions for lead blankets and removal of valves from lines, while retaining seismic capability.
- Provision of spare valves, breaker, pump/motor assemblies for replacement. Overhauls would be done in the shop after the outage.
- Insulation on the secondary side is removable to allow FAC inspections.
- Dedicated lay down areas for parts staging are provided.
- Office areas for outage management are provided.

IV. Forced Outage Improvement

Equally important, or perhaps more so, to the station’s lifetime capacity factor is the amount and duration of unplanned, or forced, outages. Many of the design improvements noted in the planned outage discussion, above, are equally applicable in reducing the duration of a forced outage. However, preventing a forced outage requires a different approach.

Preventing forced outages is a difficult assignment. There has been a tendency in past nuclear plant design to take a snapshot in time of major problems of the previous design. Designers then focused on resolving those half dozen items, expecting the next plant to have a higher capacity factor. This has not proven to be the case because equipment differences in a 10-year later plant prohibit replication of the original. Very subtle changes in the new equipment can produce significant negative results. There are 1000’s of pieces of equipment that, if they fail, may not cause an immediate shutdown, but may prevent operation to the next planned outage. What has been learned over the decades is that a much more systematic and rigorous approach to developing the preventative maintenance program is needed, and this is generally referred as Reliability Centred Maintenance (RCM). The benefits of conducting the review in the design phase – prior to equipment selection – appear obvious. The benefits are clear in selecting such equipment much more carefully than in the past with the input of equipment experts.

From Figure 1 it can be seen that the opportunities on the left are not usually afforded to an operating plant. Retrofitting equipment and installing scaffolds or even airlocks are cost prohibitive and rarely done. However, for new plants these opportunities can be exploited. Of course there are trade off’s in higher capital cost for lower operating costs. The objective must therefore be to optimise the design while maintaining flexibility, allowing the utility to envisage the plant in an operating phase and assure itself that the combination of equipment and preventative maintenance plan will produce the necessary low operating cost. Hence, the following maintenance strategy is embodied in the ACR-700 design:

- RCM approach used throughout the design. By identification of critical components early in the design, the highest quality equipment can be provided. With a clear understanding of failure modes that must be avoided, the sub-components of the equipment can be evaluated for reliability. In addition, maximum accessibility is designed for critical components to allow easy routine maintenance.
- A maintenance plan will be delivered to the owner/operator.
- A recommended major spares list will be provided to the utility.
- The necessary infrastructure for condition- based maintenance (vibration, oil, AOV, MOV, thermography, etc.) is provided for.

V. O&M Cost Improvements

The most significant way to cut operating costs is through the reduction of staff needed to run the plant. It is apparent that a unit with short planned outages and few forced outages will require fewer staff and encounter lower overtime costs than an unreliable unit. Hence, the focus of the ACR-700 has predominantly been in that direction. In
addition to the features noted above, additional design initiatives have also been taken.

1. Field Work Reduction

One of the ACR-700 innovations is a light water Heat Transport system rather than heavy water in older CANDU designs. This reduces heavy-water replacement and upgrading costs by 90%. The other benefits are a reduction in the operator workload to drain and fill systems, and to process downgraded water. Outage and fuel handling equipment maintenance is also faster.

To secure additional cost savings, the designer has to review the nature of the work in the station. The largest component of O&M cost is labour, and therefore the focus must be on the three biggest work groups, which are Operators, Maintainers and Engineering. Work for all three has a common denominator, which is reliability of equipment. Installing high quality equipment for both NSP and BOP critical equipment will reduce preventive maintenance intervals and breakdown maintenance occurrence.

A major effort in standardization of components will result in a reduction in maintenance and training effort. Fieldwork would be done faster because of the familiarity with the equipment. Jobs on hold for parts would occur less often because a larger supply will be on hand (but less than the total compared to numerous suppliers); therefore there would be a lower cost for inventory storage.

Interviews with CANDU operators have identified more than a dozen areas of opportunity to reduce the maintenance load. ACR designers will eliminate historically high maintenance equipment by selecting equipment more suitable to the application.

A significant reduction in the need for scaffold, lifting devices and insulation removal can be achieved by ensuring they are catered to in the design stage. The planning for jobs is simplified and jobs that are put on hold for inadequate assessment of access will be few. This effort is largely directed to those components that are part of the preventive maintenance program, due to the recurring need for access.

Design improvements have been implemented to reduce maintenance of the Fuelling Machines (F/M). The high maintenance oil hydraulic system used in older plants is being replaced with electric drive motors. The modules in the fuel handling distributed control system can be removed and replaced very quickly while energized. The improved fuel handling distributing centre will have more self-diagnostics. Lastly, the new F/M uses D₂O instead of D₄O for the cooling system, reducing time and radiation exposure when servicing the F/M.

There are evolutionary labor saving changes in more recent CANDU plants that are included in the ACR. The following design features contribute to low operator requirements in the ACR:

- All process parameters are displayed in the control room reducing the need for detailed operator field rounds.
- The licensed operator, or a qualified panel operator, does almost all tests in the control room rather than a combination of field and control room.
- Shutdown System 1 and 2 (SDS1/SDS2) are computerized, thus enabling automated testing. The operator is required to initiate the test. The test computer checks that tests are successful and displays the results for operator verification.

I&C maintenance is reduced by:

- Automatic calibration of the in-core detector control signals to reactor thermal power.
- Spread checks of SDS1/SDS2 performed by the safety system monitor computer. Calibration is done when a detector reads significantly different from others measuring the same parameter.
- There are no trip units to be calibrated; the SDS1/SDS2 trip computers check actual measurement against the set point in digital format.

ACR engineering is also evaluating computerized testing of the ECC system.

2. Design Information

An electronic equipment data system is provided that can be easily loaded into the utility work management system. This contains all aspects of design information for each piece of equipment in the plant, including vendor information. This reduces engineering, supply, and maintenance effort to perform day-to-day functions. While most plants have a sophisticated system for this, the effort is tens of man-years to populate the database. This can be done in the design stage such that the benefits are realized from day one of operation.

Design Requirements have to be itemized, measurable, and contain both normal and minimum acceptable performance, with clear reference to supporting rationale. In the past, the supporting rationale was sometimes difficult to find, and for less important systems the operating band was not specified. The ACR design documents address how each requirement is met. This will reduce engineering assessments of equipment operability when faced with degraded performance.

Engineers performing system and component surveillance make up a large portion of the on site engineering department. Previous design efforts focused on the control panels and information systems for the operator. Clearly a new design must recognize these new users of data, and their different time scale for trending. In addition to plant parameters, new information systems must sort maintenance information in formats that allow quick assessments of deteriorating equipment performance, repeat work, excessive effort to maintain and so on. The ACR 700 is providing state of the art support software to enable reductions in engineering staff
Performing such functions. Some applications have been developed in house such as:

- ChemAND. This monitors feed-water chemical parameters
- ThermAND. This monitors the heat cycle efficiency

The above three innovations reduce staff in engineering, with the added benefit of contributing significantly to maintaining configuration management during the operating life of the plant.

VI. Conclusion

The ACR-700 design innovations will deliver a 2-unit plant that can operate at 93 to 95% year-to-year capacity factor.
Fig 1. Improved Plant Performance Flow-chart