DESIGNING FOR MAINTAINABILITY: USE OF OPERATING EXPERIENCE AND FEEDBACK TO IMPROVE PERFORMANCE OF THE ACR-1000®∗; DETAILING THE SPECIFIC CASE OF POWER OPERATED VALVES

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1.0 Introduction

The AECL, ACR-1000®, is being designed to achieve high lifetime capacity factor, low unplanned forced outages and short planned outages once per 3 years. In order to achieve this target extensive use is made of operating experience and industry feedback to improve the plant design. There is also a target to operate and maintain the plant with less staff than current CANDU®∗ power plants. The design will accommodate improvements in staff productivity.

While the focus is set on the targets above there is also one more objective, to contain the capital cost of the new plants. AECL and partners are designing the ACR-1000 plant using a number of initiatives that are client driven [e.g. through COG]. This paper outlines the use of industry feedback in general with specific details for Power Operated Valves (POVs). The nuclear industry has promoted that the basis for good operation and maintenance is best achieved by building in improvements in the initial design. AECL has endorsed this philosophy and feedback is central to the design of the ACR-1000.

2.0 The ACR-1000 Project Targets

The ACR-1000 is an evolutionary CANDU reactor design and enhances features relative to previous CANDU designs. The design will produce a gross output of approximately 1150 MWe, depending on siting. The design emphasizes improvements in safety margins, capital costs, operating performance, reliability and Operation & Maintenance (O&M) costs. The high level targets for the 60-year design life of the plant are:

- Lifetime capacity factor >90%
- Annual year-to-year capacity factor >95%
- Planned outages of 21 days every 3 years (nominal)
- Forced outage rate <1.5% /year
- Reduced staff (at least 10% less than previous CANDU power plant designs)

A major contributor to achieving these ambitious targets is use of operating experience and feedback.

3.0 Operating Experience and Feedback

The ACR-1000 design process takes into account operational experience as per CSA N286.2 "Design Quality Assurance for Nuclear Power Plants". Operating experience feedback comes from CNSC reports and Incident Reporting System (IRS), reports provided by the CNSC, pre-screened operating feedback provided by the CANDU Owners Group (COG), and feedback directly from utilities. Feedback from WANO & INPO and direct experience from the international contracts of AECL are also a source of feedback. Following review, CANDU power plant relevant feedback is compiled in the corporate Feedback Monitoring System (FMS) database. Feedback is assessed on a continuous basis for applicability to the ACR-1000 design. Applicable issues are then entered into the ACR-1000 specific FMS database and addressed in design, analysis, construction, commissioning, or O&M depending on the nature of the issue.

Major operational feedback issues such as those related to emergency core cooling (ECC) strainer deposits, etc has been captured by the CNSC as Generic Action Items (GAI). Other pertinent issues important to safety and production are assessed for application to the ACR-1000 design. Remaining issues related to construction, commissioning and O&M are addressed by plans and/or procedures.

4.0 The Purpose of Feedback Monitoring

The purpose of feedback monitoring is to improve overall plant performance by improving the reliability of safety and production equipment, extending the online maintenance provisions, enabling shorter outages and providing facilities and services which will reduce the OM&A costs. Numerous examples are available to demonstrate how the ACR-1000 is taking on the challenge for **Operational Excellence.** The focus of the feedback has been directed at three main areas:

1) Development of 4-channel safety systems -a significant design change to improve their reliability and maintainability.

2) Evaluation of design features of the reactor to eliminate problems in nuclear steam plant (NSP) systems, for example, changes to pressure tubes and feeders, removal of Liquid Zone Control and Dousing Systems

3) Identification of problem areas in the Balance of Plant (BOP) related to both production and safety support systems.

5.0 ACR-1000 Feedback Process

The issues for the ACR-1000 feedback were compiled from a number of diverse sources, such as:

COG – Provides details of all CANDU Power Plant Disturbances and Performance Reports.

AECL Service Contracts - Support contracts between AECL and the various utilities provide a clear indication of problem areas in the NSP.

AECL International Contracts - Work performed by AECL designing, construction and commissioning CANDU plants has provided a rich source of lessons learned for AECL. There is a formal process at the end of each contract to document these lessons for the benefit of future designs.

AECL Consultants & Staff – AECL has employed a number of individuals with extensive NPP operations and maintenance experiences. These staffs members work directly with designers to augment the feedback process and influence improvements in the ACR design.

CNSC – Issues from the Generic Action Items and application of revised requirements.

External Review Teams – A number of project reviews have been conducted by using a peer review approach. External specialists are engaged to review aspects of the ACR-1000. Their feedback is assessed for application to improve the ACR product.

5.1 Feedback Diversity of Inputs

Numerous sources of nuclear industry operating experience and feedback are monitored and used by AECL. Details of the diversity of the inputs accepted for review are shown in Fig.1, ACR-1000 Accepted Issues Sources. For example, the contributions from Qinshan are the result of formal post project assessment done by AECL on the completion of commissioning for the Qinshan Project. The Others, (15%), come from contributions from internal and external audits, WANO, INPO, IAEA, NRC and CNSC etc. The various issues are reviewed and a discipline manager is assigned as the owner of the issue. The issue is then dispositioned for follow up and action taken as appropriate for changes to design or business processes.

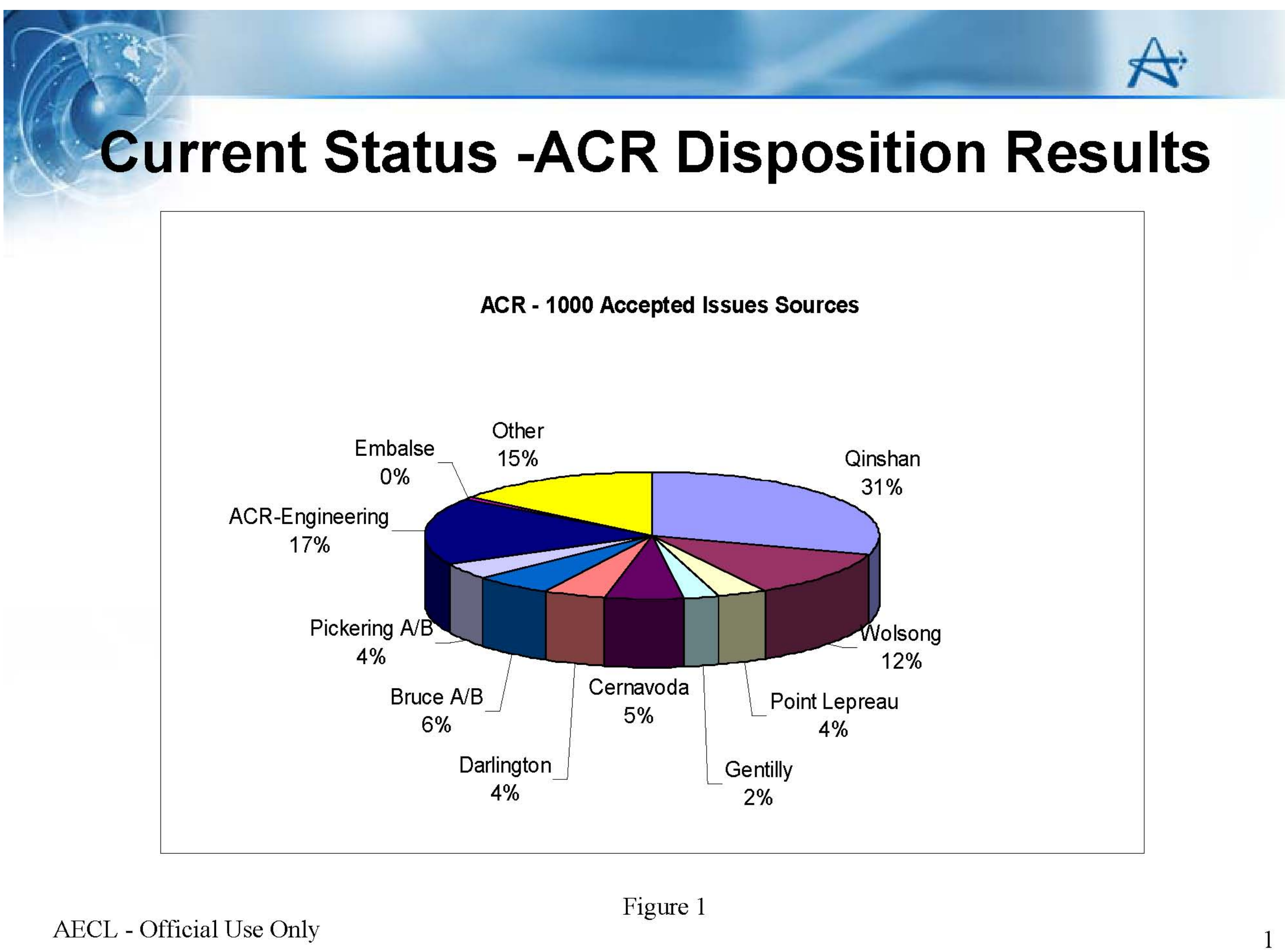

Figure 1

5.2 Types of Accepted Feedback Improvements

As part of the dispositioning process, the area where the issue has greatest impact is identified, as shown in Figure 2 - ACR Accepted Feedback-Improvements. The "Best Practices" category is usually assigned where improvement will impact more than one area, with no clear dominant contribution.

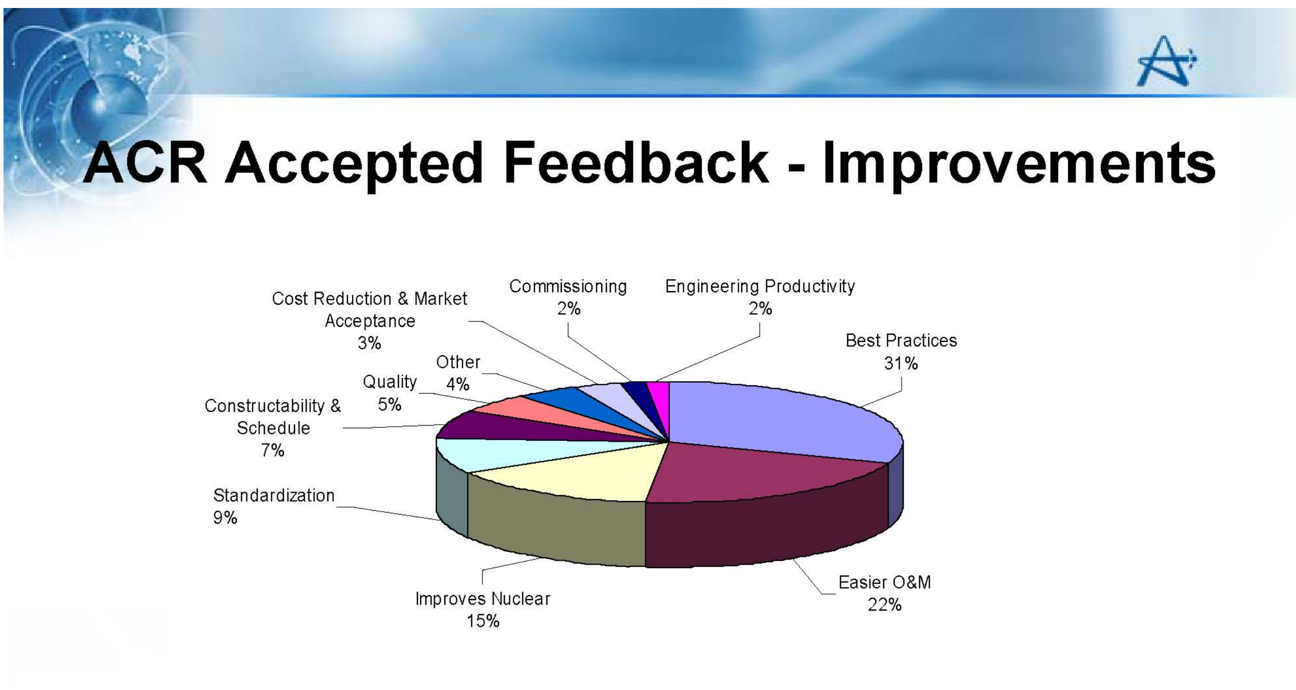

Figure 2

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6.0 Examples of Design Changes for Operating Experience and Feedback

6.1 Feedback for Reactor Safety

Several examples are provided in Table 1 – Operational Feedback Issues Important to Safety. While the examples listed were chosen mainly for their importance to safety they also will contribute to ACR-1000 improved plant reliability and operating performance.

For example, the improvement in Regional Over-Power (ROP) trip margins will avoid derating of plant output due to aging. The provision of four channels for Shutdown System 1 (SDS1) and Shutdown System 2 (SDS2) [and other features of the Safety System] will facilitate on-line maintenance, which in turn contributes to achieving the target of 21-day outages and elimination of spurious channel trips resulting in outages.

Improvements to the Heat Sink availability will also remove time restrictions for draining steam generators and going to the "low level drained" state, which will accommodate an early start to pressure tube critical pathwork with a subsequent benefit in a short outage period.

Table 1
Operational Feedback Issues Important to Safety and Not Covered in GAIs

Issue	Resolution for ACR-1000
Heat Transport System Margin Management Reactor designs need to account for the effects of plant aging on safety margins related to regional over-power (ROP).	Design features have been incorporated into the ACR-1000 to address this issue. In addition, the following improvements have been made: • Improved heat transport system (HTS) chemistry control. • Improved core subcooling. • Incorporation of four channels of ROP detectors and instrumentation for Shutdown System 1 (SDS1) and Shutdown System 2 (SDS2).
Large Loss-of-Coolant Accident (LOCA) Margin Improvement CNSC requires demonstration that the consequences of a large LOCA are acceptable.	Improvement in large LOCA margins has been made in the ACR-1000 design by optimizing the core design to reduce coolant void reactivity.
Improvements to Thermal Margin Related to Trip Coverage Margin to dryout is reduced for Anticipated Operational Occurrences at end-of-life	Improvements implemented in the ACR-1000 design as follows: • Adding low HTS pump speed trip. • Replacing low pump flow trip with low

conditions, including crept channels.	core differential pressure trip. • Optimizing fuel bundle design. • Increasing pressure tube thickness. • Maintaining subcooled conditions throughout the life of the plant.
Heat Sink Availability for Secondary Side Accidents COG has highlighted that existing stations did not account for potential loss of boiler inventory that may occur following a reactor trip.	The ACR-1000 design addresses these issues as follows: • The emergency feedwater system is automatically actuated. • The Boiler Feed Low Pressure (BFLP) trip is designed to provide trip coverage for main steam line breaks, feedwater line breaks, and Feedwater pump trip.
Fuel Behaviour for Large LOCAs Feedback from utilities has indicated CNSC concerns related to prediction of fuel bundle behaviour for certain accidents.	The overpower transient during a large LOCA is reduced in the ACR-1000 design by having a lower, predominantly negative, coolant void reactivity.
ROP Coverage Feedback from operating plants has shown that the ROP detectors did not cover full range of flux shapes.	Based on CANDU operating experience, ACR-1000 design has provided on adequate number of detectors to cover the full range of flux shapes on SDS1 and SDS2.
Issue	**Resolution for ACR-1000**
Liquid Zone Control System Feedback from operating plants indicates that this system needs to be simplified and equipment needs to be arranged to improve operability.	The liquid zone control units have been eliminated and replaced with mechanical units for the ACR-1000 design.
Steam Generator Tube Plugging Steam generator tube plugging has been observed due to flow-assisted corrosion of the HTS feeders.	ACR-1000 is using stainless steel feeders and headers in the HTS to minimize magnetite deposition in the steam generator tubing.
Deuterium Accumulation A COG joint study has concluded that deuterium may accumulate to an unacceptable level in the reactivity mechanisms, particularly during start-up or process upsets.	To address this issue, the ACR-1000 design provides forced circulation of moderator cover gas in reactivity mechanisms thimbles.
Fuelling Machine Feedback from operating plants includes the following issues: 1. Fire protection and operation issues due to use of lubricating oil. 2. C ram tape drive causes fuelling machine to get stuck. 3. Ageing and operation issues related to	Improvements in the ACR-1000 design include: 1. Replacement of hydraulic drives with electric drives. 2. Elimination of hydraulic rams and tape drives. 3. Replacement of ball screw driven rams by rack-and-pinion driven rams.

ball screw assemblies, 4. Fuelling machine recovery via manual drives is difficult and time-consuming.	4. Addition of redundant drives to reduce downtime.
On-line Testing of Trip Setpoints Feedback from utilities indicates that high reliability may not be demonstrated by relying only on off-line testing and maintenance.	The ACR-1000 design provides automated on-line testing capability of safety systems via the safety system monitor computer system which supports the testing process.
Airlocks Results from airlock seal leakage tests have forced seals on both equipment airlock doors to be repeatedly changed.	The ACR-1000 uses solid face seals instead of inflatable seals.
Emergency Core Injection System (ECI) Feedback issues related to the ECI system include: 1. The lack of back-up check valves means the reactor must be shutdown to allow for valve repairs. 2. A CNSC issue related to thermosyphoning capability with depleted inventory and void in the intact HTS.	The ACR-1000 design addresses these issues as follows: 1. There will be a redundancy for all components required for injection including check valves. 2. Core make-up tanks are provided to limit the extent duration of voiding in the HTS during events causing rapid shrinkage of inventory.

Issue	Resolution for ACR-1000
Heat Transport Pressure and Inventory (HT P&IC) System Feedback issues related to the HT P&IC system include: 1. The HT loop isolation motorized valves might not fully close under postulated accident conditions. 2. A leak in the pressurizer drain valve caused reactor shutdown. 3. Vibration problems encountered in line from the HT purification system intercooler leading to tempering flow temperatures above the saturation temperature. 4. Orifice blockage was observed.	The ACR-1000 design addresses these issues as follows: 1. Redundant isolation valves are incorporated. 2. Double isolation valves are incorporated in the pressurizer drain line. 3. The upstream and downstream flows are combined to reduce the tempering flow temperature. 4. Orifices are installed in horizontal lines only.
Moderator System Feedback issues related to the moderator system include: 1. High vibration in the moderator piping. 2. The need to connect the main moderator heat exchanger drain lines to the moderator D_20 collection system for	The ACR-1000 design addresses these issues as follows: 1. Numerous improvements have been made reducing the maximum low velocity, reducing the number of fittings by 30%, and improving the piping layout.

commissioning. 3. Moderator make-up in case of in-core LOCA with loss of emergency coolant injection when moderator draining could be postulated. 4. Hard face isolation valves are high maintenance items and not effective.	2. All drain lines are connected to the moderator D_20 collection system to ease maintenance and reduce radiation. 3. Water make-up is provided by the reserve water tank (RWT). 4. Valve hard face material is optimized to mitigate corrosion.
Long Term Cooling (LTC) System Feedback issues related to the LTC system include: 1. The shutdown cooling (SDC) pump became gas locked during draining of the HTS and test stroking the liquid relief valves during a reactor shutdown. 2. The SDC pump bypass isolation gate valves vibrate excessively when trying to create adequate backpressure for control purposes. This results in vibration fatigue in the valve and piping. 3. SDC pump motor cooler contained zebra mussels.	The ACR-1000 design addresses these issues as follows: 1. The LTC pump is located below the reactor building (RB) sumps and, therefore, has a greater static head from the HTS and the margin of H_20 level above the LTC pump suction line while in the low level drain state has been increased. 2. For the LTC system, these gate valves are replaced with butterfly valves. 3. LTC pumps motors are air-cooled.

7.0 Examples of Operating experience and feedback for POV's

7.1 Feedback for Production, Lessons Learned

For the ACR-1000 the review of the operational experience and feedback reflect the well-known profile of problem areas. As mentioned in section 6.1 the issues for pressure tubes and feeders have resulted in significant design changes. One of the remaining dominant areas of concern has been the unreliable performance of POVs. This is a complex problematic area and a number of issues have contributed to poor performance. These include design, equipment selection, materials, application, maintenance and human factors/errors.

As a result of the feedback process AECL set up an 'Expert Panel' focus group to look at the performance of motorized operated valves and air operated valves.

Examination of valve operating history in several CANDU power plants over the last 5-6 years identified about 92 valves in 19 applications, which have contributed, to the majority of station outages and plant upsets. The impact of the unreliability of POVs is shown below.

Table 2: Problematic Power Operated Valves

Valve Application	Impact on CANDU Capacity Factor (2004 to 2006)
LISS	6.25 days
P&IC and other HTS	38.0 days
ECC	3.25 days
SDC	19 days
DOUSING VALVES	None in that time frame
CSDV'S	17 days
BLCV & DALCV's	7.25 days
RSW & RCW	None in that time frame
	91 days Total

Note – Other applications with significant POV problems are Liquid Zone and Turbines. These were not included in this review because they will be addressed by other initiatives.

Table 2 was compiled by a group of O&M specialists as a list of systems that were known to have POVs that were problematic over the years. These systems were the subject of the study and the study period shown above is only a sample of the lost production as well as being a significant maintenance burden.
The issue that was recognised was that utilities were expending significant time, money and effort to improve the reliability of POVs. The need for improved reliability is part of the ACR-1000 design. The specifics for POVs are taken into account as part of the feedback used to improve future CANDU power plant operational performance because improving the POV reliability reduces the maintenance burden and avoids unplanned outages.

7.2 Apply Lessons Learned

To meet the demands of the ACR-1000 plant performance targets, a significant area for improvement is Power Operated Valves. This is a 'work in progress' and work is currently ongoing to apply lessons learned from the study in several major areas as detailed below.

7.2.1 Design

To improve the reliability of the valves, AECL generally follows the process set out in the INPO, AP-913 process. The critical components and Single Points of Vulnerability (SPV) are being identified. The system design and application of the valves are checked and the valve specifications are being modified as required. Liaisons will be set up with the manufacturers and supplier to ensure the expected service conditions are clearly identified.

The selection of valves will ensure that reliable and robust equipment is procured.

7.2.2 Monitoring Features; Equipment Health Monitoring

POVs which are identified, as SPVs will be provided with monitoring capability, integrated into the SMART CANDU®∗ applications to provide trending features to track the equipment degradation and equipment health. The trending process will have features to proactively alert the equipment specialist in the engineering/maintenance departments. The early indication of degradation will allow the timely full scale monitoring by diagnostic equipment and appropriate maintenance to mitigate the degradation before there is failure of the equipment. The data from the diagnostic process will be added to the trending data for the equipment such that a complete history of each POV will be on hand for the equipment specialists.

7.2.3 Maintenance Program

The reliability of equipment can only be sustained with the timely application of proper maintenance. A full maintenance program for POVs (and other systems and equipment) is being prepared as part of the ACR-1000 product. This process is detailed in a companion paper at the conference by Dan Meraw, Maintenance Based Design and Equipment Reliability for AECL Advance CANDU Reactor. The benefits from the maintenance program are maximized by having an equipment health-monitoring program in place to clearly indicate the performance: good, acceptable, marginal, failure.

7.2.4 Maintenance Support Features

For the equipment identified as potential Single Points of Vulnerability, consideration is given to features that will support the maintenance and reliability improvements by accommodating easy removal and replacement of equipment. An example is PI&C

control valves with flanges to facilitate a valve exchange during the short outages. The removed valves are to be refurbished in the shop in preparation for the next outage.

For selected SPV equipment, their field location will have, within 2 metres, convenient maintenance services provision such as; hook ups for equipment calibration, electric power services, information network, phone/communications and lighting. This philosophy for POV's supports the effort to improve equipment reliability, minimise outage work, increase staff productivity and improve plant capacity factor.

8.0 Conclusions

The operating experience and feedback process is a significant contributor to the AECL ACR-1000 reactor and power plant design. The ACR-1000 has redesigned and improved many features based on current CANDU power plant performances.

The example of the feedback and lessons applied to POV problem areas demonstrates that, with the focus of AECL designers and manufacturers, together with the application of equipment health monitoring and improved maintenance, this will result in greatly improved equipment reliability. The forced outage rate will be reduced, while maintenance costs will be lowered. This will improve production and reduce planned outage time.

The problems with POVs are complex, but with the integrated approach undertaken by AECL for the ACR-1000 the majority of previous problems will be resolved. Some will remain and others will likely emerge. However, with the continued use of operation experience and feedback the application of fresh lessons will serve to meet the challenging targets for ACR-1000.