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L'ÉNERGIE ATOMIQUE
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ADVANCED TECHNOLOGY HEAVY WATER MONITORS OFFERING REDUCED IMPLEMENTATION COSTS

Moniteurs d'eau lourde de la deuxième génération moins coûteux que ceux de la première génération

W. KALECHSTEIN, K.B. HIPPOLA and C. CUMMING

Chalk River Nuclear Laboratories

Laboratoires nucléaires de Chalk River

Chalk River, Ontario

October 1984 octobre

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by

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Moniteurs d'eau lourde de la deuxième génération moins coûteux que ceux de la première génération

par

W. Kalechstein, K.B. Hippola et C. Cumming*

Résumé

On a mené à bonne fin le développement des moniteurs d'eau lourde de la deuxième génération, lesquels sont destinés aux centrales CANDU et aux usines d'eau lourde. De fait, ces instruments ont atteint le stade de la commercialisation. Le recours à une technologie avancée et à un nombre réduit de composants faits sur commande permet d'avoir des instruments coûtant moins cher que les moniteurs de la première génération et ne requérant pas de services coûteux. Le nouveau concept a été mis à l'essai sur deux prototypes. Une documentation complète a été établie, y compris les procédures d'inspection et d'essai requises pour fabriquer l'instrument conformément à la norme CSA Z299.3 touchant le programme de vérification de la qualité. L'entreprise commerciale Barringer Research Ltd. a commencé la fabrication des nouveaux moniteurs d'eau lourde. Le premier instrument, destiné au réacteur NRU de Chalk River, devrait être livré à la fin de 1984.

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ABSTRACT

The development of second generation heavy water monitors for use at CANDU power stations and heavy water plants has been completed and the instruments brought to the stage of commercial availability. Application of advanced technology and reduced utilization of custom manufactured components have together resulted in instruments that are less expensive to produce than the original monitors and do not require costly station services. The design has been tested on two prototypes and fully documented, including the inspection and test procedures required for manufacture to the CSA Z299.3 quality verification program standard. Production of the new monitors by a commercial vendor (Barringer Research Ltd.) has begun and the first instrument is scheduled for delivery to CRNL's NRU reactor in late 1984.

INTRODUCTION

On-line heavy water monitoring systems are used at CANDU power stations and heavy water plants for inventory management, process control and environmental protection. The cost effectiveness of the existing Series 400 instruments manufactured by Barringer Research Limited (BRL) has been demonstrated at Bruce NGS A following a program to improve their reliability [1].

It became apparent during the course of the above reliability improvement program that application of advanced technologies in an extensive engineering redesign of the instruments had the potential for significant further improvements in cost effectiveness. Concurrently, an investigation of alternative analytical techniques and the monitoring accuracy requirements at operating CANDU power stations was undertaken at the Chalk River Nuclear Laboratories (CRNL). This study revealed that infrared spectroscopy remains the only analytical technique offering sufficient resolution for the critical leak detection and process control applications at the extremes of the D_2O concentration range. However, a specific instrument based on density measurement was found to satisfy the less stringent requirements in the 1-95% D_2O concentration range [2].

A development program was therefore initiated as a co-operative venture of CRNL and BRL with the goal of producing instruments more tolerant of the plant environment, less dependent on special station services, simpler to maintain and yet retaining the accuracy and resolution of the Series 400 monitors.

A laboratory prototype incorporating many advanced features was constructed to demonstrate the proof-of-principle of a monitor having greatly improved environmental tolerance and therefore not requiring such station services as an air conditioned room, cooling water and process air [3]. More recently, instruments based on this laboratory prototype have been fully engineered for industrial implementation. A pre-production prototype, shown in Figure 1, has been constructed at CRNL to prove the design documentation. Commercial production of the first Series 4600 monitor is now underway at BRL.

Although the new monitors are less expensive to produce than the previous design, the major reduction in overall monitoring cost will result from the elimination of the need to provide and maintain

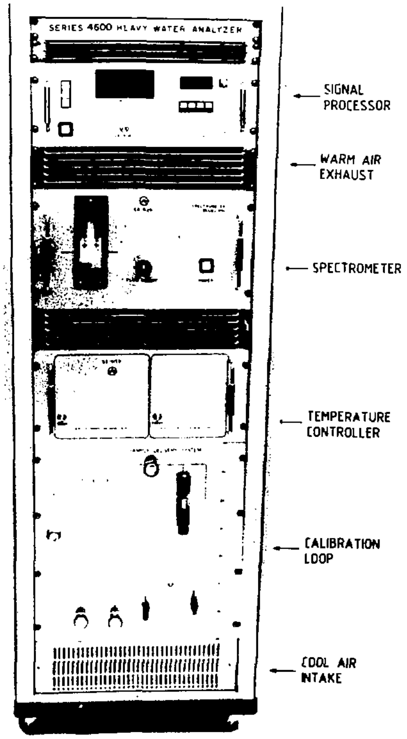

FIGURE 1: PRE-PRODUCTION PROTOTYPE SERIES 4600 HEAVY WATER ANALYZER

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cooling water, process air and air conditioning services for the monitoring systems. Adoption of the new monitors can help in the current drive to reduce the complexity of CANDU reactor systems and contribute to the reduction in the time required to design, construct and commission a new station.

DESIGN FEATURES

The basic principle of operation used in the previous instruments, that of the two wavelength rotating filter infrared absorption spectrometer, has been retained. One of the filters, the so-called S filter, is chosen so that absorption is strongly dependent on deuterium concentration, specifically the concentration of the molecular species HDO; and the other filter, the L filter, is chosen so that absorption is nearly independent of the deuterium concentration. The S and L filter wavelengths appropriate for measurement of low deuterium concentration (0-2%) are 3.9 μm and 3.6 μm, respectively, and those appropriate for measurement of high deuterium concentration (>98%) are 2.9 μm and 2.6 μm, respectively. Absorption measurements at the L filter wavelength are used in the signal processor to compensate for optical signal variations which are not related to changes in the isotopic composition of the sample.

In addition to the optical system, a heavy water analyzer includes a signal processor to convert the signal from the optical detector into a deuterium concentration and several support systems, the most critical being the temperature control for the optics and the flowing sample. Each of these systems has been redesigned, with the signal processor and temperature controllers being totally new. The redesign proceeded in two steps. First, a laboratory prototype was built to demonstrate and evaluate new concepts and second, the instrument was designed to be suitable for plant use and commercial production subject to a quality verification program meeting the requirements of the CSA Z299.3 quality verification program standard.

Because of the wide use of standard commercial grade components, suppliers have not been required to apply quality assurance procedures beyond their normal practice. Instead, modules and tests were designed such that performance can be tested and necessary corrective action taken at an early stage of assembly.

Specific features of the analyzer subunits and test program that contribute to the goals of the instrument redesign are described below.

Spectrometer Unit

The laboratory prototype was used to successfully demonstrate a non-focussed optical system having a more efficient infrared source, a shorter optical path, a simpler filter-wheel drive system and an easily serviced sample cell [3]. The optical system offers savings in manufacturing and maintenance costs and allows elimination of the requirements for process air and cooling water.

The optical system has been further improved in engineering the laboratory prototype for industrial implementation. Application of a reflective type filter wheel position sensor, needed to provide a synchronizing waveform for the signal processor, has facilitated assembly/disassembly of the optical system. Use of a lead selenide detector thermoelectrically cooled to -20°C has provided improved long-term stability and a 5-fold reduction in the noise component of the signal (10 V peak) supplied to the signal processor. The improved performance was achieved without adversely affecting system cost and complexity by using components recently introduced commercially and by eliminating a stage of amplification.

Thermoelectric technology, first demonstrated in the laboratory prototype, continues to be used for control of the sample and optical system temperatures but several changes have been made in engineering the system for plant use. Experience has shown that adequate performance can be obtained using smaller, less costly temperature controllers and sample temperature preconditioners. Packaged heat pump assemblies consisting of thermoelectric modules soldered to heat sinks have been applied to guarantee good performance and simplify construction and maintenance of the temperature control system. To protect optical and thermoelectric components against damage resulting from a loss of temperature regulation, an interlock has been added to shut off ac power to the temperature controllers when any of 5 strategically placed temperature switches is tripped.

Elimination of the cooling water service has resulted in a requirement for improved cabinet ventilation to remove the heat rejected by the thermoelectric temperature control system. As shown in Figure 1, cabinet ventilation is provided by a combination of a filter/blower unit mounted at the bottom of the analyzer cabinet and baffle/exhaust panels mounted just above the temperature controllers, spectrometer and signal processor. Within the spectrometer unit a system of fans and ductwork is used to take in cool air at the rear of the instrument, direct it at the heat pump heat sinks and exhaust warm air at the top and sides of the instrument, as shown in Figure 2. The ventilation system provides sufficient heat removal capacity to maintain good temperature control even as the ambient temperature rises above 35°C.

The temperature control system is a significant improvement over that provided in previous monitors. It is almost entirely composed of commercially available components and is far easier to assemble, test and repair. Furthermore, it can maintain the controlled temperature over a wider range of ambient temperature and settles in a matter of minutes rather than hours.

In designing the spectrometer care was taken to provide for ease of assembly, inspection and service. Thus, in spite of the crowded appearance of the spectrometer in Figure 2, all components and electrical signals may be easily accessed.

Signal Processor

The signal processor measures the relative intensity of infrared radiation transmitted through the sample at the S and L filter wavelengths and converts the result into a digital display of the deuterium concentration in the sample. In addition, it provides for operator input of alarm thresholds and calibration data and for output to remote monitors and alarms. In multistream leak detector applications, the unit further provides for automatic zero drift compensation. The unit is

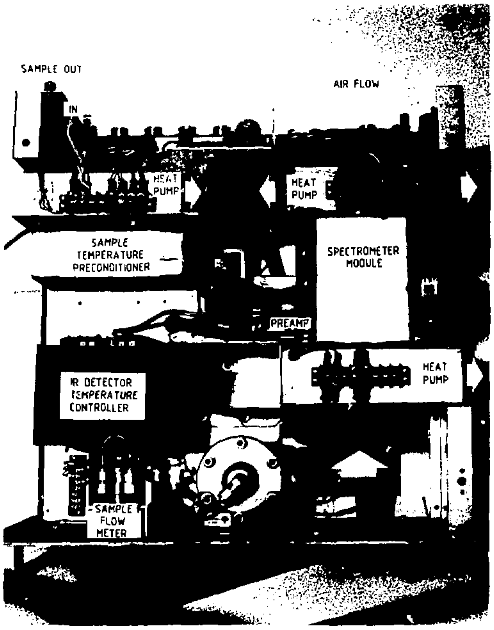

FIGURE 2: PRE-PRODUCTION PROTOTYPE SPECTROMETER UNIT

similar in concept to the laboratory prototype [3] but has been extensively redesigned for commercial production using printed circuit boards and more reliable hardware and software techniques.

The essential hardware features are shown in the block diagram of Figure 3. An Intel 8085 microprocessor controls the operation of the signal processor, provides fault diagnosis capability for the analyzer and services the operator interface. An arithmetic processor (AM 9511) provides capability for 32 bit floating point calculations and special functions. A 12 bit A/D converter provides 5 mV sensitivity at the input and the multiplexer allows monitoring of operating parameters for self diagnosis and output compensation. Analog outputs are derived using a 12 bit D/A converter and provide twice the resolution of the front panel digital display, i.e. 0.5 ppm D/D+H for leak detectors and 5 ppm D/D+H for the wider range monitors. All monitor types have essentially identical hardware and software; differences in operation are determined by instrument constants stored in EPROM and non-volatile RAM.

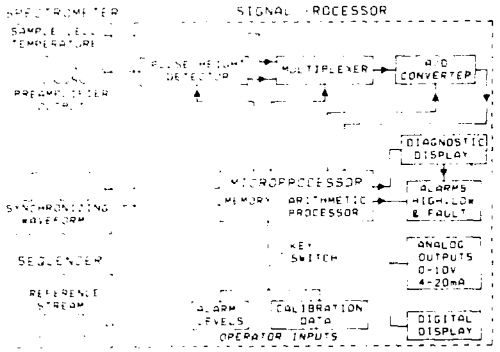

FIGURE 3: SIGNAL PROCESSOR BLOCK DIAGRAM

Data acquisition is governed by the square wave synchronizing signal from the rotor position sensor in the spectrometer. The microprocessor monitors this signal and responds to a transition by measuring the peak height of the next preamplifier pulse. The pulse is interpreted as an S or L pulse depending on the level of the synchronizing signal and, following the measurement of each pulse pair, the ratio S/L is computed and added to the running total. A measurement of the sample cell temperature is then made and the result is added to the running total of temperatures. An alarm threshold is displayed at this time if requested by means of front panel pushbuttons. The cycle is repeated at the next transition of the synchronizing signal until a preset number (128) of data acquisitions has been completed. At this point the microprocessor stops monitoring the synchronizing waveform and proceeds to execute succeeding sections of the program, as indicated in the flowchart shown in Figure 4.

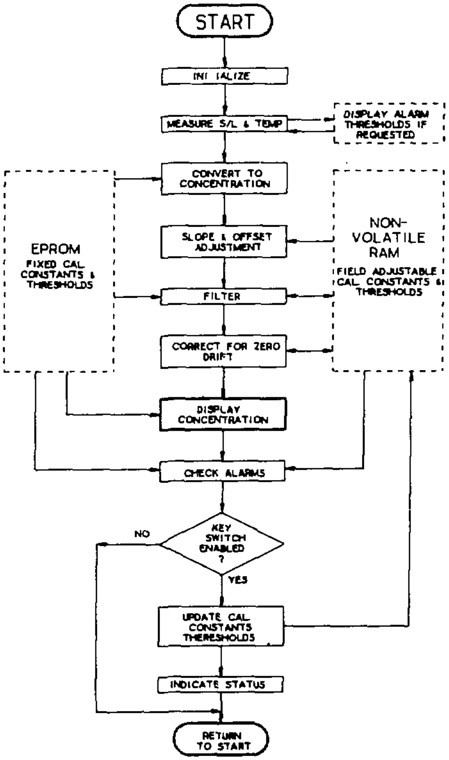

FIGURE 4: SOFTWARE FLOWCHART SHOWING INFLUENCE OF INSTRUMENT CONSTANTS ON ANALYZER OPERATION

According to Beer's Law the deuterium concentration should depend linearly on the logarithm of the ratio S/L but deviations from linear behaviour are observed for several reasons. A nonlinear algorithm is therefore required to obtain values of deuterium concentration from measurements of ln S/L. A three-section piecewise quadratic algorithm was selected as it is simple to implement and permits adequate calibration accuracy. The basic calibration of the instrument is determined by 11 constants stored in EPROM memory - 3 quadratic coefficients (A_i, B_i, C_i) in each of 3 intervals of $x=\ln S/L$ and 2 break points. The reference temperature (TREF) and temperature coefficient (TCOEF) are also stored in EPROM and used to provide a linear temperature correction to the calibration. The program further provides for adjustment of the calibration based on a 2-point field calibration entered via the operator interface. The slope (M) and offset (D) parameters are stored in non-volatile RAM memory. The parameter CONC, from which the displayed deuterium concentration is derived, is computed according to

$$CONC = M\left[A_i x^2 + B_i x + C_i - TCOEF(TEMP-TREF)\right] + D$$

A software filter is incorporated into the program so that the effective integration time may be made longer than the display update period. In virtually all applications, a response time of several minutes is adequate but a display update period longer than several seconds is undesirable. The "exponential filter" algorithm was chosen because of its good performance and ease of implementation.

An automatic ZERO drift correction is provided for multistream leak detector applications, where a stream of natural water is sampled by the analyzer about once per hour. Depending upon the sense of an input from the stream sequencer, indicating whether or not the stream monitored is a natural water stream, the signal processor computes a new ZERO correction or applies the correction stored in non-volatile RAM memory, respectively. The uncorrected concentration is displayed when monitoring the natural water stream so that operators may determine the net ZERO drift since the calibration was performed. This on-line calibration facility effectively sets the instrument accuracy equivalent to its short-term drift so that the alarm threshold level can conservatively be reduced from the 12 ppm excess D/D+H level recommended for Series 400 leak monitors to $\lesssim 5$ ppm excess D/D+H for the Series 4600 instruments.

After the various corrections are applied the value of CONC lies in the range 0 to 2 and this range corresponds to the concentration range 0-2000 ppm D/D+H for leak detectors, 0-2.000% D/D+H for tails monitors and 98.000-99.999 wt% D/D+H for product monitors. Each analyzer type is characterized by a set of 3 scaling and offset constants stored in EPROM. These govern the conversion of CONC into the displayed concentration and remote outputs.

To avoid problems resulting from improper or unauthorized modification of instrument constants, operator access is restricted to just the alarm thresholds and 2-point calibration data and requires the operator to enable a keyswitch. Having enabled the keyswitch, the operator sets the thumbwheel switches and presses the corresponding pushbutton to enter a parameter value. Alarm thresholds are addressed directly but the calibration parameters are not. Instead, the operator enters the result of a laboratory isotopic analysis of the monitored stream for two streams of differing composition. The signal processor then computes the correct calibration parameters and stores them in the non-volatile RAM. The parameters cannot be changed except by performing a proper calibration - the scheme does not allow short cuts. Further assurance of proper calibration is provided by indicator lights, mounted below the pushbuttons, that indicate improper operation or confirm that the 2-point calibration has been successfully completed.

Reliability of the new monitors has been further assured by provision of self-diagnosis capability. The signal processor monitors the major analyzer systems for conditions which prevent analyzer operation or impair its accuracy. The particular parameters monitored are listed in Table 1. In the event a fault condition is detected, the corresponding LED is lit on the diagnostic display inside the signal processor and operators are alerted by means of the FAULT alarm. The self-diagnostic feature is useful in alerting operators to unreliable operation of the analyzer and in fault location.

TABLE 1: FAULT CONDITIONS DETECTED BY THE SELF-DIAGNOSTIC FEATURE

System	Fault Condition
Optical	- S or L pulse height out of range - synchronizing pulse not found
Temperature Control	- overheating protection tripped - cell temperature out of range
Sample Flow	- sample flow too low
Signal Processor	- math error in arithmetic processor - error in EPROM programming

Quality Verification

Quality verification testing was designed to be an integral part of the manufacturing process for the new analyzers. As BRL has in place a quality verification program meeting the CSA Z299.3 quality verification program standard and is experienced in the manufacture of heavy water monitors, the task was restricted to the identification of special inspection requirements for the Series 4600 monitors, formulation of the appropriate procedures and their integration with the existing quality program.

A simplified flowchart for the manufacturing, inspection and test plan formulated is shown in Figure 5. The analyzer's three main units are formed of 12 individually inspected subassemblies and further tested upon completion of assembly and wiring of each of the major units. Although the majority of inspections at this point aim only to verify completeness of assembly and good workmanship, functional testing is specified where practical. As the principal analyzer units are integrated emphasis is shifted from simple inspection to functional testing and calibration of the analyzer.

Prior to calibration, proper function of the spectrometer's optical, hydraulic and temperature control systems is demonstrated. The latter test

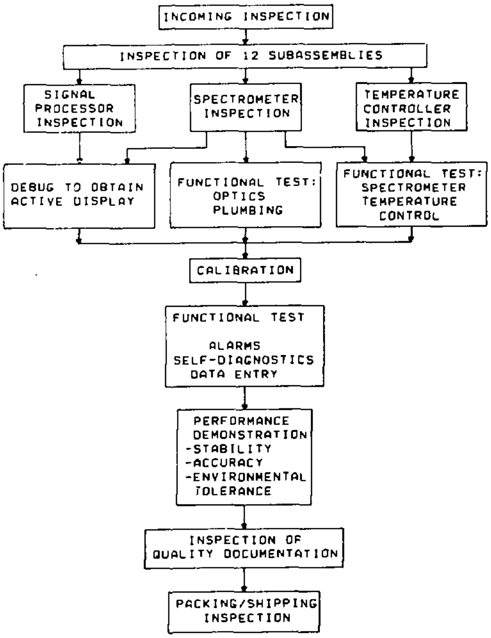

FIGURE 5: INSPECTION AND TEST FLOWCHART

is the final demonstration of temperature control capability and is therefore exhaustive. Acceptance requirements are that the temperature at the outlet of the sample temperature preconditioner and in the optical housing must remain stable within ±1°C and ±0.2°C, respectively, as the sample temperature at the inlet to the analyzer is slowly varied from 10°C to 45°C.

Analyzer calibration is performed once the subsystems are fully integrated and an active display is obtained in the signal processor. Instrument constants are set to the values $A_i=C_i=TCOEF=D=0$, and $M=B_i= 1$ so that the number displayed is the value of $x=\ln S/L$ obtained by the analyzer. The relationship between x and the true sample isotopic composition (y) is determined by analyzing at least 15 calibration standards spanning the concentration range of interest. Calibration constants are then obtained by fitting the above data to a three-section piecewise quadratic function. The 11 constants are entered into the analyzer, along with the value of TREF. Calibration of the analyzer is completed with the determination and entry of the value of TCOEF.

Proper operation of the alarm, self-diagnosis and data entry features is demonstrated by creating each alarm or fault condition in turn, or by entering new data, and verifying proper analyzer response in each case. Procedures have been written for verifying proper execution of a total of 12 functions.

The last stage of testing provides a demonstration that the analyzer meets the accuracy and environmental tolerance specifications, as given in the next section.

Customer and vendor representatives are required to witness the above performance tests and inspect all quality records. The analyzer may be released for shipment only if both inspectors sign a declaration that the analyzer meets all requirements and quality documentation is complete.

PERFORMANCE

Experience with the two prototypes constructed indicates the goals of the analyzer development program have been met, i.e. the new instruments operate over a wider range of environmental conditions, require no special station services and offer accuracy and resolution at least equivalent to those provided by the previous models. In fact, because of the compensation and linearization capabilities of the new signal processor the accurate range of the instruments has been significantly extended. The accuracy and resolution of the new monitors are specified in Table 2 and their environmental tolerance is specified in Table 3 below.

TABLE 2: ACCURACY AND RESOLUTION OF SERIES 4600 ON-LINE HEAVY WATER MONITORS

LEAK DETECTOR	
Range:	0-2000 ppm
Resolution:	1 ppm
Accuracy:	
(100-200 ppm)	±10 ppm
(0-2000 ppm)	±20 ppm
Alarm Set Point:	+5 ppm excess
TAILS MONITOR	
Range:	0-2.0%
Resolution:	10 ppm
Accuracy:	
(0.0-0.5%)	±50 ppm
(0.5-1.0%)	±200 ppm
(1.0-2.0%)	±200 ppm
PRODUCT MONITOR	
Range:	98-100%
Resolution:	10 ppm
Accuracy:	
(99.65-99.95%)	±50 ppm
(99.00-99.65%)	±100 ppm
(98.00-99.00%)	±200 ppm

*ppm = parts per million D_2O

TABLE 3: RANGE OF CONDITIONS FOR WHICH SERIES 4600 HEAVY WATER MONITORS MEET SPECIFICATIONS

PARAMETER	RANGE
Sample Inlet Temp.	10-45°C
Sample Flow	5-15 mL/min
Ambient Temp.	10-35°C
Line Voltage	105-135 VAC

The reliability of the new monitors has been demonstrated by the laboratory prototype, which has been in service for nearly 3 years monitoring the moderator at the NRU reactor alongside a Series 400 product monitor. Although not specifically engineered for reliability, the prototype operated satisfactorily for the first 1.5 years with absolutely no maintenance and no calibration adjustments. Since that time several components, including the filter-wheel motor and infrared source, have required replacement. Replacement of the infrared source produced a small calibration error (0.03 wt% D/D+H) that was corrected by performing the simple two-point calibration procedure.

The pre-production prototype has been configured as a leak detector and used to investigate long term drift. The indication is that the alarm threshold may be reduced to 5 ppm excess D/D+H with only weekly calibration adjustments rather than the automatic hourly compensation provided in multistream applications.

The linearity of the pre-production prototype has proved better than expected. A single-region quadratic linearization provides errors smaller than ±5 ppm D/D+H over the entire 0-2000 ppm D/D+H concentration range.

IMPLEMENTATION COSTS

Through the use of the new monitors the cost of implementing on-line heavy water monitoring systems will be significantly reduced. Savings will be realized in the capital cost of the monitors and supporting systems as well as in operating costs.

The reduction in complexity of the new spectrometer unit has resulted in an estimated 30% decrease in the labour required for assembly and further savings have been realized because of decreased use of custom parts. Altogether, it is estimated that the cost of producing and testing one of the Series 4600 monitors is about $25,000 lower than for the previous monitors - a saving of roughly 25%.

It is thought that even greater savings will result from the elimination of the need to design, construct, commission and maintain cooling water, process air and air conditioning services for heavy water monitoring systems. However, as these costs have not been quantified for previous installations an accurate estimate of all the savings is not available.

A lower bound on the savings resulting from elimination of the air conditioning service can be obtained based on the cost of environmental rooms provided in the past at some upgrader installations. These transportable units are presumed less expensive than the larger concrete rooms provided for the Series 400 leak monitors at Bruce NGS A. The resulting estimated saving is a minimum of $10,000 and pertains only to the capital cost of a unit.

Since 2 leak monitors are typically provided for each reactor unit and a further product and tails monitor are provided for each upgrader, the saving realized by application of Series 4600 monitors in place of the older technology is a minimum of $65,000 per reactor unit and $65,000 per upgrader. These are minimum savings and do not include engineering, installation and maintenance costs.

Experience has shown that the special services and sample delivery systems account for the major share of maintenance costs, the analyzers themselves being very reliable in comparison. As a result, a saving of at least 30% of the maintenance cost is expected in applying the new monitors, corresponding to the contribution from the special services. For a 4 unit station having a total of 12 monitors the cost saving amounts to at least $20,000 annually.

The economic benefits of applying the new monitors will stem not only from a reduction of costs but also from a reduction in heavy water losses made possible by the reduced heavy water leak alarm threshold.

CONCLUSIONS

A second generation of on-line heavy water monitors has been developed to overcome limitations inherent in the original design. These new instruments have been brought to the stage of commercial availability. Complete documentation of manufacturing, inspection and test procedures has been developed and proven on a pre-production prototype. Barringer Research Limited is currently working on the first commercially produced instrument of the new design.

Application of advanced technology in the design of the new instruments has made possible a significant reduction in the cost of implementing heavy water monitoring systems without sacrificing performance. It is estimated that cost savings approaching $500,000 can be realized by application of the second generation monitors in a new 4-unit nuclear generating station.

Operator acceptance of the new monitors has been assured by careful engineering to provide reliable service, an improved operator interface including a self-diagnostic facility and reduced difficulty in maintenance and repair.

ACKNOWLEDGEMENTS

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