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ATOMIC ENERGY OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

REACTOR COOLANT PUMP SEALS: IMPROVING THEIR PERFORMANCE

Circuit d'étanchéité des pompes de caloporteur de réacteurs: amélioration de leur efficacité

N.E. POTHIER and R. METCALFE

Paper presented at Symposium on Advanced Nuclear Services Toronto, Canada, 1986 June 11

Chalk River Nuclear Laboratories

Laboratoires nucléaires de Chalk River

Chalk River, Ontario

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RÉSUMÉ

Les grandes centrales CANDU profitent des quatre ans de service utile des circuits d'étanchéité fiables, résistants aux transitoires, des pompes de caloporteur de réacteurs: résultat direct du programme EACL complet d'amélioration des circuits d'étanchéité s'étendant sur 20 ans et dans lequel sont engagés le personnel de R et D, les fabricants, les concepteurs et exploitants de centrales. On donne un aperçu de ce programme qui couvre la conception de modification des circuits d'étanchéité, les essais, l'examen après service, la maintenance spécialisée et le contrôle de la qualité. En outre, on examine la convenance de la technologie utilisée pour les circuits d'étanchéité des pompes de caloporteur de réacteurs à eau légère.

Technologie des joints d'étanchéité
Pièces et instrumentation
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ABSTRACT

Large CANDU plants are benefitting from transient-resistant four-year reliable reactor coolant pump seal lifetimes, a direct result of AECL's 20-year comprehensive seal improvement program involving R&D staff; manufacturers, and plant designers and operators. An overview of this program is presented, which covers seal modification design, testing, post-service examination, specialized maintenance and quality control. The relevancy of this technology to Light Water Reactor Coolant Pump Seals is also discussed.

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REACTOR COOLANT PUMP SEALS: IMPROVING THEIR PERFORMANCE

INTRODUCTION

When reactor coolant pump (RCP) seals work reliably for long periods, they can be regarded as godsends, keeping the "heart" of the station "ticking away" to the point where operators forget seals exist. However, when they perform unpredictably or fail too often, they become "pains-in-the-neck" to station operators.

Both situations have been experienced by CANDU* operators. Initial prototype CANDU plant operation was fraught with RCP seal problems. Realizing the severity of the problem, especially for the larger commercial plants then under design, AECL** mounted a major effort to improve the performance of RCP seals for CANDU plants. The payback has been huge: early "pains" converted to today's godsends and four-year lifetimes are now being reliably achieved with AECL improved RCP seals.

In this paper, the CANDU RCP seal experience, the methodology for attaining reliable long RCP seal life and the adaptability of this technology to US LWRs are described and discussed.

CANDU RCP PUMPS

Almost all CANDU stations (30 units built or under construction) have Byron-Jackson (B-J) RCP pumps (Fig. 1). Those in the later generation CANDU stations (Bruce A&B, Pt. Lepreau, Wolsung and Darlington), are similar in size to the RCPs in most other modern nuclear stations. The seals operate at similar differential pressure (500 - 700 psi/stage, using both two and three-stage cartridges to seal against a 1400 psi reactor system pressure) but at a higher speed (1800 rpm) than in LWRs. A two-stage Bruce A NGS seal cartridge is shown in Fig. 2. Additional details on CANDU RCPs are given in Ref. 1.

CANDU RCP SEAL EXPERIENCE

Nuclear Power Demonstration (NPD) Station

The earliest prototype CANDU reactor, NPD (25 MW), was started-up in 1962 and is still operating today. It has three small B-J RCPs of which two are needed for full power operation; the third pump is a standby. Initial seal performance proved unsatisfactory; the seals failed unpredictably and frequently, causing station outages.

As supplier-attempted fixes did not improve the situation, AECL, as part of its national mandate to assist industry develop nuclear plant components, initiated an R&D program to develop seal improvements for NPD and subsequent stations. From this program, new seal designs were

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* CANada Deuterium Uranium
** Atomic Energy of Canada Limited

developed, retrofitted in the NPD RCPs, and the seal problems went away. This early NPD seal experience warned reactor designers that RCP seals deserved special attention in both design and maintenance, and that improved technology was needed for subsequent larger CANDU stations.

Douglas Point Nuclear Generating Station (DP NGS)

Douglas Point (200 MW) was the second prototype CANDU plant. It was started-up in 1968 and operated until 1984. It has eight B-J RCPs of which two are standbys.

Because of seal problems at NPD, the DP RCPs were initially supplied with close clearance bushing-type seals, but these alone were unsatisfactory due to high heavy water losses (expensive heavy water is used as reactor coolant in CANDUs). Again an AECL-designed seal was added, along with improved seal maintenance practices, and satisfactory RCP seal performance ensued.

Pickering A & B NGS

Pickering A and B comprise two co-sited similar 4 X 550 MW stations. The first and eighth units were started-up in 1972 and 1985, respectively. Each unit has 16 B-J RCPs of which four are standbys. Laboratory testing was begun in parallel with station start-up. This enabled the causes of a rash of early seal failures ("infant mortalities") to be pinpointed and overcome. These primarily related to seal maintenance and operating practices. Paying close attention to details in critical dimensions, lapping, assembling, etc., has since proven sufficient to make "standard" B-J seals operate sufficiently well not to detract from the reliability of these stations.

Bruce A & B NGS

Bruce A and B comprise two co-sited similar 4 X 800 MW unit stations. The first Bruce A unit started-up in 1976 with the eighth (Bruce B) unit scheduled for 1986. Each unit has four large (10 000 HP) B-J RCPs, and no standbys.

The move to larger pumps and zero redundancy for Bruce A and B and subsequent CANDUs was primarily to reduce plant capital cost. Two pump test facilities were built in Toronto for Bruce pumps, one by B-J Canada for functional testing before delivery, and a more versatile one by Ontario Hydro (Ref. 2) for investigative tests of pump and seal behaviour under various conditions.

Seals gave problems from the start (pressure oscillations, de-staging and unacceptable wear) and could not be overcome using the manufacturer's technology alone (e.g., slotted rotating face, feedback design, various U-cup shapes and spring forces). Hence, renewed AECL R&D efforts were made to develop design modifications to improve the performance of the Bruce seals.

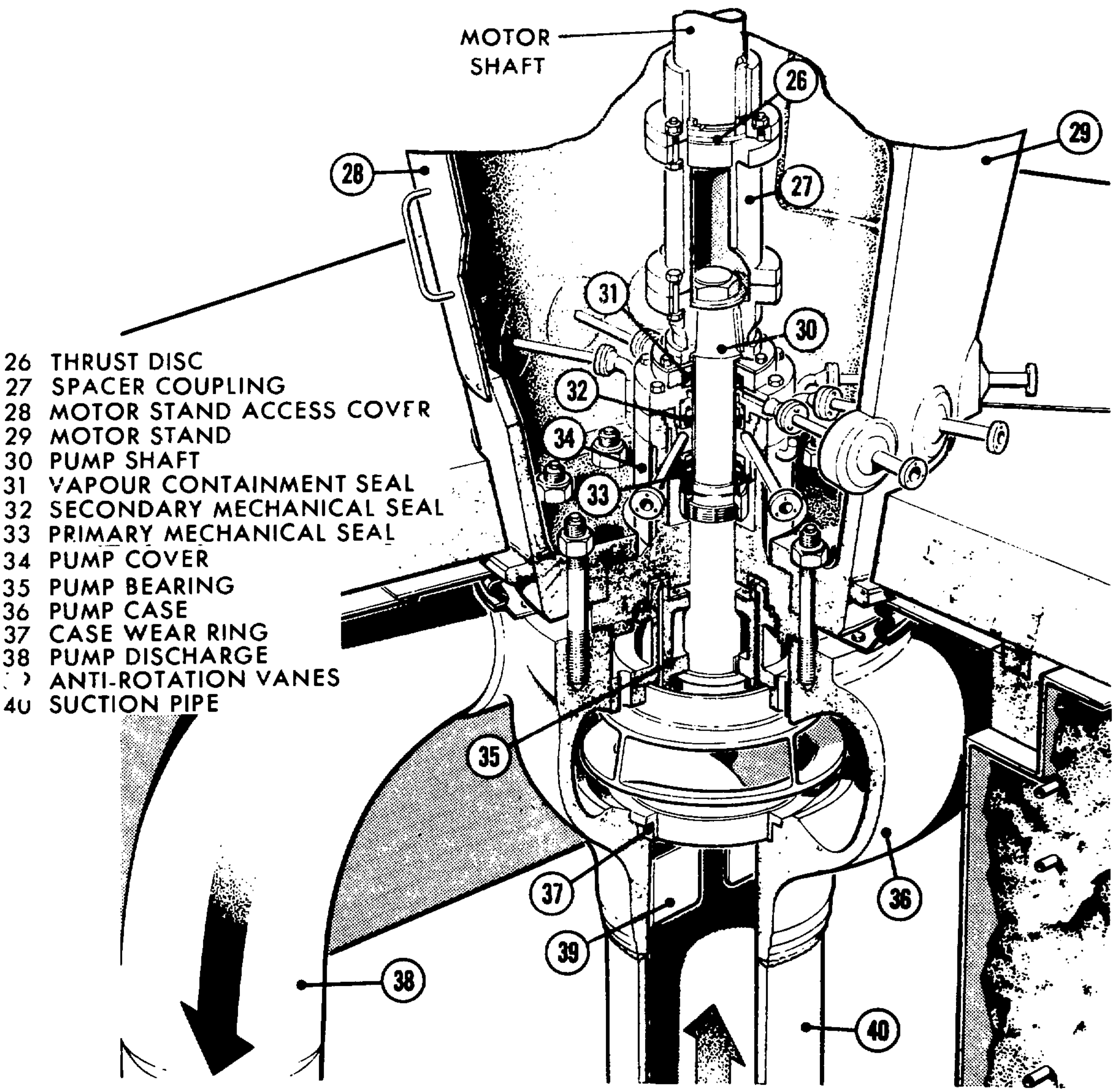

FIGURE 1: TYPICAL BRUCE NGS MAIN COOLANT PUMP

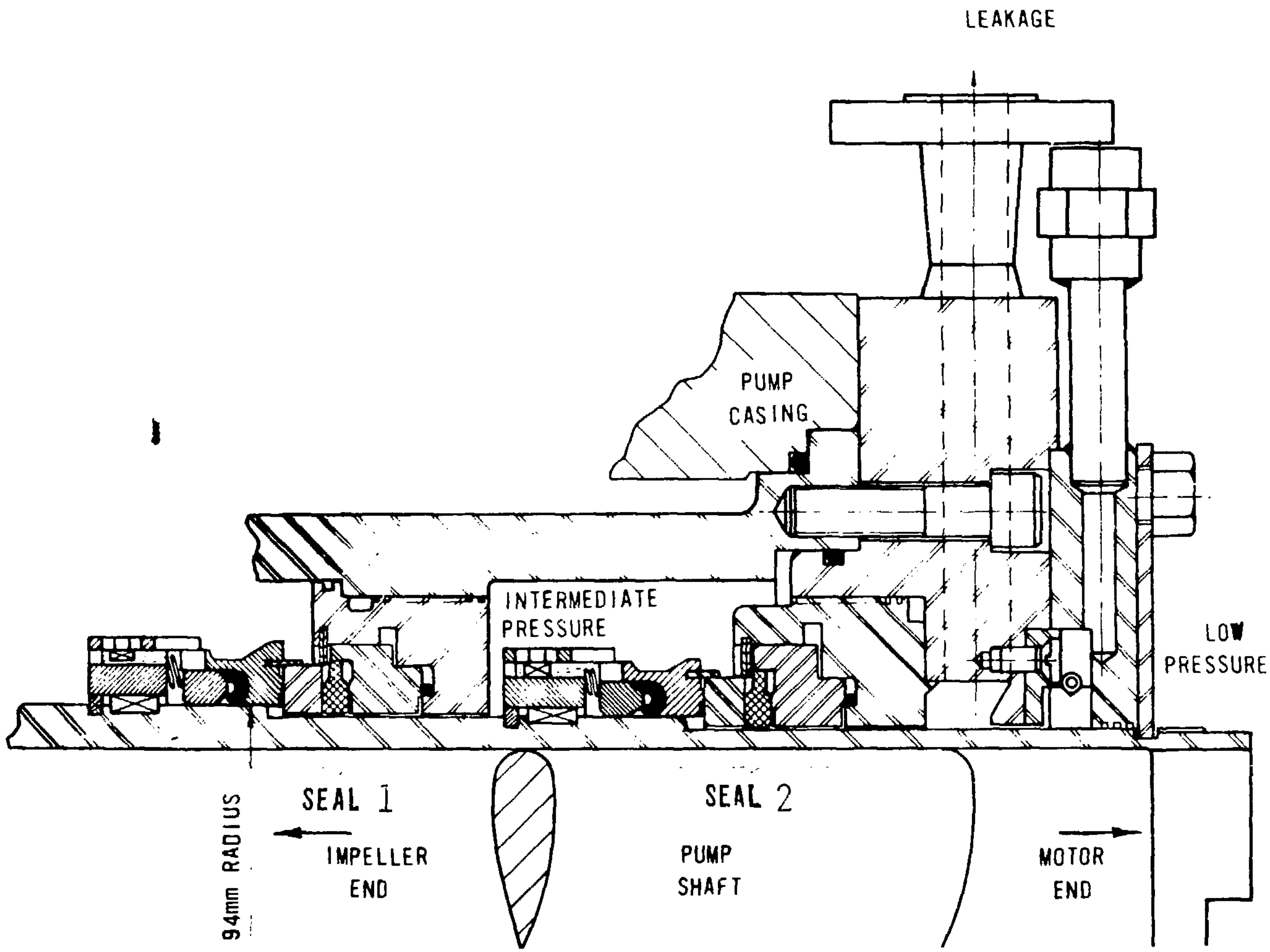

FIGURE 2: TWO-STAGE BRUCE A&B CAN2 SEAL CARTRIDGE

Seal modifications (Fig. 3) were quickly developed and proof-tested in actual pumps. The modified seal, known as the CAN1 seal, proof-tested well and was installed at Bruce A along with the B-J standard seal (two of each per unit). Seal performance was carefully monitored for all Bruce A units, and seals were removed by choice for examination when convenient.

From operating performance and post-service examination, the CAN1 seal (and its descendant, the CAN2 seal) proved superior in terms of greater reliability and longer lifetime; hence, CAN-seals have become the seals of choice for both Bruce A and B. Four year reliable lifetimes have been demonstrated at Bruce A, and a five year lifetime target is considered attainable with the CAN2 seal as presently used. Bruce operators are now very happy with the performance of their RCP seals.

Point Lepreau and Wolsung NGS

Pt. Lepreau (New Brunswick) and Wolsung (South Korea) are 600 MW single unit stations. Each has four large RCPs similar to Bruce A's. CAN2 seal design was developed for and first used in these stations. Both were started-up in 1982. Excellent seal performance has been achieved; two of the original Pt. Lepreau seals are still in service.

Darlington NGS

Darlington NGS is a four unit station similar to Bruce A and B and currently under construction. B-J pumps with CAN2 seals or a further evolution of this design will be used.

Experience Summary

The CANDU seal experience with B-J RCPs is summarized in Table 1. As indicated, serious problems were experienced during start-up of early CANDU plants (NPD, DP and Pickering) and during functional testing of Bruce A pumps. These were all solved by AECL, in close collaboration with the utility and manufacturer. "Standard" B-J seals were made to work successfully at Pickering, but this was primarily due to their small size and the 25% standby pumping and valving-out capability of that station.

B-J pumps in CANDU plants of later design have eventually all been fitted with AECL-designed seals. Since first installation, these CAN-seals have kept the heart of each station ticking-away reliably - no forced outages due to seals in about 40 reactor years (160 pump-years) of service. With this performance, operators are forgetting the seals exist.

HIGH RELIABILITY, LONG LIFE - HOW ACHIEVED

The good seal performance enjoyed by CANDU utilities didn't come about quickly or easily; it derived from the timely, strategic mandate given to AECL to develop improvements to commercial components whose reliability was not originally in line with the greater demands of the new and special nuclear industry. The work began more than 20 years ago and has continued ever since. The success of today's seals can be attributed to effort in five specific areas:

(1) Seal design.
(2) Seal testing.
(3) Specialized maintenance.
(4) Quality control.
(5) Post-service examination.

SEAL DESIGN

CAN-seal designs have evolved as a reflection of AECL's advances (Ref. 3) in this specialized technology. These advances have been mainly in the understanding of what happens between the stationary and rotating seal faces and how to maintain and control the incredibly thin film of leaking fluid for optimum lubrication and life. There have been many milestones along the way:

-1962: Seal face materials extensively tested for "compatibility", erosion and wear resistance. Result: AECL pioneered the use of solid titanium carbide in an RCP seal.

-1963: Hydrodynamic cooling and lubricating effects quantified. Result: AECL elliptical seal design applied in first three CANDU station RCPs.

-1965: Hydrostatic effects and the significance of seal face convergence investigated and understood. Result: AECL hydrostatic seal designs adopted for on-power fuelling machine applications in succeeding CANDU stations.

-1972: Computational methods for calculating individual seal ring deformations and the effects of pressure and temperature changes developed. Result: Practical design improvements identified to promote lubrication and avoid hard rubbing of Pickering B-J RCP seals.

-1973: Carbon-graphite, bushing-type back-up seals developed. Result: AECL design installed in Pickering and committed for the Bruce RCPs.

-1973: Deflection analysis techniques for multi-component assemblies developed and applied to re-design of B-J RCP seals for Bruce. Result: AECL "CAN1" seals co-installed with B-J seals in first two Bruce units.

-1975: Deflection interactions during transients fully appreciated and demonstrated. Result: "CAN2" seals designed for installation first in Pt. Lepreau and Wolsung, then Bruce B.

-1977: Lubrication theory developed for various forms of seal face convergence, including tilt stability. Result: Design limits for minimum balance ratio applied to AECL seals.

B.J.- CAN1 DESIGN

PERFORMANCE CHARACTERISTICS (TYPICAL AT 650 lb/in^2, 1800 RPM)
LEAKAGE 20-500 mL/min
FRICTION ESSENTIALLY ZERO AT START

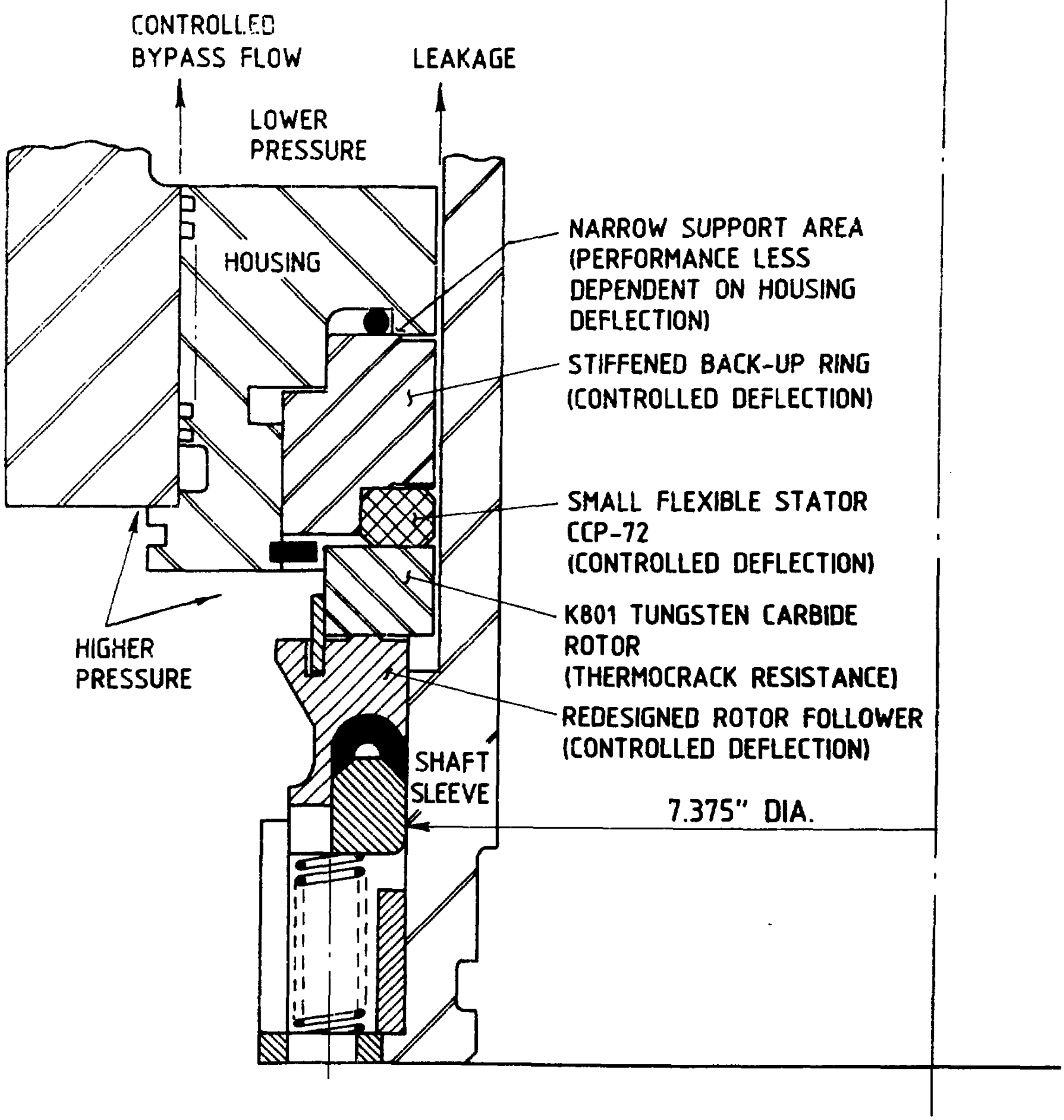

FIGURE 3: DESIGN FEATURES OF CAN1 RCP SEALS FOR BRUCE A&B

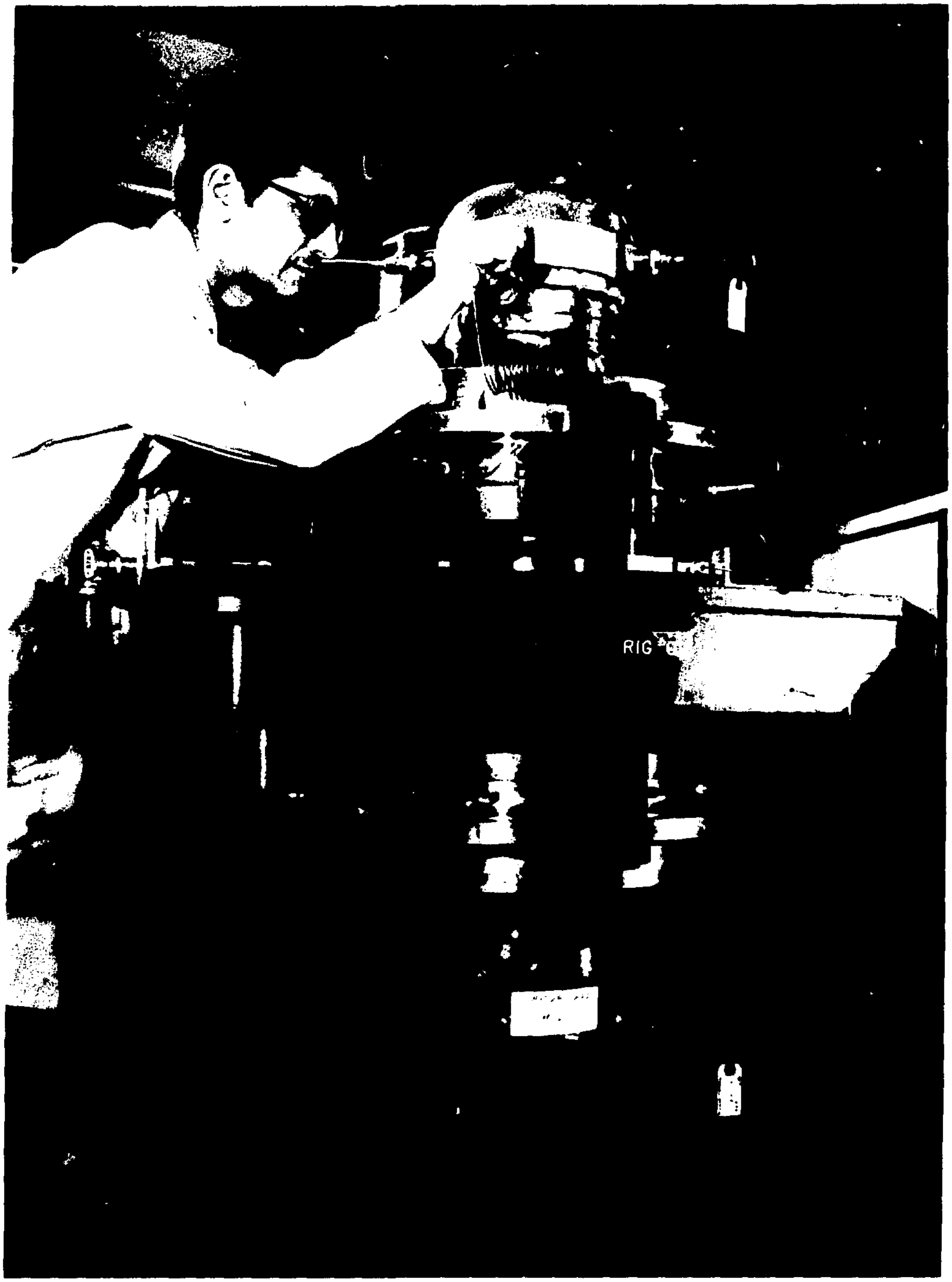

FIGURE 4: DOUBLE-ENDED SINGLE OR TWO-STAGE TEST RIG FOR PICKERING A RCP SEALS

-1978: Resistance of various elastomer "axial seal" materials to hot water quantified. Result: Ethylene propylene compounds specified for hot service.

-1980: Angular misalignment of seal faces recognized and investigated as a cause of deterioration, particularly between B-J U-cup and sleeve. Result: Specific elastomer materials, shapes and sleeve coatings applied to CAN-seals.

-1981: Computational methods developed and applied to CAN-seals to predict performance in response to complex sequences of operating conditions during station transients. Result: Work initiated on "second generation" of CAN-seals, designed to be almost insensitive to transients.

-1983: Effects of shaft eccentricity on seals analyzed. Result: Flange support modifications applied to B-J RCP seals in a US BWR* station.

-1984: Elastomer molding technology adopted. Result: Safety ("capping") seal of high temperature material designed for Bruce application.

-1984: Conditions causing pressure oscillations in staged seal cartridges analyzed and confirmed. Result: Inherent stability designed into the AECL CAN-seal scheduled for BWR installation, spring 1986.

-1985: Vaporization effects on seal face lubrication, stability and wear investigated. Result: CAN4 seal designed with greater capabilities for low pressure operation and integrity under station blackout conditions than existing seals.

The AECL CAN4 seal is today's embodiment of this design knowledge, and has been tailored to suit the particular requirements of CANDU, BWR or PWR RCP application. It retains full interchangeability with the B-J seals in the field, yet is twenty years removed in terms of technology.

SEAL TESTING

Specialized test equipment (Ref. 4) has played a major role in each design milestone. All developmental testing has been performed at AECL's Chalk River laboratories using numerous rotating rigs, high pressure hot and cold loops, and the associated facilities for seal preparation, instrumentation, data handling and materials analysis, etc. The typical test program for a prototype RCP seal design is outlined below. It includes single stage testing, multistage testing and various supplementary tests.

*BWR - Boiling Water Reactor
PWR - Pressurized Water Reactor
LWR - Light Water Reactor

Single Stage Testing

Using a rig as shown in Fig. 4, two single stage seals can be tested simultaneously in opposite ends to explore in detail their individual characteristics. Pressure, temperature, shaft speed, face flatness and alignment are the principal controlled parameters, with leak rates, torque and wear being measured in addition.

Typical types, durations and objectives of single stage testing are as follows:

1. Low pressure testing, 50-100 psi, 2 X 250 h - to investigate susceptibility to deterioration in low pressure operation and to select the best compromise of carbide material and initial face lapping specification. (NOTE: Station start-up often imposes abnormal conditions on RCP seals, inducing wear-out rather than wear-in.)

2. Seal characteristic testing to reactor system pressure, static and dynamic - to verify design characteristics through the range of system pressures, temperatures and transients, and thereby confirm the design analysis.

3. High temperature test, 750 psi, 100 h, 200°F - to demonstrate seal capability at abnormally high temperature, confirming integrity and resistance to hot conditions.

4. High pressure test, normal temperature, 4 h at 750 psi then ramped to full reactor system pressure in less than 5 s for a further 250 h running - to proof test above normal operating pressure to demonstrate the harmlessness of single stage failures in a multistage arrangement.

Multistage Testing

A multistage rig (Fig. 5) allows two or three stages, as used in RCPs, to be tested in a manner closely simulating actual pump service, including transient conditions and shaft motions. The rig is balanced by at least one seal in the opposite end, whose performance can represent the case of all but one seal failing in service.

Typical types, duration and objectives of multistage testing to qualify a CAN-seal for pump installation are:

1. Cartridge characteristic testing, overpressure, static and dynamic, variable staging flow and shaft axial movement - to verify design characteristics of all seal stages and demonstrate absence of any tendency towards pressure oscillations or other instabilities.

2. Low pressure testing, 50-100 psi, 250 h, with and without staging flow - to assess seal "survivability" during low pressure start-up of stations and to show how the damage can be minimized.

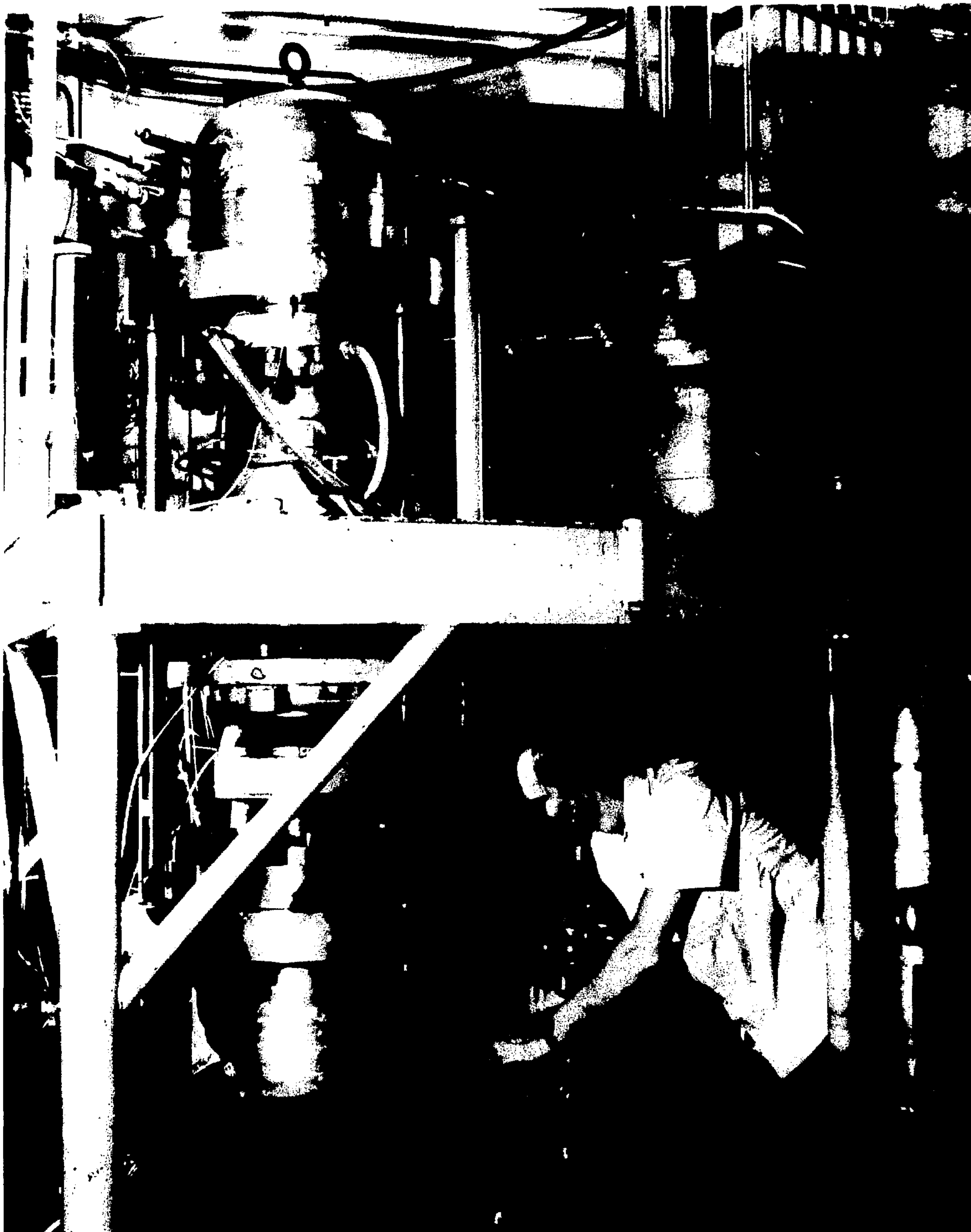

FIGURE 5: DOUBLE-ENDED BRUCE RCP SEAL CARTRIDGE TESTER

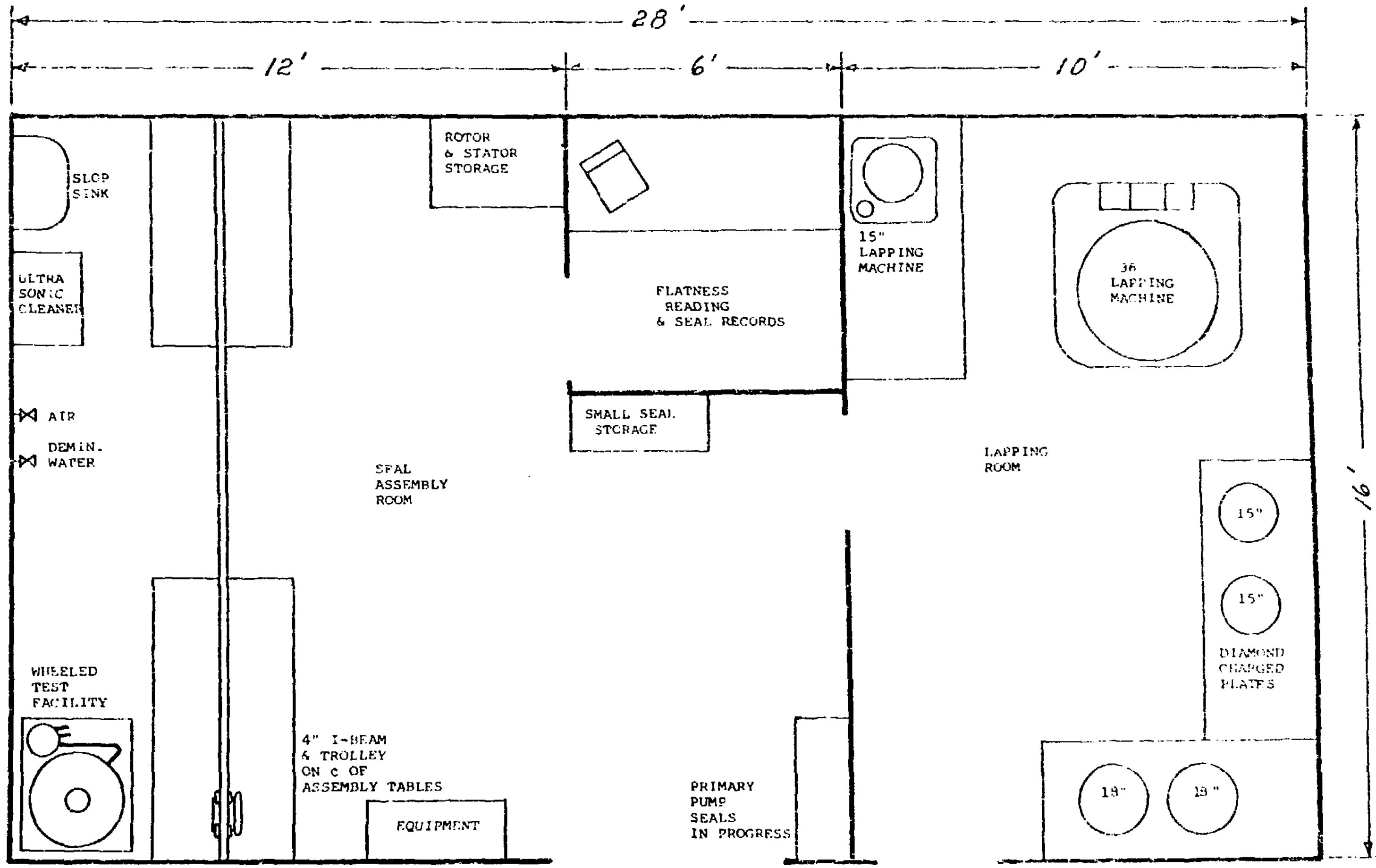

FIGURE 6: BRUCE NGS 'A' SEAL MAINTENANCE FACILITY

3. Proof testing, 2500 h, with temperature, pressure and shaft axial motion and speed transients representative of at least one year of service - to demonstrate long, reliable performance without undesirable leakage, wear or other significant deterioration.

Supplementary Testing

Various supplementary tests are conducted to address specific duty requirements for a prototype RCP seal design. They can be represented under the following headings.

1. Suitability of seal materials for system chemistry, e.g., corrosion tests, leach tests for halogens, tests for effects of crud, crack propagation tests.

2. Response of seals to extreme conditions, e.g., hot standby and start-up tests, "station blackout" tests for elastomer extrusion and seal faces "popping-open".

3. Accelerated wear, e.g., seal face wearout tests, U-cup and sleeve wear tests at excessive misalignment.

Some of these and some that are unique to the application are normally required in any test program.

SPECIALIZED MAINTENANCE

RCP seal maintenance must be treated as a specialty activity; to be performed by mechanical maintainers trained in the practical aspects of seal technology, using a dedicated facility and following detailed written procedures. Greater attention to details must be paid while rebuilding RCP seal cartridges than almost any other reactor mechanical maintenance activity. Many things have to be right for even good seals to work reliably.

Such a seal maintenance system has been in place at Bruce A since plant start-up and is being faithfully adhered to. This is another of the key underlying reasons for Bruce A's excellent RCP seal performance.

A dedicated RCP seal maintenance facility consists of a room or enclosure containing equipment for receiving, lapping, measuring and storing RCP seal parts, and for assembling and pressure-testing RCP seal cartridges. It is normally kept locked and is used exclusively for RCP seal maintenance; the lapping equipment is used for nothing else. Layout of the Bruce A facility is given in Fig. 6. Decontamination and disassembly of used seals is done elsewhere. The cost of setting-up these facilities is small compared with replacement power cost of a single forced outage for RCP seal replacement.

RCP seal cartridges should be assembled only by maintainers who are cognizant of the crucial details of seal face lapping, optical flatness measurement and seal cartridge assembly. Written procedures should be well detailed, validated as accurate, then adhered to. Only seal parts that conform to established tolerances should be used. Their critical dimensions should be recorded on prepared check-sheets to verify conformance to design and for record keeping, which may prove invaluable during post-service examination.

Procedures from RCP pump vendors have been remiss in many areas but have gradually been supplemented by AECL and are being applied successfully in CANDU stations. They are readily adaptable for PWR and BWR applications.

QUALITY CONTROL

It is generally accepted that reliable RCP seal cartridges are made of high precision parts, but procedures for the user to assure that supplier parts are within specification are not generally available. Pump suppliers and reactor vendors generally have not provided sufficient information to check out seal parts before cartridge assembly.

For Bruce A and subsequent CANDU plants, such check-lists and procedures have been developed by AECL and Ontario Hydro to effect a stringent RCP seal parts quality control process. This is another underlying reason for good CAN-seal performance. Significant additional cost-savings have also accrued through this process, since it provides criteria for re-use of seal parts. Generally, only the carbon-graphite seal rings and elastomers need replacement during seal cartridge rebuilding; the other parts can be refurbished.

The cost savings through refurbishing are much greater than just the savings in replacement parts. Used parts with a pedigree of successful service give double assurance of their serviceability, and hence should normally be preferred. Such seal parts refurbishment is practised at all CANDU stations and is readily adaptable to BWR and PWR plants.

POST-SERVICE EXAMINATION

The practice of diligently examining seal parts removed from service has been a key element in extending seal lifetimes. The essence of such examination is to determine the cause of seal failures or assess remaining lifetime of removed, non-failed seals. Used seals contain many tell-tales of operational behaviour and of time-dependent degradation phenomena.

During the early operating life of Bruce A, seal cartridges were removed from service by choice during planned outages, just to have a good look at how they were standing up to service conditions. This was initially done after one year's service, then two, etc. The routine interval is now four to five years service - the design target set in the late seventies. The subsequent Bruce B, Point Lepreau and Wolsung stations have profited from this experience.

Shaft sleeve degradation at U-cups was one unexpected, potentially life-limiting phenomenon that was identified early at Bruce A and has been successfully circumvented by application of industrial hard coating on the shaft sleeve in the U-cup region (Fig. 7). Other degradation phenomena were also identified and rectified before they caused outages. Such CANDU know-how is readily adaptable to BWRs and PWRs.

APPLYING AECL'S SEAL TECHNOLOGY IN LWR STATIONS

Recently, AECL has worked with several outside utilities to improve the performance of BWR and PWR seals. This has involved several facets of seal technology: seal maintenance training; parts quality control; technical guidance during seal cartridge rebuilding; seal cartridge testing under simulated plant-specific seal operating conditions; and, design and proof-testing of retrofitable CAN-seal parts. Two CAN2 seal cartridges are scheduled for installation in the Nine Mile Point - Unit 1 BWR in 1986 April (Ref. 5).

R&D services and consultancy have also been rendered to the Nuclear Regulatory Commission on the "Station Blackout" issue (Ref. 6) and to the Electric Power Research Institute on generic seal problem areas (Ref. 7 and 8). Hence, a good start has been made in improving LWR seal performance by adapting CANDU seal technology.

SUMMARY

Early CANDU plants experienced serious RCP seal problems. AECL has resolved them by retrofitting seal design modifications and developing and implementing better seal maintenance procedures - the result of an extensive R&D program on RCP seals. Four year RCP seal lifetimes are now being reliably achieved. CANDU operators are very happy with their AECL-developed CAN-seals - they hardly know they exist. This proven CANDU RCP seal technology is readily adaptable to BWR and PWR plants. The process has now begun.

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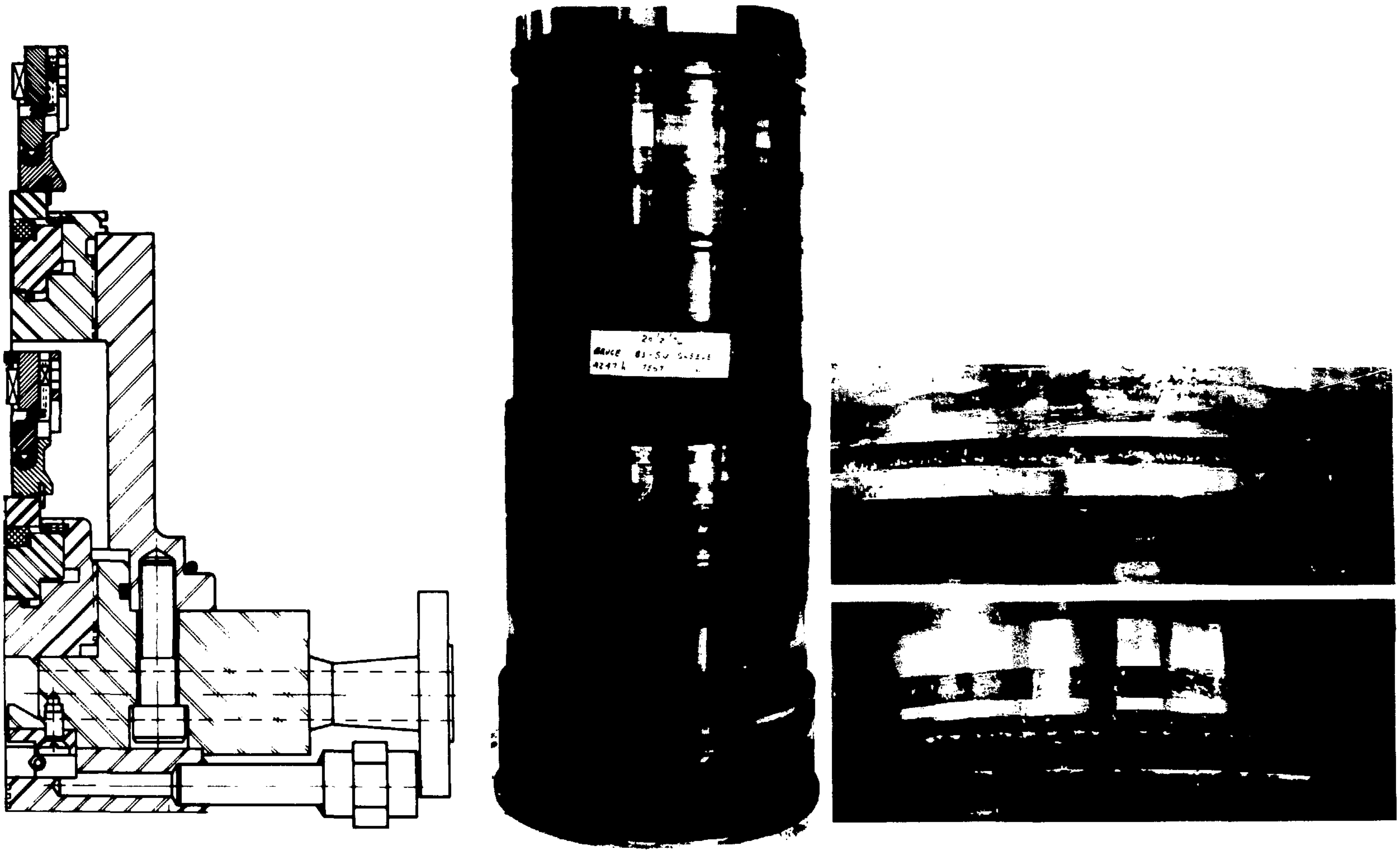

FIGURE 7: SHAFT SLEEVE WEAR AT U-CUP LOCATION, OVERALL AND DETAILED VIEWS

TABLE 1

CANDU RCP SEAL EXPERIENCE

STATION	START-UP DATE	NO. OF PUMPS OPERATING	NO. OF PUMPS STANDBY	SEAL DIAMETER	SEAL EXPERIENCE
NPD 25 MW	1962	2	1	4.1 in. (104 mm)	POOR INITIAL PERFORMANCE. R&D PROGRAM INITIATED. SATISFACTORY MATURE PLANT PERFORMANCE WITH AECL SEAL DESIGN.
DOUGLAS PT. 200 MW	1968	8	2	5.0 in. (127 mm)	POOR INITIAL PERFORMANCE; IMPROVED AECL SEAL DEVELOPED FROM NPD EXPERIENCE AND AECL R&D PROGRAM.
PICKERING A & B 8 X 550 MW	1972	12	4	5.1 in. (130 mm)	DERATING DUE TO RASH OF EARLY FAILURES. SATISFACTORY MATURE PLANT PERFORMANCE WITH COMMERCIAL SEALS.
BRUCE A & B 8 X 800 MW	1976	4	0	7.4 in. (188 mm)	B-J SEALS FAILED PRE-INSTALLATION QUALIFICATION TEST. COMMERCIAL SEALS REPLACED BY AECL DESIGNED SEALS. FOUR YEAR LIFETIMES RELIABLY ACHIEVED. NO SIGNIFICANT DERATING DUE TO SEALS AFTER 40 REACTOR-YEARS OF OPERATION.
PT. LEPREAU 600 MW	1982	4	0	7.8 in. (198 mm)	AECL DESIGNED SEAL. GOOD PERFORMANCE TO DATE. NO DERATING DUE TO PUMP SEALS.
WOLSUNG (KOREA) 600 MW	1982	4	0	7.8 in. (198 mm)	AECL DESIGNED SEAL. GOOD PERFORMANCE TO DATE. NO DERATING DUE TO PUMP SEALS.
DARLINGTON 4 X 850 MW	1987	4	0	7.8 in. (198 mm)	AECL SEALS TO BE INSTALLED.

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