QUALIFICATION AND PERFORMANCE OF AN IMPROVED INFLATABLE SEAL FOR CONTAINMENT

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Abstract

Airlocks provide passageways through nuclear containment. Therefore, limitations in their functionality and availability can adversely affect the operation of a nuclear station. A program to develop and qualify inflatable seals has been driven primarily by the needs of operating CANDU® stations. In response to these needs, the Fluid Sealing Technology Branch of AECL has designed and developed an inflatable seal—the DSA3 (Door Seal Alternate Design 3). This design incorporates optimized geometry and improved materials and it has been environmentally qualified by test to meet CANDU 6 station requirements for both containment and confinement boundaries.

1. INTRODUCTION

Inflatable seals in airlock doors are part of the containment envelope of CANDU® nuclear reactors. They prevent leakage during normal plant operation and withstand the higher pressures, temperatures and radiation levels of postulated accidents. Airlocks allow personnel, equipment and fuel to enter the reactor vault in CANDU stations. The seals are inflated to push them into contact with the frame of the door after the door is closed. When deflated, they must quickly disengage and retract into their retainers to enable the door to be opened without damage to the seals. They are intended to seal the door against pressures approaching their inflation pressure, and are installed two-per-door for reliability.

Inflatable seal performance is affected by various factors such as the following: seal geometry; material properties (of the elastomer and its fabric reinforcement); retainer shape; gap size and uniformity; sealing counter-face texture; corner radii; sealing configuration (edge-sealing or face-sealing); inflation pressure; and the service conditions of temperature, radiation, number of opening-closing cycles, and pressure across the seal.

The purposes of this paper are to describe the results of the environmental qualification (EQ) test program of the DSA3 inflatable seal design for the equipment and personnel airlock doors of CANDU 6 stations and to summarize the operational experience that has validated this design.

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2. BACKGROUND

Historically, inflatable seals had not met performance and reliability expectations for several reasons. They cracked due to fatigue and then leaked (requiring their replacement), they deflated and retracted slowly (requiring costly vacuum systems to compensate), and they sometimes stuck to their counter-faces and were un-seated from their retainers when a door was opened. This combination of poor performance characteristics caused unnecessary delays at airlock and shielding doors, decreased airlock availability and increased maintenance costs.

In response to this poor performance and because inflatable seals had never been environmentally qualified, the Ontario Hydro Research Division conducted a series of tests ending in 1992 to assess the performance of the two seal designs that were being used in CANDU stations at that time. When both designs failed the environmental qualification tests, Ontario Hydro sought assistance from AECL via COG to address this problem; i.e., components unable to perform their safety-related functions were being used in safety-related systems. AECL worked with the two existing suppliers to help them improve their designs and when it was concluded that progress with them was inadequate, AECL designed a new seal and worked with a Canadian company to manufacture it.

At about the same time, the Third Qinshan Nuclear Power Company awarded a contract to AECL to build two new CANDU 6 stations near Shanghai. This was the first AECL new-build project to require that inflatable seals used in the containment boundary be environmentally qualified. Previously, the results of fatigue tests on un-aged seals, combined with material property degradation rates (following irradiation to design-based accident conditions), was accepted as evidence that the seal design could perform its safety function following a design-basis LOCA for a CANDU 6 station.

The main problems with the earlier designs being used were unacceptably low fatigue life and slow retraction. These problems were overcome by conducting intensive research into these failure mechanisms and then by changing the AECL seal design to reduce its sensitivity to these mechanisms. AECL developed the DSA1 design to meet the demanding requirements for CANDU containment seals. Although the details of this research and the seal design are intellectual property, the results of this work can and should be shared with utility owners and operators.

3. DEFINITIONS

Gap is defined as the distance between the shoulder of the seal retainer and its counter-face as shown in Figure 1.

LOCA is defined as a Loss of Coolant Accident.

MSLB is defined as a Main Steam Line Break.

Cross-Seal Leakage is the total leakage across the seal, both past its striker and its foot.

Make-Up Air is the leakage of inflation air through the seal wall.

Retraction Time is defined as the time it takes the body of the striker to retract from the sealing counter-face, to a position in which it lies within the plane of the retainer shoulder, after the seal has been vented to atmosphere.

4. EQUIPMENT DESCRIPTION

Each seal is mounted in a retainer that extends completely around a door in such a manner that permits its removal for maintenance or replacement. The retainer may either be in the edge of the door or its face, as shown in Figure 2. Photographs of DSA1 seals installed in an airlock door in a face-sealing configuration are shown in Figure 3 and Figure 4. The retainer profile used in all CANDU 6 stations has sides perpendicular to its base as shown in Figure 1. To fulfil its purpose, the seal must bridge the gap across the door's clearance and come into pressurized contact with the sealing counter-face on the frame of the door. When deflated, it must quickly disengage and retract into its retainer to enable the door to be opened without damage to the seal. There are normally two seals in each door and two doors for each airlock—one at the reactor building (or containment) side and one at the service building side. For passage through the airlock, doors are opened one at a time. The seal is required to bridge the range of gaps shown in the following table:

Sealing Configuration	Gap Range (mm)
Edge-Type	5.5 to 13.8
Face-Type	0.6 to 5.5

The seal is inflated via its moulded-in inflation tube. A nominal inflation pressure of 310 kPa[1] is maintained by inflating the seals to an upper bound value (325 kPa for CANDU 6 stations) and then re-inflating when their pressure drops to a lower bound value (295 kPa for CANDU 6 stations). The seals are captured by their retainers and the frame of the door in which they are fitted.

[1] All pressures specified throughout are gauge unless otherwise noted.

5. QUALIFICATION REQUIREMENTS

Table 1 specifies the normal service and accident conditions for which the seals were qualified. It is assumed that such an accident could occur at any time during the service life of the seal (as defined in Section 6.5).

Table 1: CANDU 6 Airlock Door Seal Operating Conditions

Operating Condition	Cross-Seal Pressure (kPa)	Temperature (°C)
Normal	-0.5	35
Containment Pressure Testing	143	35
Containment Leak Testing	125	35
LOCA (peak values)	125	125
MSLB-with-Dousing (peak values)	200	135

The qualification requirement for LOCA conditions includes an air-equivalent integrated dose of 110 kGy for normal service life and accident exposure. During an accident, airlock door seals are required to contain steam and airborne contamination within the reactor building. The seals are not required to be qualified to open or recluse an airlock door after an accident. Conditions not covered by the scope of this qualification test program were scuffing or exposure[2] to any of the following: ozone, oil, tritiated heavy water, acid, or alkaline solutions.

6. ACCEPTANCE CRITERIA

6.1 Make-Up Air

Make-up air is required to maintain inflatable seals at a specified inflation pressure during cross-seal leakage tests. A make-up rate of less than 12 standard cubic centimetres per minute (sccm) per meter of seal was considered acceptable for performance tests at LOCA and MSLB-with-Dousing conditions.

6.2 Cross-Seal Leakage

A leak-rate of less than 1.6 mg/s per meter of seal length was considered acceptable for a cross-seal pressure of 125 kPa, a temperature of 125°C and a seal inflation pressure of 295 kPa[3]. A leak rate of less than 3.2 mg/s per meter of seal was considered acceptable for a cross-seal pressure of 200 kPa, a temperature of 135°C and a seal inflation pressure of 295 kPa.

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[2] These environmental conditions were neither well known nor explicitly specified for the airlocks of CANDU stations. Previous research and development and operational experience of elastomers in other applications had shown no significant degradation of these materials by water at pH 11.

[3] The use of the lower bound of the seal operating inflation pressure is conservative when testing the gap-bridging capability of the seal during accident simulation testing.

6.3 Retraction Time

A retraction time of less than 60 seconds following the seal being vented to atmosphere was considered acceptable.

6.4 Post-Test Inspection

Non-destructive inspections and tests were performed on the seals following their testing. Indications of imminent failure (e.g., pin-holes) were considered unacceptable.

6.5 Qualified Life

The qualification was based upon thermal aging to simulate five years of storage (at 20°C) followed by five years of operation (at 35°C) and on 40,000 and 75,000 inflation-deflation cycles for edge-sealing and face-sealing configurations, respectively.

6.6 Margins

The requirements for margins (for environmental qualification by type-test) were met as follows:

Radiation: The required margin of 10% was added to the postulated accident dose of 110 kGy to derive the requirement of 121 kGy.

Pressure and temperature during LOCA transient: The peak LOCA transient conditions were applied, but with margins of (8°C) on temperature and (10%) on pressure.

Pressure and temperature during MSLB transient: The peak MSLB transient conditions were applied twice, without temperature and pressure margins.

7. TEST PROCEDURES

7.1 Sets of Tests

Two sets of tests, designated A and B, were performed. The Set A tests established the baseline performance of un-aged (new) seals at LOCA conditions and their maximum cross-seal pressure capability. The Set B tests confirmed the ability of the seal design to withstand accident conditions in an end-of-life (aged) condition. To accomplish this, the seals were tested after undergoing age conditioning (accelerated thermal aging and fatigue aging). The Set B tests confirmed the ability of the seal design to withstand both LOCA and MSLB-with-dousing conditions. As a LOCA accident would include significant radiation exposure, the seals were irradiated also.

Figure 5 is a cross-section through one side of the test rig and Figure 6 is a photograph of the test rig with test seals installed and with the lid of the test rig removed.

7.2 Seal Inspections

Before the seals were tested, they were photographed, visually inspected, and their critical features were measured.

Seals used for the Set A and B test were divided into two groups, also called A and B. They were subjected to different thermal aging, radiation exposure, inflation-deflation cycling, and accident testing, as described below.

7.3 Baseline Functional Tests at LOCA Pressure (Group A Seals)

This test, to confirm the ability of a new seal to contain steam, was performed at a minimum temperature of 125°C with a minimum cross-seal pressure of 125 kPa. The leakage rate past each seal was monitored and recorded for the full duration of this test. The flow rate of inflation make-up air required to maintain the seals at their inflation pressure was also recorded. The parameters for this test are summarized in Table 2.

Table 2: Test Parameters for the Baseline Functional Test

Test Parameter	Parameter Value
Inter-Seal Pressurizing Fluid	Steam
Minimum Cross-Seal Pressure (kPa)	125
Minimum Test Rig Temperature (°C)	125
Maximum Seal Inflation Pressure (kPa)	295
Duration (h)	10

All tests were conducted in a full-size mock-up of an airlock personnel door contained in a test chamber. The door contained one edge seal and one face seal, as shown in Figure 5 and Figure 6, plus additional O-ring seals to collect leaked steam. The space between the two seals was pressurized to simulate the cross-seal pressure on the door.

7.4 Maximum Cross-Seal Pressure Capability (Group A Seals)

The temperature of the test rig was raised to 150°C and then the seals were inflated to 295 kPa. Using steam, the inter-seal pressure was increased to 200 kPa. Steam was injected to increase the inter-seal pressure until one of the seals suffered ‘blow-by’. The seal that suffered ‘blow-by’ and the pressure at which it occurred were recorded. This test was repeated after disassembling the test rig and re-setting the seals.

7.5 Thermal Aging—Normal Operation (Groups B Seals)

The seals were installed in their retainers, the test rig was assembled, and the inter-seal cavity was vented to atmosphere. The inter-seal cavity temperature was maintained at a minimum value of 117 °C by controlling the test rig to thermocouples touching the inter-seal wall. These conditions were held for 123 hours. According to the Arrhenius methodology for a material with an activation energy of 0.77 eV, this is equivalent to five years of storage at 20 °C followed by five years of operation at 35 °C. (The activation energy for the DSA3 seal materials was determined experimentally by AECL.)

7.6 Inflation-Deflation Cycling—Normal Operation (Group B Seals)

The seals were cycled by inflating to normal operating pressure (310 kPa), holding for 5 s, venting to atmosphere, and maintaining a pressure below 10 kPa for 7 s before re-inflating. The face seal was cycled 75,000 times and the edge seal was cycled 40,000 times. The retraction time of both seals was measured and recorded upon completion of the fatigue-aging sequence. Both seals fully retracted within an average period of 12 seconds, well within the acceptance criterion of 60 seconds.

7.7 Radiation Exposure (Group B Seals)

The set B seals were installed in the test rig and inflated to 310 kPa (+ /– 5 kPa), then irradiated by a ^{60}Co gamma source. Compensation was made for shielding due to the geometry of the test rig. The seals received an air-equivalent integrated dose of 121 kGy (which includes a 10% margin added to the specified 110 kGy).

7.8 Functional Tests at LOCA Conditions (Group B Seals)

The test rig, with the seals installed, was placed in the test chamber. The temperature of the rig was increased to a minimum of 133°C. Once at temperature, the seals were inflated to a maximum pressure of 295 kPa. Steam was then injected into the inter-seal space to raise the inter-seal pressure to a minimum of 137.5 kPa in less than two minutes. Once these conditions were stabilized, a control program was used to follow the rest of the temperature and inter-seal pressure profiles summarized in the table below. Conditions were programmed to change linearly between the points specified in Table 1.

Table 3: Functional Tests at LOCA Conditions: Pressure and Temperature Profiles

Time	0	2 min	1 h	10 h	19 h	20 h
Temperature (°C)	133	133	133	133	105	105
Pressure (kPa)	0	137.5	137.5	15	15	15

7.9 Functional Tests at MSLB-with-Dousing Conditions (Group B Seals)

The test rig, with the seals installed, was placed in the test chamber. The temperature of the rig was increased to a minimum of 135°C. Once at temperature, the seals were inflated to a maximum pressure of 295 kPa. Steam, at a pressure of 200 kPa or higher, was then injected into the inter-seal space. Once these conditions were stabilized, a control program was used to follow the temperature and inter-seal pressure profiles summarized in the table below.

Table 4: Functional Tests at MSLB-with-Dousing Conditions:
Pressure and Temperature Profiles

Time (h)	0	6	7.5	10	15	20	24	25.5	26.5
Temperature (°C)	135	135	135	130.8	122.5	114.2	107.5	105	105
Pressure (kPa)	200	200	184.6	158.9	107.5	56.1	15	15	15

The leak rate past each seal and the flow rate of air supplied to each seal to maintain its inflation pressure were monitored and logged. When the program finished, the test was repeated.

7.10 Post-Test Inspection (Group B Seals)

After testing was completed, the condition of the seals was inspected and recorded. A leak inspection was also performed by inflating the seals under water and any location that produced bubbling in excess of five bubbles per minute was recorded.

8. EQ TEST RESULTS

The test results, which are summarized in

Table 5, were similar for these two tests in that both demonstrate large margins in performance as compared to their specified qualification requirements.

Table 5: Summary of Performance Test Results for the DSA3 Seal Design

Performance Parameters		**Baseline Test**		**Combined LOCA and MSLB Test**	
Description of Variable		Face	Edge	Face	Edge
Cross-Seal Leakage Rate [mg·s^{-1}·(m of seal length)$^{-1}$]	Acceptance Criterion	← 1.6 →			
	Actual	0.04	0.26	0.17	0.50
	Margin	*1.56*	*1.34*	*1.43*	*1.10*
Mean Permeation [(sccm air)·(m of seal length)$^{-1}$]	Acceptance Criterion	← 12 →			
	Actual	3.9	5.1	3.5	4.6
	Margin	*8.1*	*6.9*	*8.5*	*7.4*
Cross-Seal Pressure [kPa] (To un-seat a seal or to cause blow-by)	Acceptance Criterion	← 200 →			
	Actual	>249	249		
	Margin	>49	*49*		
Retraction Time [s]	Acceptance Criterion	← 60 →			
	Actual	12	12		
	Margin	*48*	*48*		

9. OPERATIONAL EXPERIENCE

AECL began supplying DSA1 seals in 2001 September with Qinshan III being the first station to install them. AECL continued to improve its inflatable seal design since then with the development of the DSA2 and DSA3 designs. The later designs have greater fatigue life than their predecessors as shown in Table 6.

Table 6: Fatigue Life of DSA Seal Designs for Two Sealing Configurations

Design	Fatigue Life (Inflation-deflation cycles)	
	Edge-Sealing	Face-Sealing
DSA1	6,000	60,000
DSA2	30,000	60,000
DSA3	40,000	75,000

There have been no performance problems with any of these seals related to either their design or their manufacture. Figure 3 and Figure 4 are photographs taken 2003 August of DSA1 seals installed in a personnel door of the Qinshan Equipment Airlock. Table 7 summarizes the operating experience of the DSA seal designs.

Table 7: Operating Performance of the DSA Seals

Station	Designs Supplied
Wolsong	DSA1, DSA2, DSA3
Cernavoda II	DSA1
Embalse	DSA1
Gentilly II	DSA2
Qinshan III	DSA1, DSA2, DSA3

10. SUMMARY AND CONCLUSIONS

The DSA3 seal design has been tested successfully in both edge and face-sealing configurations to both verify (by EQ test) and validate (by operation) its design. The DSA3 seal design is qualified, with a large margin, for service in both edge (5.5 to 13.8 mm gap) and face-sealing configurations (0.6 to 5.5 mm gap) for CANDU 6 plants. The DSA3 seal design, with its rapid retraction and improved fatigue life, can be expected to provide five years of trouble-free service at normal operating conditions.

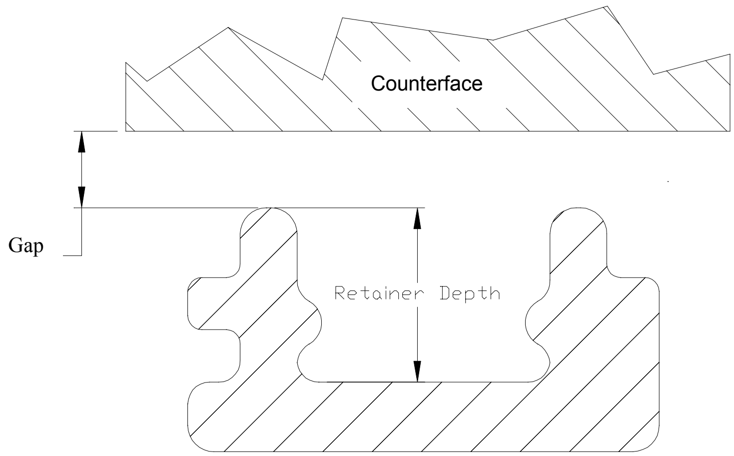

Figure 1: Gap Definition Shown on a Half-Section of a Retainer for Inflatable Door Seals in CANDU 6 Plants

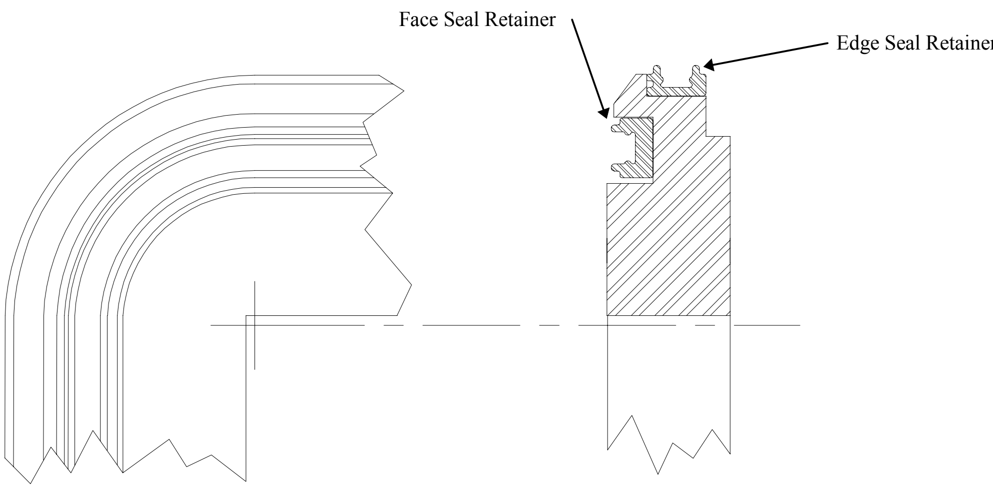

Figure 2: A Cross-Section of the Door Seal EQ Test Rig Showing Edge and Face-Sealing Configurations

Figure 3: DSA1 Seals Installed in a Personnel Door of the Qinshan Equipment Airlock

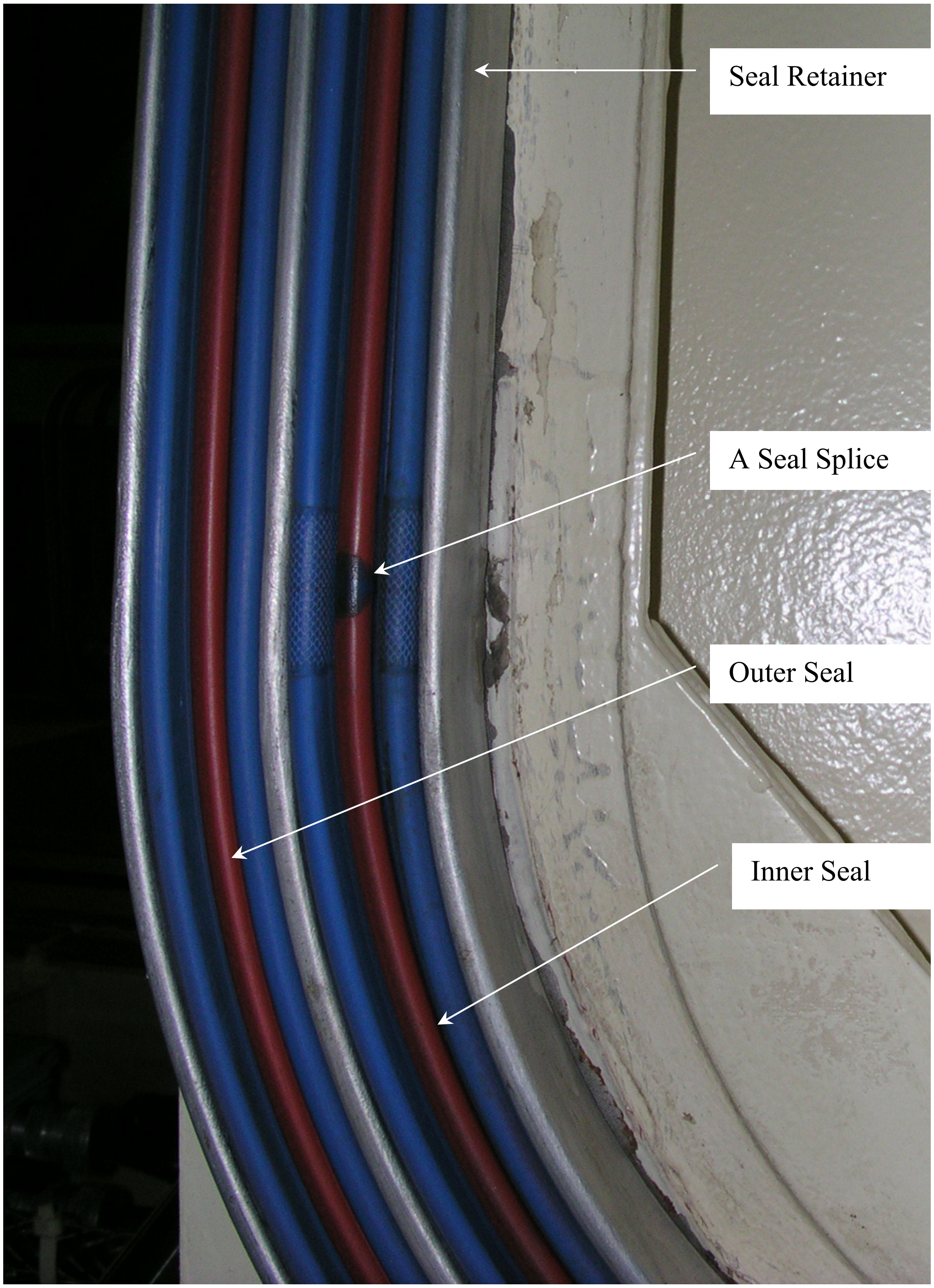

Figure 4: One Corner of a Personnel Door Showing DSA1 Seals Installed in Their Retainer

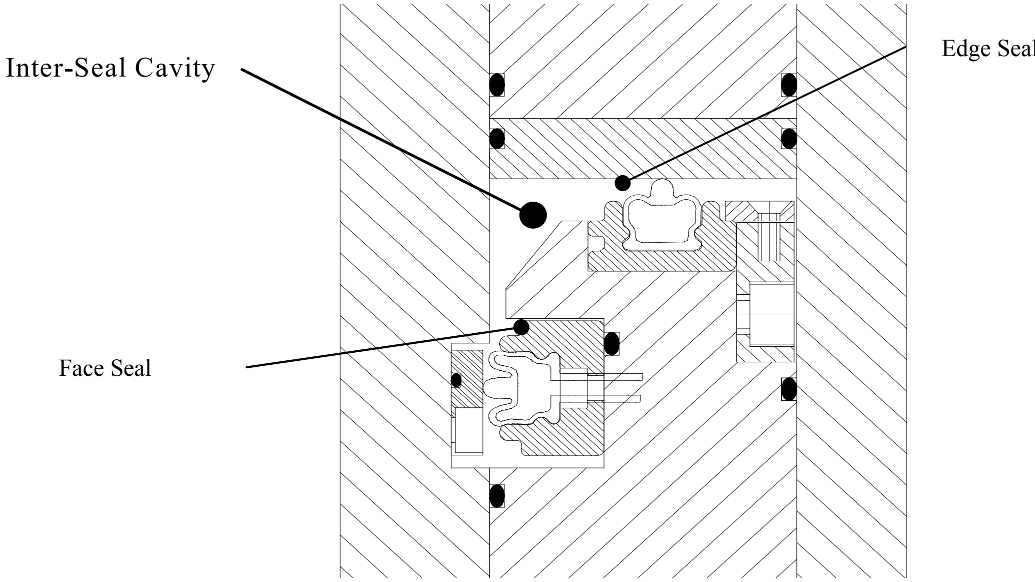

Figure 5: Test Rig Cross-Section Showing Sealing Configurations and Testing Arrangement

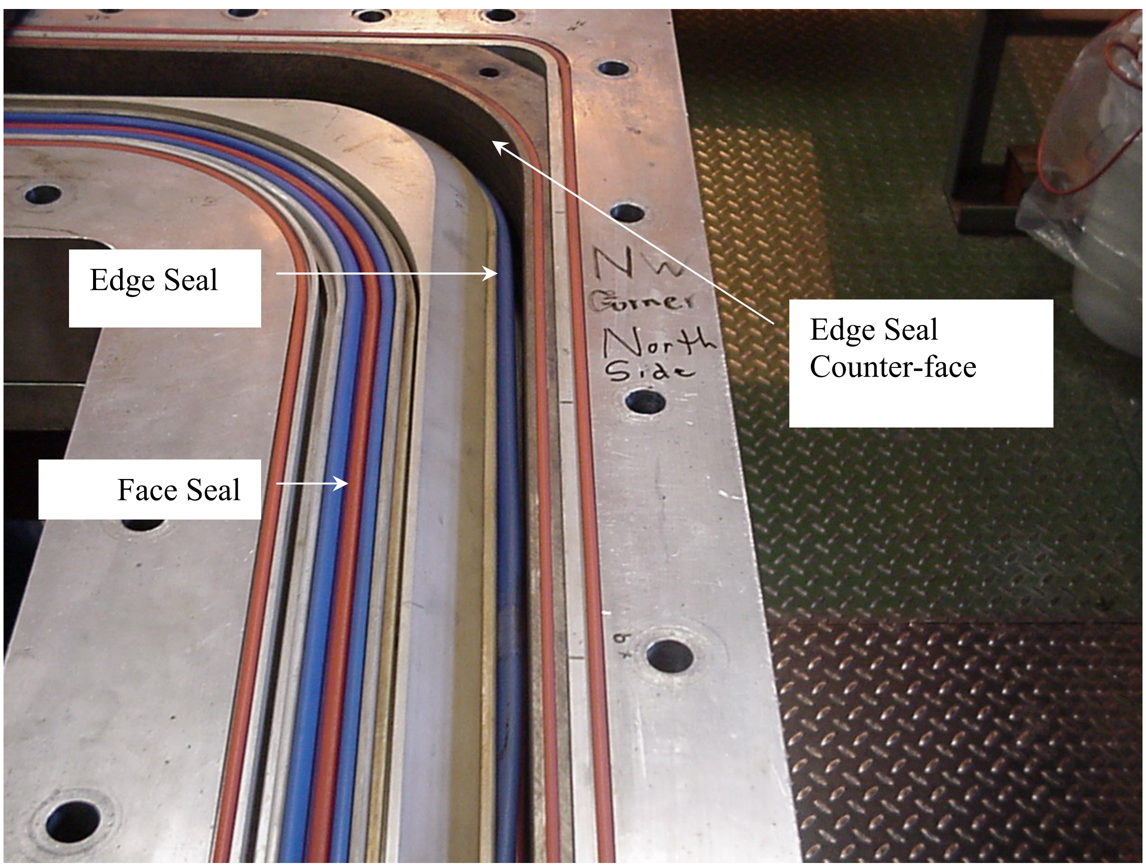

Figure 6: Edge Seal Shown Partially Un-seated Following a Maximum Cross-seal Pressure Test