Containment Structure Performance as Controlled by Penetrations and Extensions

Julia Milman[1)] and Tarek S. Aziz[1)]

1) CANDU Services Civil Engineering, Atomic Energy of Canada Limited, Mississauga, ON, Canada

ABSTRACT

The containment represents the ultimate barrier to fission product releases to the environment in a Nuclear Power Plant (NPP). Existing design and operating strategies are in place to protect this final barrier in CANDU®[1] NPPs. It is very important to understand the containment capabilities and the margins in performance that go beyond design loads and severe accidents as further provisions to improve containment performance for CANDU® plants are contemplated.

Several NPPs are nearing the end of their original design life and are considering the possibility of extending service life and performing containment improvements in order to meet the Probabilistic Safety Assessments (PSA) related targets. Examination of various options that can improve containment performance under severe accident conditions caused by external events requires, amongst other parameters, knowledge of the pressure capacity of containment penetrations and extensions since it is expected that the containment penetrations are the weak links with respect to the ultimate pressure capacity and not the concrete containment structure itself.

Recently, AECL has performed assessment of the pressure capacity of containment penetrations and extensions for CANDU® 6 Nuclear Power Plants undergoing life extension. A systematic assessment methodology was developed to identify the weak links for the containment system under severe accidents. An effort was made to identify those penetration components, the pressure capacity of which is below the cracking pressure of containment concrete at high temperature of 150°C (302°F) associated with severe accident scenarios.

As a result of the assessment, only inflatable airlock seals were identified as having the pressure capacity below the cracking pressure of containment concrete. Therefore, the pressure capacity of the containment is governed by the capacity of the inflatable airlock seals.

The estimated pressure capacity of containment extension portion of the Reactor Building (R/B) ventilation system ductwork is above the cracking pressure of concrete at a room temperature. However, higher temperature of the atmosphere inside the containment associated with severe accident scenarios may result in a lower value for the pressure capacity of the ductwork.

INTRODUCTION

In 2006, AECL has performed assessment of the pressure capacity of the following containment penetrations and extensions of two CANDU® 6 NPPs:

- A typical electrical penetration;
- A typical mechanical penetration;
- Equipment and personnel airlocks inflatable seals;
- A pair of containment isolation valves in the R/B ventilation system.

The assessment was based on review of existing design and analysis reports, Environmental Qualification program findings and qualification reports, test results, and suppliers' data. Calculations were performed to estimate the ultimate pressure capacity of penetrations components based on the existing stress reports.

The assessment concentrated on components, pressure capacity of which is below the cracking pressure of containment concrete. As per Reference [1], the cracking pressure of concrete is 334 kPa-g (48 psig). The maximum temperature of the air inside containment considered for the assessment was 150ºC (302ºF).

[1] CANDU® is a registered trade-mark of Atomic Energy of Canada Limited

ELECTRICAL PENETRATION

Function

Electrical Penetrations (EP) provide a leak tight method by which power and control cables enter the containment. In addition, electrical penetrations sustain containment requirements during and after a design basis event, while maintaining electrical characteristics of cables.

Description

Typical electrical penetration is illustrated in Figure 1. Most electrical penetrations in CANDU® 6 use the same size embedment of rectangular shape, which slopes down, at an angle to the outside of the reactor building containment wall.

The basic seal for the cables is obtained by using prescribed method to encapsulate the cable in a block of epoxy resin fitted into a steel gland, which is welded to a seal plate. The block is sealed in the gland by an arrangement of sealing gasket, sealing ring, spring, and washer.

The seal plates that carry the cable glands are welded to the embedment face. The gland face is perpendicular to the seal plate. Various configurations of plates were used depending on the glands' sizes.

Seal Plate Testing

The full-scale testing was performed by AECL to determine capacity of electrical seal plates. Duplicates of installed cable seal plates have been prepared and subjected to hydraulic pressure at room temperature. The average pressure at which three tested plates yielded was 1896 kPa-g (275 psig). One plate was subjected to increasing hydraulic pressure till failure occurred at 7929 kPa-g (1150 psig). The weakest part was the fillet weld at the bottom of the plate.

The qualifying pressure for the plate was calculated based on the results of the test taking into account pressure that compensated for cable loads and a corrosion factor. The qualifying pressure was calculated to be 596 kPa-g (86.4 psig).

Gland Seal Assembly Testing

The laboratory testing of the High Voltage (HV) power cable penetration assembly performed by AECL established that it is resistant to leakage at 634 kPa-g (92 psig). The test was performed at room temperature.

Environmental Qualification

Environmental Qualification (EQ) assessment of electrical penetration components was performed. Only Silastic gasket and epoxy casting were considered for EQ assessment as being age-sensitive EQ-critical components. In addition to those, the "hotsplice" was considered for HV power cables.

EPs satisfied a postulated peak ambient temperature requirement of 112.6ºC (235ºF) and were environmentally qualified to pressures of up to 159 kPa-g (23 psig). EPs were environmentally qualified for at least 56 years in typical CANDU® 6 service conditions, which included the following accidental parameters: temperature of 143ºC (289ºF) and pressure of 290 kPa-g (42 psig).

Implications of 150°C (302°F) Temperature

Based on the documented expert judgment and evaluation, it is unlikely that pressure capacity of the electrical penetration will be significantly affected if atmosphere temperature in containment reaches 150°C (302°F) due to the reasons summarized below, however no tests have been performed to confirm that.

- When temperature of the atmosphere inside containment reaches 150°C (302°F), it is not the case on the outside of the containment, where the seal plates and glands are located. The temperature will be dissipating from the outside surface of the containment wall.
- The critical element in the EP, as far as temperature is concerned is epoxy. Its critical temperature is 150°C (302°F). Epoxy softens at about 121°C (250°F). However, even if epoxy softens and starts to flow, it does not necessarily mean that it will cause a leak.
- Based on the results of EQA of electrical penetrations, the critical element for HV power cable penetration is the EPR tape used for Hotsplice. Its extreme service temperature rating of 130ºC (266°F) is based on the value for the EPR tape

used for HV1 cable splices since no data was available on this particular tape. Higher temperature may cause embitterment and result in cracks and leak paths. From the experience of AECL electrical specialist, it is judged unlikely that the EPR tape, which is vulcanized, will turn brittle and crack.

- The cables inside the penetration are qualified for Loss of Coolant Accident (LOCA) conditions and have the following characteristics:

Normal Operation	90°C (194°F)
Emergency overloads	130°C (266°F)
Short Circuits	250°C (482°F).

Conductor temperature of 250°C (482°F) shall be limited to 10 seconds or less. When subjected to high temperatures for a long period of time, the cable might lose its insulation causing short circuits. It would compromise the function of the cable, but would not necessarily impact the pressure capacity of the EP.

MECHANICAL PENETRATION

Function

Containment seals between the containment embedments and the process pipes, which pass through them form a portion of the containment boundary, hence must have the same integrity as the rest of the containment envelope. They may also provide an anchor or support function for the penetrating lines.

Description

There are provisions for over 240 pipelines and tubing passages passing though containment and connecting to about 46 different process systems in CANDU® 6 NPP. Most of the mechanical penetrations use typical circular configuration as shown in Figure 2. Penetrations range from about 76mm (3”) to 914 mm (36”) in diameter. There are also a few rectangular penetrations.

Containment seal plates of the mechanical penetrations are designed as pipe supports. Thus, their pressure capacity depends on the stresses caused by the process system that is passing through the penetration. Since all mechanical systems have different characteristics (pressure and temperature), there is no typical mechanical penetration as far as pressure capacity is concerned. The approach used in this assessment was to assess the pressure capacity of selected mechanical penetration of typical configuration.

Stress Analysis

Stress report of one system was reviewed to estimate pressure capacity of the selected penetration for the Emergency Core Cooling (ECC) System. The ECC system is designed to supply water to the Primary Heat Transport (PHT) System following a LOCA to remove residual decay heat from the PHT circuit. The piping system was designed for 1551 kPa-g (225 psig) pressure and 104ºC (220ºF) temperature. In addition to the piping loads, the differential pressure of 124 kPa-g (18 psig) was considered for analysis of the seal plate. It was estimated that this differential pressure at a temperature of 104ºC (220ºF) could be increased to approximately 1551 kPa-g (225 psig) before the calculated stresses for the weld, which governs the capacity of the penetration, will reach allowable value.

EQUIPMENT AND PERSONNEL AIRLOCK INFLATABLE SEALS

Functions

The function of the airlocks is to provide an access for personnel and equipment transfer to the interior of the R/B without breaching containment. Two types of airlocks are provided in CANDU® 6: the equipment airlock with personnel transfer doors and the emergency airlock for personnel transfer only.

The airlock inflatable seals provided between the door and the frame of the airlock form a barrier to maintain the pressure difference between the R/B and Service Building (S/B).

Description

The equipment airlock is located on a raised slab in the main hall of the service building. The two airlock doors are at opposite ends of a cylindrical passage. The equipment airlock has a personnel door inside the equipment door at each end. The personnel airlock is located in the S/B basement. Each airlock is provided with hermetically sealed doors. The operation of these doors, their seals and the valves are sequence interlocked in order to maintain the integrity of containment at all times. All airlock operations are performed pneumatically.

Two inflatable door seals are provided on each door to seal the joint between the door and the frame. Seals are deflated when the doors are opened and re-inflated after closing. Each seal is retained in a groove (Figure 3) that extends around the door in such a manner that seals can be removed for maintenance and replacement.

Inflatable seals are replaceable components. Original seals are being replaced with Trentec EPDM seals at some CANDU® 6 NPPs. However, in some cases, the gap between the door and its frame is larger than 13 mm (0.512") for which Trentec EPDM seals are qualified, thus it is intended to replace original seals with AECL DSA2 seals.

The AECL Model DSA2 inflatable seal is made of polyester reinforced silicone rubber. The seal is installed in the retainer, which is mounted on the edge of the door and therefore, is referred to as an edge type seal. When inflated, the seal is designed to close the gap in the range of 5.5 mm (0.216") and 13.7 mm (0.539") between the seal retainer and the doorframe (Figure 3).

Trentec EPDM Seal Testing

Trentec has performed a number of tests to qualify the EPDM Edge type seals. To simulate in-service conditions, a test fixture was constructed for the edge seal including seal retainers of identical interface dimensions as retainers supplied for the equipment airlock's equipment doors. The seal was installed in the fixture assuring that a gap between the door and its frame varied between 6 mm (0.237") and 13 mm (0.512").

The blow by test was performed following LOCA/Main Steam Line Break (MSLB) simulation. The blow by test was performed at 150ºC (302ºF) with seal inflated to 296 kPa-g (43 psig). Two tests were conducted. The differential pressure at which blow by occurred was 241 kPa-g (35 psig) for the first trial and 234 kPa-g (34 psig) for the second trial. During each excursion, approximately 381 mm (15") of the seal was blown out of the retainer.

The results of the blow-by test can be influenced by the following factors:

- The actual gap between the door and the doorframe: If the gaps (especially in the corners) are larger than 13 mm (0.512"), then results of the blow-by test might not be valid.
- The displacement of the doorframe: Relative movement of the doorframe with respect to the door in the direction parallel to the plane of the door will not affect the seals, as it does not change the gap. The door bolts should control relative movement in the direction perpendicular to the plane of the door.

AECL DSA2 Seal Testing

A number of tests were performed on AECL Model DSA1 seal, which are considered applicable for model DSA2 as these models are very similar. Additional manufacturing controls have been applied to the model DSA2 to improve the fatigue life but this does not negate the test results based on the model DSA1.

The tested seal was about 5.7 m (18.7') long and was installed in the test rig with a corner radius of 10.5 cm (4.125"). The length of the seal does not affect qualification of the seal except that total leakage will be affected proportionally.

The seal was mounted in aluminum retainers with 0° groove profiles (Figure 3). The nominal 5.5 to 13.0 mm (0.276" – 0.512") gap retainer was used. With this configuration, the edge seal had to span a nominal gap of 13.0 mm (0.512") on two adjacent sides of the door, 5.5 mm (0.216") along one long side, and 11.0 mm (0.433") along the second short side. Transitions in gap sizes occurred in three of the corners. The maximum gap was measured to be 13.7 mm (0.539").

The baseline functional test was performed at temperature above 125°C (257°F) with a minimum cross-seal pressure of 125 kPa-g (18 psig). After that, the temperature of the test rig was raised to 150°C (302°F) and the seals were inflated to 295 kPa-g (42.8 psig). Using steam, the inter-seal pressure was increased to 200 kPa-g (29 psig). The increase in inter-seal pressure was continued by injecting steam until the seal suffered 'blow-by'.

The "blow-by" was indicated by a rapid decrease in cross-seal pressure, and a rapid increase in the apparent level of collected condensate. The maximum cross-seal pressure was found to be 264 kPa-g (38.3 psig) in the first test and 260 kPa-g (37.7 psig) in the second. Post-test visual inspection concluded that the seal was in good condition. No cracking was observed.

Environmental Qualification

Trentec seals were qualified for 10 years of service or 30,000 cycles of inflation and deflation in typical CANDU® 6 service conditions, which include accidental parameters: temperature of 126ºC (259ºF) and pressure of 140 kPa-g (20.3 psig).

Environmental Qualification Assessment (EQA) of the AECL Model DSA2 inflatable seals was performed. The temperature and pressure parameters for qualification are outlined in Table 1. The seals have been qualified for 6.2 years of service under 35ºC (95ºF) and 30,000 inflation-deflation cycles.

CONTAINMENT ISOLATION VALVES OF THE R/B VENTILATION SYSTEM

Function

A network of supply and exhaust ductwork inside the R/B distributes the air to those accessible rooms in the R/B, which do not contain D_2O vapour. It has two containment penetrations, each provided with two automatically closing containment valves in series. These valves are a part of the Containment Isolation System, which is a Group 2 safety system designed to seal the R/B when high radioactivity or an abnormal pressure rise is detected.

Description

There are two containment penetrations in the R/B ventilation system: the R/B ventilation exhaust and the R/B fresh air inlet supply. Each penetration is provided with a double set of leak-tight isolation valves. The general arrangement is shown in Figure 4.

The R/B ventilation system containment extension is composed of 30” carbon steel ducting and a pair of isolation valves, which are air-operated butterfly valves manufactured by Fisher Controls International. Butterfly valves operate using a circular valve disc that rotates at the centre by way of the valve shaft. A rubber valve seat clamped in the valve body creates the seal around the disc edge.

Valve Tests

An air shell test of butterfly valve of size 30” was performed at pressure of 552 kPa-g (80 psig). Valve seat was leak tested at 124 kPa-g (18 psig) air at ambient temperature and was found leak tight.

The 16” and 18” Fisher butterfly valves with identical design of EPDM seats were seat leak tested at 552 kPa-g (80 psig) air at ambient temperature and were found bubble tight.

AECL performed an aging test of identical design of 36” Fisher butterfly valve with an EPDM seat ring. The valve assembly was placed in the chamber with an average temperature of 115°C (239°F) for 10 days. No visible damage was observed on the seat ring after ten days. The valve was cycled for 1000 cycles. The hydrostatic seat and stem leakage test was performed at about 152 kPa-g (22 psig) and 53°C (127°F). No visible leakage was observed after five minutes.

Environmental Qualification of Valves

Environmental Qualification (EQ) assessment of the Fisher valves was performed. O Ring / T Ring and valve packing were considered for EQ assessment as being age-sensitive.

Fisher butterfly valves satisfied peak accident temperature requirement of 129ºC (264ºF). The pressure limit is based on the maximum operating pressure limit shown on the manufacturer’s drawing, which is 517 kPa-g (75 psig).

Fisher butterfly valves were environmentally qualified for over 50 years in the typical CANDU® 6 service conditions, which included the following accidental parameters: temperature of 143ºC (289ºF) and pressure of 290 kPa-g (42 psig).

Implications of 150°C (302°F) Temperature

The EPDM seat ring design is suitable for operating temperature of 149°C (300°F). Chesterton style of 1724 stem packing installed on the Fisher containment isolation valves is suitable for an operating temperature of 260°C(500°F).

Based on the documented information and expert judgment, the valves will be able to withstand the pressure in excess of 334 kPa-g (48 psig) and remain leak tight when the temperature in containment reaches 150°C (302°F), however no tests have been performed to confirm that.

Analysis of Duct

The section of ductwork from the inside face of the R/B wall to the outer isolation valve is designed as Class 2 under ASME Section III Sub-section NC. The design conditions included the pressure of 124 kPa-g (18 psig) and temperature of 38ºC (100ºF). Material specified for the class 2 portion of the ventilation system ductwork is ASME SA 285 GR “C” plate, 5 mm (3/16”) thick.

Based on the analysis, it was estimated that the containment pressure at room temperature could be increased to and above the cracking pressure of concrete of 334 kPa-g (48 psig), before the calculated stress would reach allowable value. Depending on the design of the ductwork, the margin varies for different CANDU® 6 NPPs.

Implications of 150°C (302°F) Temperature

The piping analysis is based on the maximum temperature of 38°C (100ºF). If the temperature is increased to 150°C (302ºF), the bending stresses will increase. To assess the implication of increasing the temperature in containment to 150°C (302ºF), reanalysis would have to be performed.

CONCLUSIONS AND RECOMMENDATIONS

As a result of the assessment, only inflatable airlock seals were identified as having the pressure capacity below the cracking pressure of containment concrete. Therefore, the pressure capacity of the containment is governed by the capacity of the inflatable airlock seals, which is 234 kPa-g (34 psig) for Trentec EPDM seals and 262 kPa-g (38 psig) for AECL DSA2 seals at a temperature of 150°C (302°F).

The estimated pressure capacity of containment extension portion of the 30” diameter Reactor Building (R/B) ventilation system ductwork is above the cracking pressure of concrete of 334 kPa-g (48 psig) at a room temperature. Higher temperature of the atmosphere inside the containment may result in a lower value for the pressure capacity of the ductwork.

Further work is recommended to estimate the pressure capacity of the containment extension portion of the R/B ventilation system ductwork at 150°C (302°F). It is also recommended to identify critical mechanical penetrations and to review individual stress reports of the system passing through these penetrations to assess their pressure capacity. Assessment of pressure capacity of mechanical penetrations of non-typical configuration, i.e., those including seal plates with bellows and those with more than a single pipe passing through is recommended. It is recommended to verify that actual gaps between the doors and doorframes of the airlocks at CANDU® 6 NPPs, especially those in the corners, are below the value for which inflatable seals are qualified. Assessment of pressure capacity of perimeter seals is also recommended. Further work is recommended to identify and assess pressure capacity of other containment penetrations/components, which were designed for a pressure of 18 psig (124 kPa-g).

REFERENCES

[1] MacGregor, J.G., Murray, D.W., Simmonds, S.H., “Behaviour of Prestressed Concrete Containment Structures”. INFO-0031 A Technical Report Prepared by The University of Alberta Department of Civil Engineering for the Atomic Energy Control Board, Ottawa Canada. May 1980.

Table 1
CANDU® 6 Airlock Door Seal Typical 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

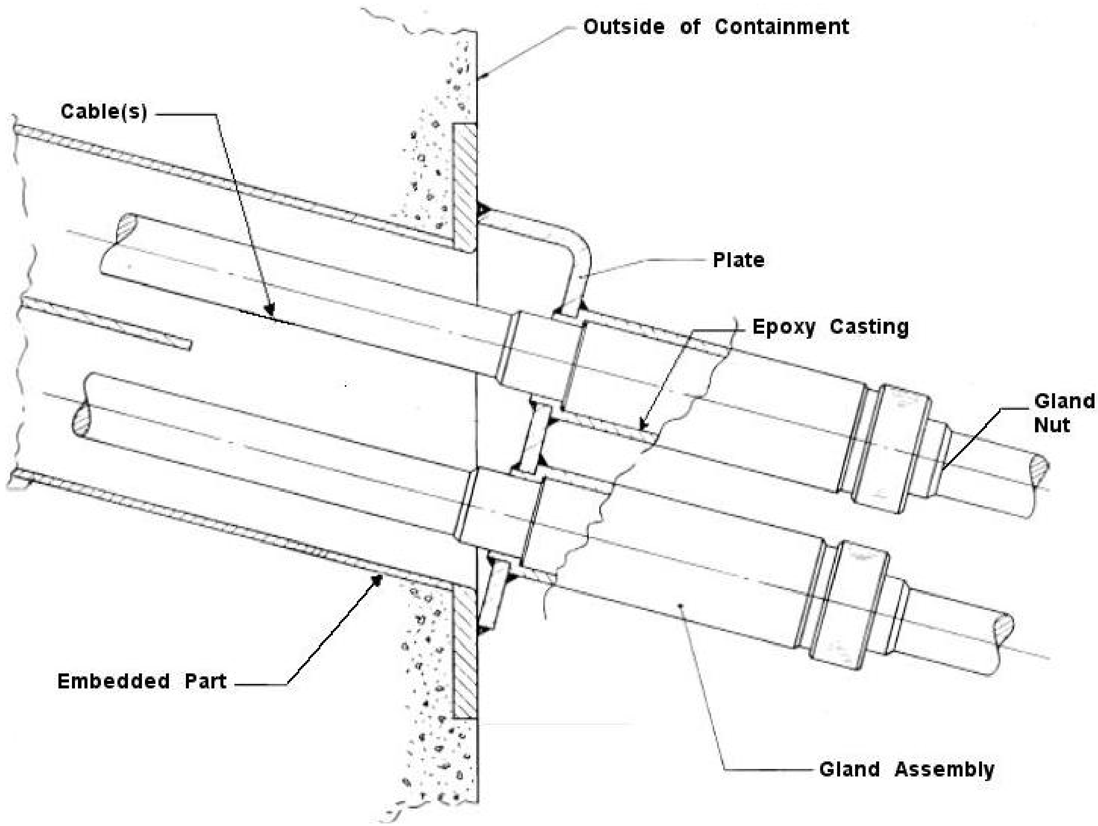


Figure 1 Typical Electrical Penetration

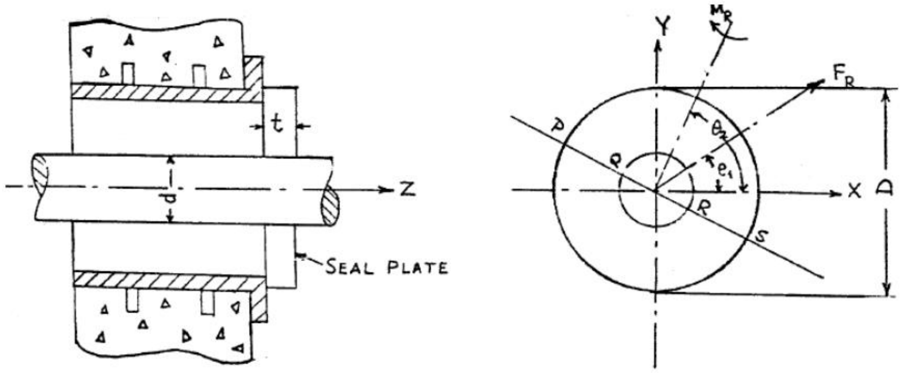
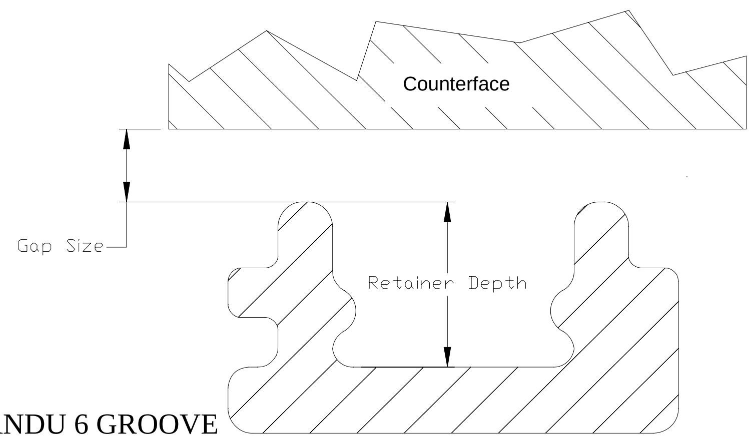


Figure 2 Typical Mechanical Penetration



STRAIGHT (0°) CANDU 6 GROOVE

Figure 3 Inflatable Door Seal Retainer in CANDU® 6 Plants

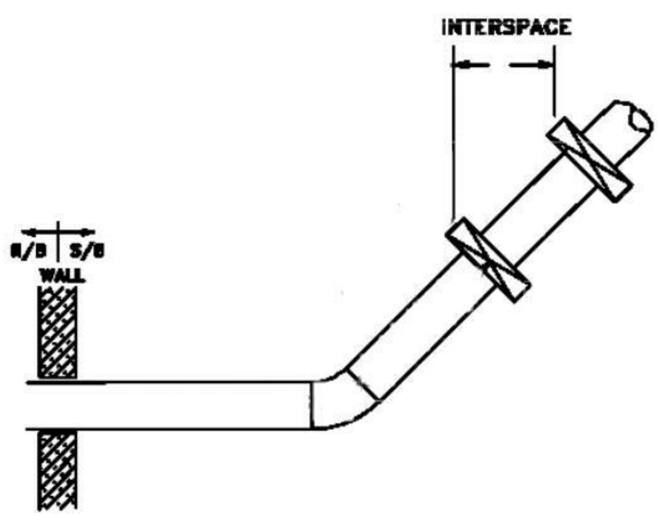


Figure 4 Typical Containment Isolation Valve Arrangement