ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPMP003

DEVELOPMENT OF REMOTE HANDLEABLE AXIALLY DECOUPLED RADIATION RESISTANT VACUUM SEAL*

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Abstract

Advanced Rare IsotopE Laboratory (ARIEL) facility is a major expansion of TRIUMF's rare isotope research program. Aiming to triple the production of rare isotopes, ARIEL facility includes the new electron linac driver and two target stations for electron and proton beams [1]. Particularities of ARIEL target stations design define the requirements for vacuum interfaces with both primary electron and proton beamlines and rare-isotope beamlines. None of the existing products fully met the requirements, driving the development of custom vacuum interfaces. The design of new vacuum seals is driven both by unique design specifications (limited amount of allowed axial forces, extreme radiation resistance, remote handleability and high repeatability) as well as limitations of the proposed design of beamline infrastructure in the target hall (limited available space and the choice of materials for certain components). This paper discusses preliminary results of the vacuum seal development and presents first results of prototype testing.

INTRODUCTION

ARIEL facility is a major expansion of TRIUMF's rare isotope research program. The target stations of ARIEL facility will employ electron and proton beams. An electron driver will be utilized to produce radioisotopes via photofission by irradiating Isotope Separator On-Line (ISOL) targets. Electron beam will be converted to gamma spectrum Bremsstrahlung photons via an electron to gamma (e-γ) converter located upstream of the ISOL target [2]. The anticipated lifecycles of both the e-γ converter and ISOL target define the replacement schedule of 4 weeks for both components, requiring a vacuum break interface at the driver beam side and RIB side of the target module with a maximal allowed leak rate of 1×10^{-5} Torr/L/s. High radiation fields in the vicinity of the e-γ converter and ISOL targets dictate remote handleability for replacement and maintenance activities of target infrastructure as well as all-metal design of components, including vacuum interfaces. The structural design of the target module and its alignment system limits the maximum allowed axial forces applied towards the target assembly by $\approx$ 800 N in the direction of driver beam, severely reducing commercially available solutions applicable for vacuum interfaces. Target replacement and maintenance schedules require that vacuum seals be capable of engaging and disengaging within minutes and maintain their leak-tightness over one year of operation.

A number of implementations of vacuum interfaces are being studied. This paper presents preliminary results of the development and testing of vacuum interfaces based on thin inflatable metal membranes.

DESIGN DEVELOPMENT

Evaluation of Existing Vacuum Interface Solutions

A number of existing solutions, each of which satisfies all but one requirement, were studied in an attempt to improve the characteristics of known vacuum seals in order to meet required criteria. Results are summarized in Table 1.

Table 1: Evaluation of Existing Vacuum Interfaces for ARIEL Target Modules Application

Sealing interface	Evaluation summary
elastomer-based seals	no known elastomers withstand 800 MGy per-run dose
soft-metal gasket seals	prohibitively high compression forces, low repeatability
spring-energized ("helicoflex")	prohibitively high compression forces, low repeatability
polymer based seals	some materials applicable at reduced radiation dose, e.g. PEEK
"pillow" seals	high initial cost, prohibitively large radial dimensions, prohibitively high axial forces
memory-metal based seals (CERN)	not commercially available, high cost per target replacement, limited aperture sizes available

Initial operational phase of the electron target station will utilize lower energy electron beam (up to 10 kW), reducing expected radiation doses to less than 10 MGy per run in the vicinity of vacuum interfaces. PEEK-based compression gaskets are being considered for initial runs. No existing solutions were found to be adequate for the full beam energy.

Design Approach

In order to meet the requirements of maximum permitted axial loads applied to the target module, a design approach of decoupling the vacuum sealing forces in the axial direction and using radial sealing surfaces was studied. Cylindrical mating surfaces can be engaged with virtually infinite contact pressure while exerting negligible axial forces. The concept

* ARIEL is funded by the Canada Foundation for Innovation (CFI), the Provinces of AB, BC, MA, ON, QC, and TRIUMF. TRIUMF receives federal funding via a contribution agreement with the National Research Council of Canada.

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is known and widely used in pneumatic and hydraulic applications (e.g. inflatable pipe plugs). However, a major challenge of achieving the radial deformations required for engagement of the vacuum sealing interface complicates its implementation using all-metal designs. Both mechanical and thermal driven deformations in metals are limited by their high elastic modulus and low thermal expansion coefficient. Design considerations limit minimal pre-engagement clearance by ≈ 0.1 mm per radius, thus defining the minimal required radial deformation. Achieving such deformations and providing contact stresses for vacuum sealing using conventional metals and alloys requires special design considerations. Possible solutions include reducing system stiffness by utilizing thin metal membranes inflated by internal pressure, or using thermally driven systems with high temperature difference between inner and outer components.

CERN's recent development of all-metal radial vacuum couplers utilizes shape memory alloys in order to achieve the high radial pressures required for UHV applications [3]. While an attractive solution, the implementation of this approach at TRIUMF is hindered by the extensive expertise required for manufacturing of shape memory alloys and the fact that this product remains in R&D stage of development at CERN. Further, the reliance of this technology on external electrical components to heat and cool the coupler elements required for activation of shape memory alloys is complicated by limited availability of electrical services and by γ-radiation induced heating of components in the vicinity of target module.

Due to a higher allowed leak rate for ARIEL target module vacuum interfaces (≈ 1×10^{-5} Torr/L/s), radial sealing with reduced contact pressures might be applicable. A simplified concept of inflatable metal membranes sealing against cylindrical surfaces was investigated for the application.

PROTOTYPE DEVELOPMENT

In order to confirm the feasibility of inflatable membrane coupling for ARIEL target module application, a set of performance indicators was defined to be verified.

In order to operate reliably and efficiently, the design and manufacturing process of the inflatable membrane coupler needs to satisfy the following criteria:

- ability to manufacture or procure thin (≈ 0.1 mm) aluminium or stainless steel cylindrical membranes;
- ability to produce leak-tight welds in between the membranes and cylindrical carriers.

Restricted by space limitations, the maximum diameter of the vacuum interface is set at 100–150 mm and the maximum length of the coupler in the axial direction is ≈ 300 mm (including the actuation system).

Based on these limitations, first prototypes of cylindrical membranes 60–110 mm in diameter and ≈ 0.12 mm (0.005 in) in thickness were manufactured for mechanical tests (Fig. 1 a). Two welding techniques were evaluated, TIG-welding of membrane edges using retaining rings and e-beam welding of membranes directly on cylindrical carriers. Edge welding was found to be satisfactory in the presence of two retaining rings (Fig. 1 b) and difficult to perform reproducibly with a single ring (Fig. 1 c) due to thermal deformations caused by the welding process.

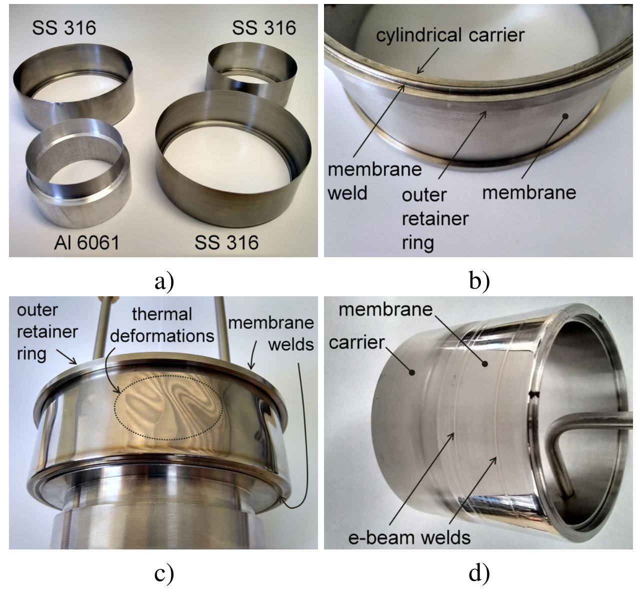

Figure 1: (a) aluminium and stainless steel test membranes; (b) membrane edge welded using two outer retaining rings; (c) membrane edge welded using single retaining ring; (d) membrane e-beam welded directly on its carrier.

Required membrane lifecycle was determined using the operational and maintenance schedule for ARIEL target facility. Based on one year operational runs, weekly e-γ converter and target vessel replacements, and assuming 10 engagement cycles of vacuum interface per replacement, a total of ≈ 500 cycles can be expected. A membrane fatigue wear test was set up to determine the maximal working pressure for 2000 cycles, implying a safety factor of 4.

In order to evaluate the applicability of inflated membranes as sealing elements in ARIEL vacuum interfaces, the following membrane characteristics were tested:

- usable range of radial deformations;
- maximal inflation pressure for a single inflation cycle;
- maximal inflation pressure for 2000 inflation cycles.

Ultimate Stress Test

In order to define the operational range of radial deformations, a single-cycle inflation-deflation test was performed at gradually increasing pressure setpoints with 2 psi steps using a membrane of ≈ 0.15 mm (0.006 in) thickness and 80 mm diameter. Deformations were measured around the circumference at the middle point of the membrane. Results (Fig. 2) demonstrate the following:

- residual deformations appear at pressures ≈ 300 psi;
- ultimate burst pressure is evaluated to be ≈ 500 psi;
- operational range of radial deformations grows steadily up to 300 psi and reduces due to accumulated residuals;
- average deformation per radius is 0.15 mm (0.006 in).

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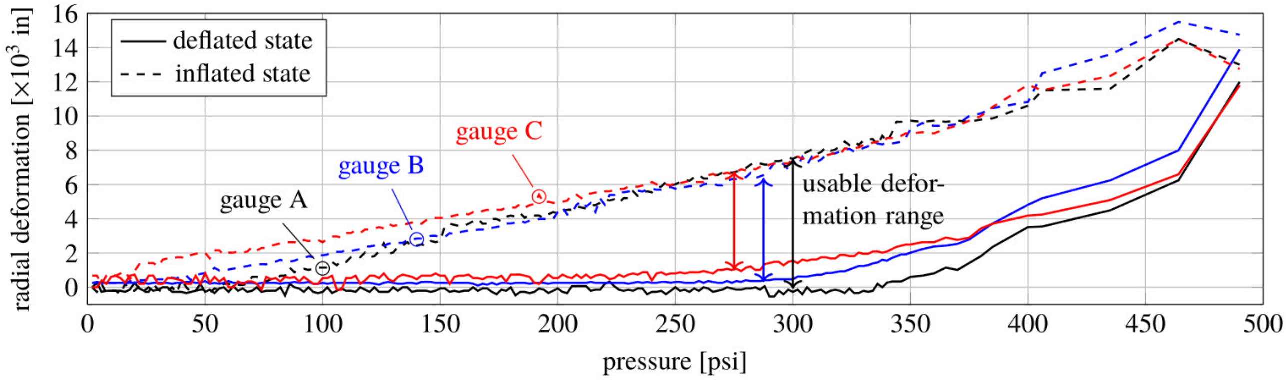

Figure 2: Pressure vs. radial deformation plots of single cycle membrane test.

Fatigue Stress Test

In order to define the maximum working pressure during continuous operation of the vacuum interface over an operational run, 2000 cycles inflation-deflation tests were performed at gradually increasing pressure setpoints with 10 psi steps using a membrane of ≈ 0.12 mm (0.005 in) thickness and 110 mm diameter. Deformations were measured around the circumference at the middle point of the membrane continuously during both inflation and deflation processes in order to observe pressure vs. deformation characteristics and their deviation from linear dependence. Results (Fig. 3, 4) demonstrate the following:

- residual deformations appear at pressures ≈ 200 psi;
- fatigue cracking of the membrane was found at 270 psi;
- operational range of radial deformations grows steadily up to 200 psi and reduces due to accumulated residuals;
- average deformation per radius is 0.25 mm (0.010 in).

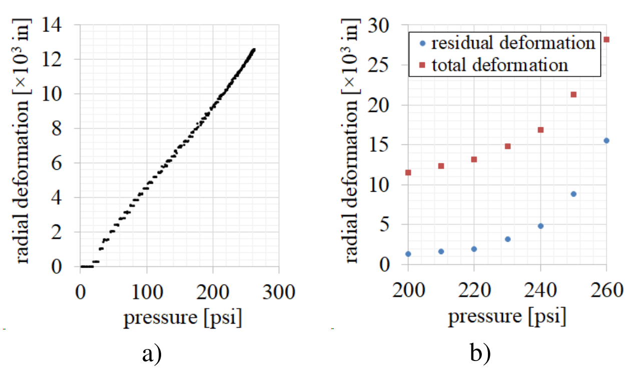

Figure 3: (a) pressure vs. deformation characteristic measured during 2000 inflation cycles up to 260 psi; (b) total and residual deformations after 2000 cycles at various pressures.

The established membrane lifecycle confirms the feasibility of the vacuum interface concept. Different welding techniques were utilized for the membrane assemblies between tests and it is therefore not possible to directly compare the radial deformations between the single-cycle and 2000 cycles tests. The edge-welded membrane was observed to cause uneven radial deformations around its circumference. Further investigation is required in this regard.

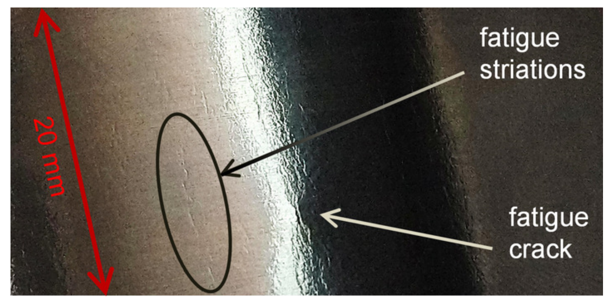

Figure 4: Membrane fatigue aging and failure.

CONCLUSION

Mechanical testing of the membranes confirmed the feasibility of the vacuum coupler concept based on inflatable membrane sealing interfaces. Required radial deformations were achieved at pressures ≈ 1/2 of the expected burst pressure. One year operational runs are achieveable according to fatigue test results without the risk of membrane failure.

ACKNOWLEDGMENTS

Authors would like to express their gratitude to Kevin Trithardt and Edi Dalla Valle for their support in manufacturing of metal membranes and test fixtures, and to TRIUMF Machine Shop for their continuous support with design and production of prototypes.

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