A NEW CANDU CHANNEL CLOSURE WITH A CONICAL SEAL

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ABSTRACT

A new channel closure is under development for future CANDU reactors. It takes up less radial space by using a conical all-metal sealing element that rotates and flexes for insertion and retraction. It seals using a face seal on both ends of the sealing element and is pressure energized over the entire working range of pressures. This seal element has many of the practical attributes of a bore seal such as was used in Gentilly-1, but is not limited by the tight tolerances and large strain range required to seal on the actual inner diameter of an end fitting. A major benefit of maintaining a constant bore diameter throughout an end fitting (with about 3 mm radial increase at the sealing area) is to permit refuelling without using a guide sleeve. The same seal design is readily adaptable to a larger end fitting diameter and could be used as part of a proposal to retube a CANDU reactor at mid-life without removing the end fittings. The sealing element has been tested over a wide range of test conditions appropriate to primary heat transport conditions of a CANDU reactor. A full-scale model of the new channel closure is under test.

1. INTRODUCTION

A research program was undertaken at Chalk River Laboratories to revisit the topic of a bore-seal channel closure, such as used in Gentilly-1[1], to replace the face-seal channel closure in current CANDU reactors. This program was initiated because there has been recognition[2] for many years of the potential values of a bore seal channel closure for use in future CANDU reactors. Some of the benefits include: elimination of guide sleeves and insertion tools, reduced ram loads and clamping loads which, in turn can lead to reduced seismic qualifications. It may also be possible to reduce the lattice pitch between the adjacent fuel channels. If these potential features can be achieved then in the longer term one can hope to design a simplified fuelling machine.

A bore-seal channel closure was used in Gentilly-1 and in several other prototype reactors around the world, designed about the same time. The main difficulty with bore seals of this type is the large change in diameter needed for the sealing element. The high temperatures – above 300°C at the outlet end fitting – preclude the use of elastomers as sealing elements. Metals have an elastic range of typically 0.2 to 0.35 percent strain which for a nominal 102 mm (4″) diameter translates to only 0.2 to 0.36 mm (0.008″ to 0.014″) expansion - retraction. Other concerns were expressed about the reliability of using a channel closure of the Gentilly-1 design for routine on-line refuelling, especially when used with horizontal pressure tubes in a CANDU reactor. Because of these concerns, the research program focused on metal seal designs that required out-of-plane motion in the seal to permit greater radial accommodation than was available from radial strain.

The channel closure under development is equally adaptable to a larger end fitting diameter. One proposal[3] is to use a 131 mm (5.15") clear internal diameter in an end fitting which is sufficiently large to permit an old pressure tube to be withdrawn at mid-life of a CANDU reactor and a new one installed without removing an end fitting.

2. CANDU CHANNEL CLOSURE

The CANDU 6 reactor utilizes 380 individual fuel channels consisting of a zirconium (2.5% niobium) pressure tube connected to two end fittings. Figure 1 shows a schematic drawing of a typical fuel channel. The coolant flow is through the input feeder (3), past the fuel bundles (8) and out the exit feeder (3). A channel closure (1) is used at each end of a fuel channel to provide a leak-tight seal of the heavy water in the channel at operating conditions that range from near room temperature at 0.2 MPa up to 300°C and 11 MPa. The channel closure forms part of the fuel channel pressure boundary and as such must comply with the requirements of the ASME Pressure Vessel Code for Class 1 Nuclear Power Plant component. It also must be remotely handled with a fuelling machine using only axial motions of rams.

The present CANDU 6 channel closure seals on a closure seal insert (2). A large preload force is provided by the fuelling machine to produce the initial seal against the seal insert and as the hydrostatic pressure is increased, the sealing force is increased. The internal diameter of the end fitting is larger from the entrance until the seal insert and then a nominally constant diameter is used throughout the fuel channel. During fuelling operations, the channel closure is removed by the fuelling machine and an guide sleeve is installed to maintain a constant diameter for fuel passage. Guide sleeves have been a source of recurring problems during refuelling and could be eliminated with a new channel closure – a significant benefit.

The existing channel closure (1) has had many years of reliable operation. Any new design must meet the same high performance as well as introducing some useful new features. It is expected that the new channel closure will be able to achieve these admittedly challenging goals.

3. THE FILSEAL

After some initial investigation, the research program focussed on development of an old idea - a seal element based on non-axisymmetric bending to achieve radial accommodation. One seal element that met these requirements was proposed and patented by P. Stubley[4] about 20 years ago, but has never been developed. The principle of operation of this seal, called the "filseal", is shown in Figure 2. The sealing element is machined as part of a cone whose diameters are such that it can be installed and removed by rotating out of its sealing plane and flexing into an elliptical shape that clears the bore diameter, as shown in Figure 2. If the seal element is made from a high-strength material, it can be manipulated as shown without exceeding the elastic limits of the metal and be removed and reinstalled many times. The seal disk must be held against the seal element with some preload force to provide initial sealing at low pressures. The water pressure in the fuel channel increases the sealing force.

4. SEAL DEVELOPMENT

4.1 Seal Element

The first part of the research program was concerned with the details of the sealing interface. A conical seal element was developed whose thickness and length represented a compromise between (i) the force required to produce sufficient elastic deflection to install the seal element, and (ii) the hoop stress in the seal over the full operating pressure range. Several different shapes were tested before the shape shown in Figure 3 was produced. The seal element is made as part of a cone with an angular difference between the seal element and the mating surfaces causing initial sealing contact at the outside edge. There was a significant effort placed on the development of the specifics of the sealing interface angle. There must be some angular difference between the seal element and the interfacing surfaces in order to maintain a leak-tight seal at low hydrostatic pressure and a low preload force. Since this seal design is pressure-assisted over the full operating range, the sealing properties at low pressure are particularly important. As the interface angle is increased, the preload force decreases. However, the loading at high pressure can become sufficient to produce damage to a sealing surface. A number of load tests were done at different interface angles and the results correlated with hydrostatic tests to arrive at a good compromise. Tests were also carried out at very high loads (nearly 4 times the force at operating pressure) to try to determine a failure mode of the sealing components. A small permanent deformation of the end fitting was produced - with no indications of damage to the seal element or seal disk. These tests give good confidence that the sealing components can withstand severe loading.

The seal element was also distorted into an elliptical shape on a MTS 810 Material Test System to check the force required to deflect it for installation, and to test that this distortion did not exceed the elastic limits of the material. Seal elements of 103, 112 and 131 mm diameter were tested. Two seal elements were deflected through this same cycle for 500 repeats, more than required for the useful lifetime of the channel closure. There was no permanent set after these test.

4.2 Hydrostatic Tests at Room Temperature

After a series of load tests had demonstrated that a conical seal element would meet the required mechanical loads, a hydrostatic test fixture, illustrated in Figure 4, was built. This was used to measure leak rates while sealing water from 0.2 to 21 MPa (15 to 3000 psig) at room temperature. The outer housing was made from annealed 403 stainless steel with the same nominal internal diameter as in use for present CANDU end fittings. The threaded plug was designed to mate with this hub and seal the required pressures. A 12.7 mm (0.5″) diameter stainless-steel rod was used to apply a preload force to the seal disk via Belleville washers and the brass plate. In a separate experiment, the load vs. deflection of the Belleville washers was measured with a calibrated load cell.

The sealed volume was filled with water and pressurized using a hand-operated hydraulic pump. The leak rate was monitored by measuring the pressure drop over some time period. The volume change was measured as a function of pressure drop in a separate experiment. Table 1 shows estimates of the maximum leak rate for selected pressures and preload forces. This seal design is inherently pressure-assisted and the most difficult pressure regime to seal reliably is near one or two atmospheres. Once a preload force of 5.3 to 6.6 kN (1200 to 1500 lbf) was applied, there was no measurable leakage over the pressure range from 0.2 to 11 MPa (15 to 1600 psig). Tests were also run at about 15 to 19 MPa. The system was also cycled at least 100 times between 0.2 and 11 MPa with a 5.3 kN preload force. During these tests the seal element was removed and replaced a number of times to simulate refuelling operations.

After these tests the seal was disassembled and inspected with a high-quality optical microscope. There were no visible marks on the seal element or seal disk – the seal surface inside the mock-up end fitting could not be measured. During all of these tests - and many others that are not reported - there was no re-machining of the sealing surface of the end fitting and the system re-sealed with about the same preload force.

4.3 High Temperature Tests

The silicon O-ring in the high-pressure test rig limited the maximum testing temperature to about 250°C, for short testing periods. To overcome this limitation, a new test chamber was built that had no O-rings. This chamber was tested in an oven at pressures approaching 10.4 MPa (1500 psig) and temperatures near 300°C. Figure 5 shows the data from this test covering 100 hours and three cycles to nearly 300°C. Water was supplied from a cylinder of about 5 litres volume that was one-half filled with water and pressurized with nitrogen. The solid line shows the temperature while the dashed line shows the pressure. After the initial temperature increase to 285°C, the nitrogen was valved off and the water supply was isolated for the rest of the test period. The pressure (near room temperature) remained nearly constant indicating that there was very little leakage during the last 60 hours of the test.

5. SEAL INSERTION

In order to use the seal components as part of a channel closure, a reliable method to insert and extract the sealing components is required that is also compatible with the axial motions of a fuelling machine. A seal insertion tool to permit control of the sealing element during insertion, extraction and storage was designed, and a prototype built and tested. Figure 6 shows two photographs of a simulated end fitting with a seal element and seal disk. The upper photograph shows the seal disk at the entrance to the end fitting. The seal element is rotated about 45° ready for insertion. The lower photograph shows the seal element partially inserted into the end fitting. The seal element and disk can then be pushed into an end fitting until the region where the seal element will be seated. The seal element is rotated back into a cylindrically symmetric cone and the seal disk is pulled into contact with it to provide a preload force. This insertion tool was tested through the number of seal insertions that would occur in a 30-year lifetime. The seal element displayed no permanent set after these tests.

6. CHANNEL CLOSURE

A prototype of a complete channel closure was built to fit a 103 mm (4.07") diameter end fitting. The axial motions required for insertion and extraction of the channel closure are compatible with a CANDU 6 fuelling machine. Figure 7 shows a photograph of this channel closure with the seal element rotated in preparation for insertion into an end fitting. In this view, a fixture that provides the axial motions of a fuelling machine is attached to the right-hand end of the channel closure. The jaws are withdrawn and the seal disk is advanced about 2 cm to permit the seal element to rotate. Figure 8 shows two close-up photographs of the seal disk and seal element ready to be installed (lower photograph) and in the installed position (upper photograph). The conical seal element is now in the relaxed state with a diameter larger than the bore diameter.

This channel closure has been tested in both a plastic and a 304 stainless steel mock-up end fitting. There have been at least 100 insertions and extractions without any mechanical difficulties. It has sealed reliably at room temperature at pressures from 0.1 to 11 MPA (15 to 1600 psig) with about 6 to 7 kN preload force. It has been cycled to 300°C and back to room temperature without water. All of the mechanical operations were still reliable. Tests are planned with pressurized water at 300°C.

7. CONCLUSIONS

A new channel closure is under development that uses a conical sealing element to seal with only a small radial increase in bore diameter in the region of the seal. This combines the benefits of a true bore seal with the advantages of a pressure-assisted face seal. A technique has been developed to insert and retract this seal reliably. Experiments have been completed to demonstrate reliable operation of the seal element for three different end-fitting diameters and over the full operating range of pressure and temperature of the primary heat transport system of a CANDU reactor. Many tests have been done to optimize the sealing interface including surface treatments of the end fitting. A complete channel closure, compatible with present CANDU 6 fuelling machines, has been fabricated and tested over most operating conditions. This new channel closure has the potential to be part of significant new developments of a CANDU reactor.

8. ACKNOWLEDGEMENTS

The author would like to acknowledge W. Bentz for the valuable technical assistance and also N. Wilson for both useful input to the program and especially the loan of components developed for the CANDU 3 reactor that were used as part of the channel closure.

9. REFERENCES

1. R. Pocock and K.L. Smith, "Gentilly Nuclear Power Station Fuel Channel Design Submission", BLW-250 Note 47, Appendix 3, 1967.

2. R.K. Nakagawa and D.J. Koivisto, "Bore Seal Channel Closure Preliminary Investigation", 95-35000-400-071, Rev. 0, 1989.

3. S. Kuran, A. Muscat, B.J. Gracie, R.J. Gunn, M. Cobanoglu, and C. Yager, Future CANDU Fuel Channel Retubing; Pressure Tube Only Replacement (PTOR), this conference.

4. P.H. Stubley, Flexibly Installed Seal Closure, Patent # 1027886, 1975-05-08.

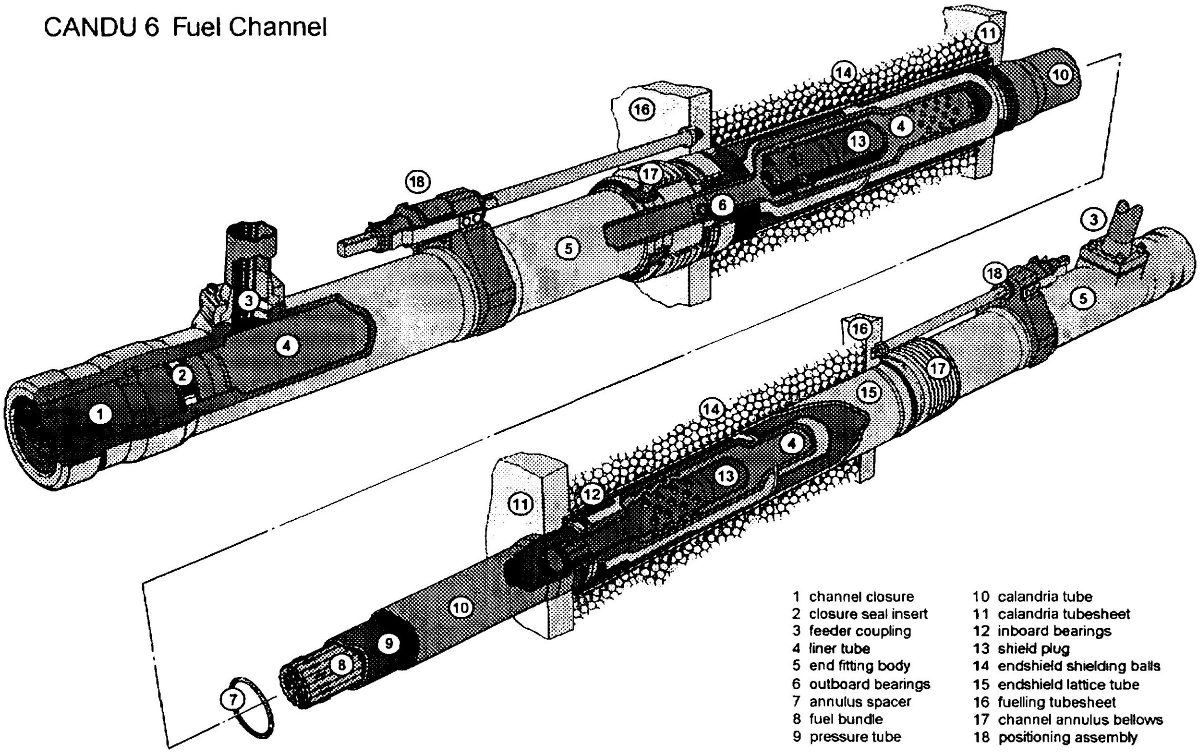


Figure 1. A CANDU 6 Fuel Channel. A channel closure (1) is used at both ends of each fuel channel to seal the heavy water at 300°C and 11 MPa.

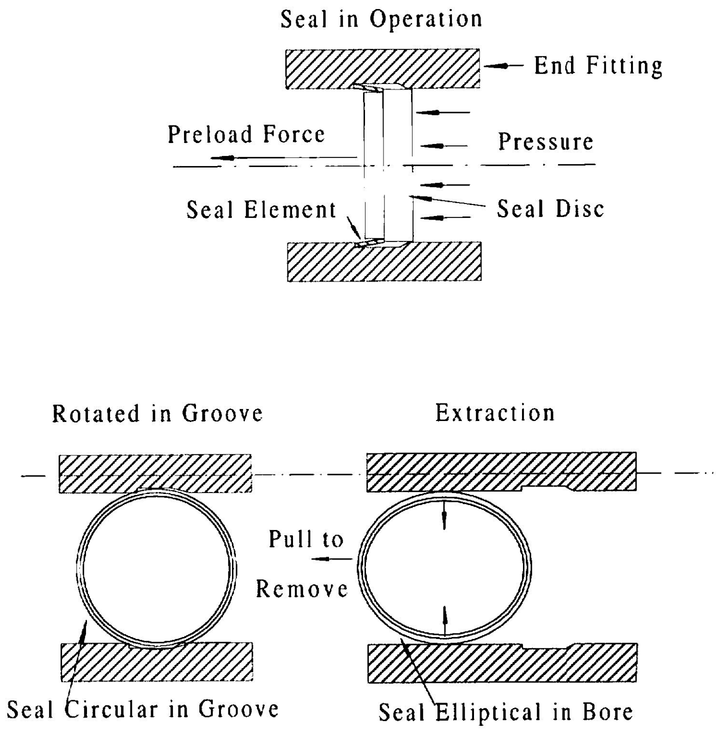


Figure 2. Principle of a seal designed by P. Stubley[4]. A conical seal element is distorted into an oval shape for extraction (insertion) from a bore with a smaller diameter than the unflexed conical ring.

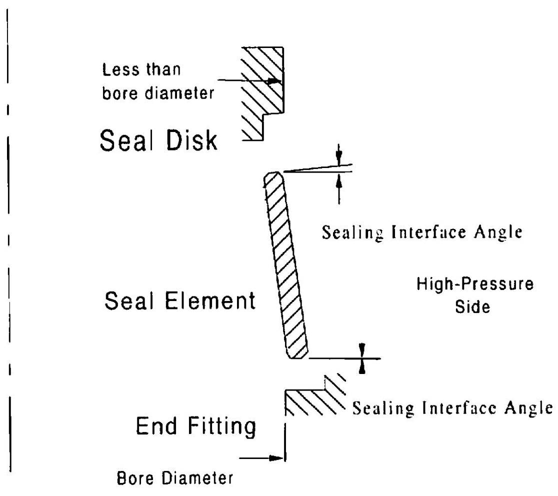


Figure 3. Cross-Sectional Details of the Seal Element.

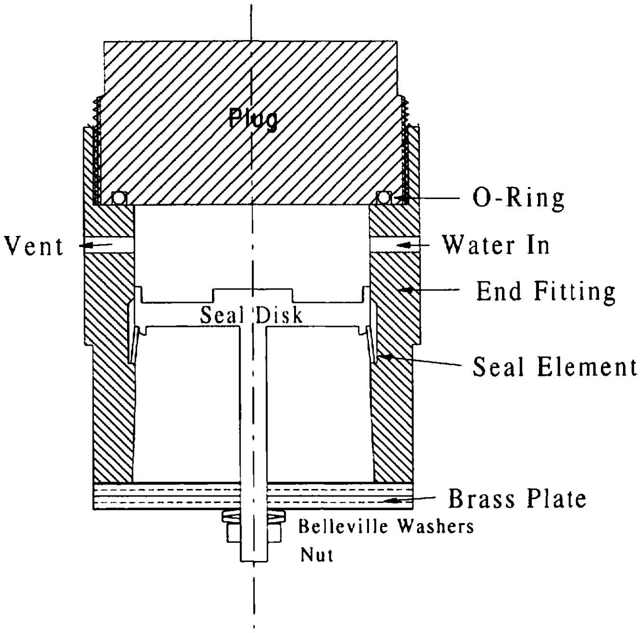


Figure 4. A Test Fixture for Hydrostatic Tests of the Filseal.

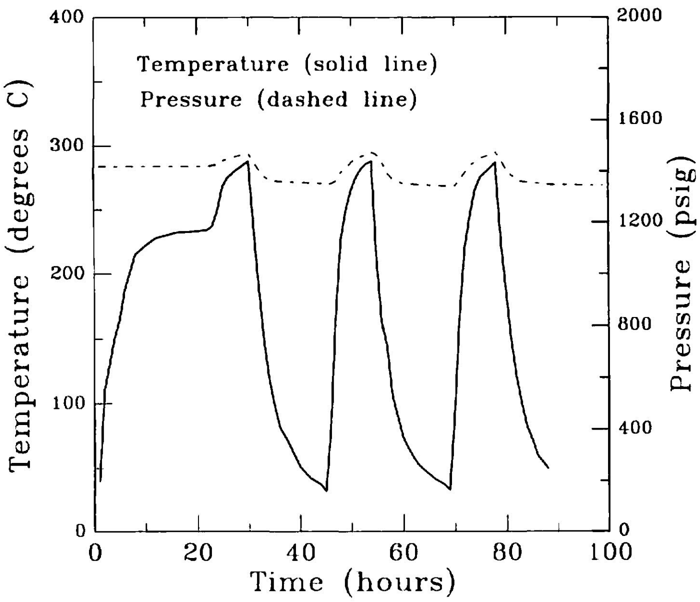
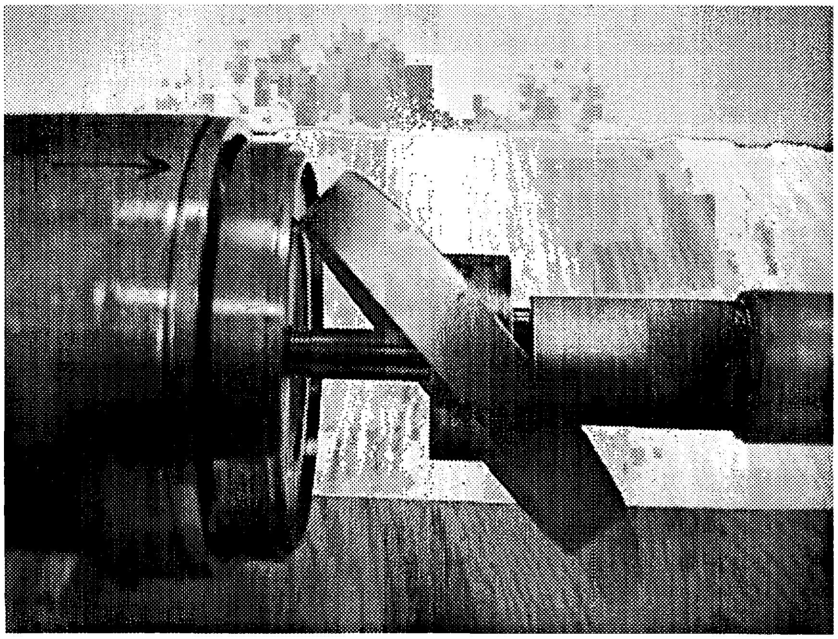


Figure 5. Test at Primary Heat Transport Conditions.



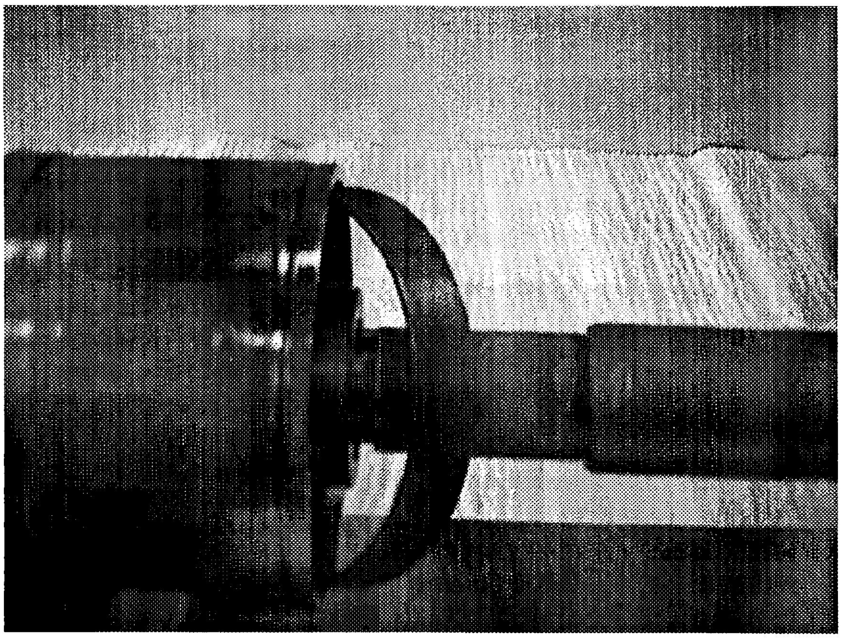


Figure 6. Tests of Installation and Extraction of the Seal Element and Seal Disk. The upper photograph shows the seal disk at the entrance of an end fitting with the seal element rotated into insertion position. The lower photograph shows the seal element partially inserted into the end fitting.

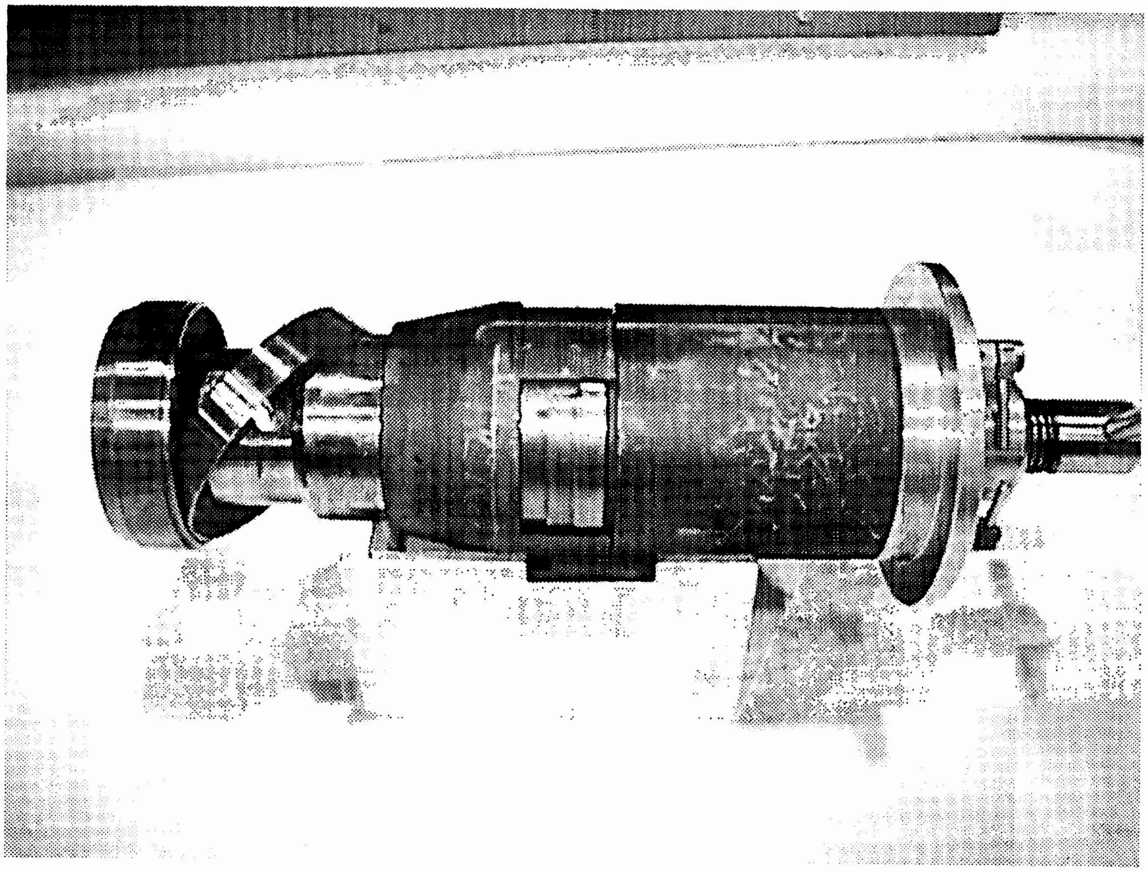


Figure 7. Channel Closure Utilizing a Conical Seal Element. This photograph shows the seal element rotated into position for insertion or extraction. The fitting at the right-hand end provides the axial motions of a fuelling machine.

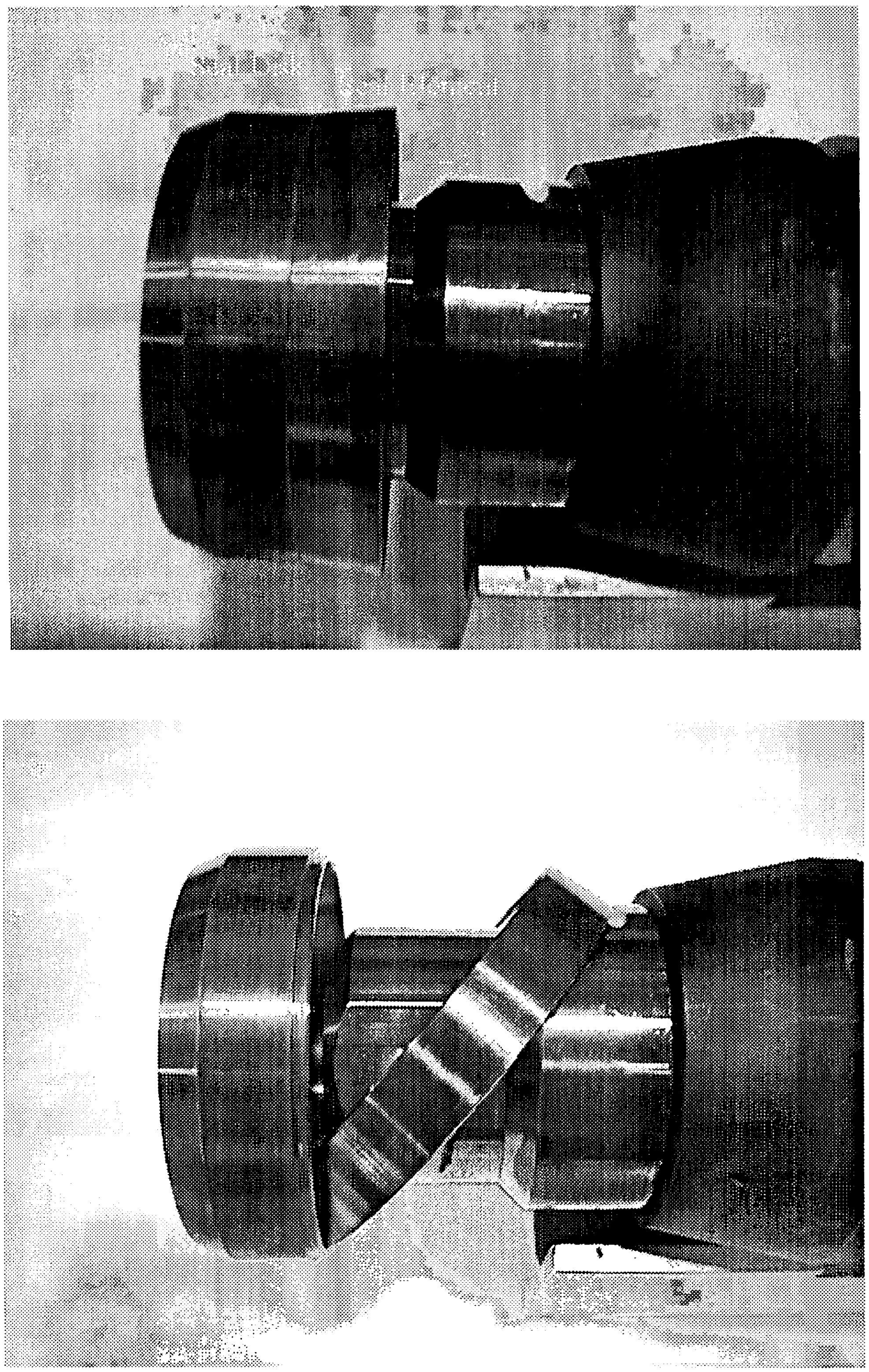


Figure 8. Close-up of the Seal Disk and Seal Element. The upper photograph shows the seal in the installed position and the lower photograph shows the seal element rotated for insertion or extraction.