

Experimental and Finite Element Analysis of High Pressure Packer Elements

by

Stephanie Berger

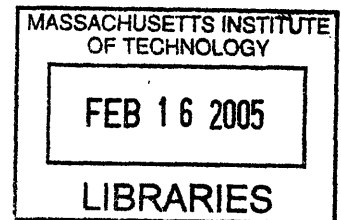
B.S., Materials Science and Engineering
Massachusetts Institute of Technology, 2003

Submitted to the Department of Materials Science and Engineering
in Partial Fulfillment of the Requirements for the Degree of

Masters of Science in Materials Science and Engineering
at the
Massachusetts Institute of Technology

September 2004

© 2004 Stephanie Berger. All rights reserved



The author hereby grants MIT permission to reproduce and to distribute publicly paper and electronic copies of this thesis document in whole or in part.

Signature of Author.....
Stephanie Berger
Department of Materials Science and Engineering
July 23, 2004

Certified by.....
Ali S. Argon
Professor Of Mechanical Engineering
Thesis Supervisor

Certified by.....
David K. Roylance
Professor of Materials Science and Engineering
Thesis Reader

Accepted by.....
Carl V. Thompson
Stavros Salapatas Professor of Materials Science and Engineering
Chair, Department of Committee on Graduate Students

ARCHIVES

Experimental and Finite Element Analysis of High Pressure Packer Elements

by

Stephanie Berger

Submitted to the Department of Materials Science and Engineering on

July 23, 2004

in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Materials Science and Engineering

ABSTRACT

Packer elements are traditionally rubber seals that can operate under specified downhole conditions and provide a seal for either a short-term, retrievable, or a long-term, permanent, completion. In this case a retrievable 19.7cm (7-3/4") packer element for a high-pressure high-temperature (HPHT) environment was designed and tested. The element created a seal between the mandrel, or tubing, and the casing. At high temperature and pressure rubber needs to be contained so that it will create and maintain an energized seal. In this study only Aflas rubber was tested. Various backup systems were examined; some more traditional designs such as the carbon steel foldback ring were compared to more experimental ideas. Results of theoretical simulations were compared to actual test results in order to gain a greater understanding of element behavior. Experiments were also performed to study the process of element setting, which is difficult to observe due to the high pressures and temperatures required. In a related study alternative materials to rubber such as annealed high-conductivity oxygen-free copper were tested to determine if the properties could be applied for packer element applications. The most successful design was the foldback ring with an anti-extrusion PEEK ring under the gage ring. This design passed a liquid test at 134 MPa (19.5k psi) differential pressure and a gas test at 87.6 MPa (12.7k psi) differential pressure. New designs such as the split ring with mesh and the garter spring with mesh did not pass fixture tests but could be successful with further modifications. FEA was used as an analytical tool to create simulations of the element after a setting force is applied. The modeling was shown to correlate to the actual test results and therefore it would be a good tool to use in future studies.

Thesis Supervisor: Ali S. Argon

Title: Professor of Mechanical Engineering

Acknowledgements

I would like to thank my supervisor at MIT, Professor Argon for guiding me throughout this program. This project was accomplished with the help and support of many engineers and employees at the Schlumberger Product Center in Rosharon, Texas. Mainly I owe thanks to my supervisor, Dr. Yanmei Li who had the patience to explain the world of packers and to help me tackle many challenges. Also, I would like to thank Dwayne Leismer who created this opportunity. Most importantly I would like to thank my family and friends for their love and support.

Table of Contents

Abstract	2
Acknowledgements.....	3
Table of Contents.....	4
Chapter 1 Background.....	6
Chapter 2 Seal Designs and Materials	8
2.1 Element Designs	8
2.2 Materials	9
2.2.1 Aflas@.....	9
2.2.2 Fluoroelastomers.....	10
2.2.3 Carbon Steel	11
2.2.4 Wire Mesh	11
2.2.5 Polyetheretherketone	11
Chapter 3 Testing Procedure.....	12
3.1 Element Fixture Tests.....	12
3.1.1 Liquid Tests	12
3.1.2 Gas Tests.....	12
3.2 Element Setting Tests	13
Chapter 4 Results	14
4.1 Summary	14
4.2 Foldback Ring Design	14
4.3 Mesh Designs	15
4.3.1 Two piece mesh	17
4.3.2 Triangular mesh	18
4.4 Split Shoe with mesh	18
4.5 Garter Spring with mesh	19
Chapter 5 Discussion	20
5.1 Foldback Ring Design	20
5.2 Mesh Designs	21
5.3 FEA Study.....	22
Chapter 6 Further Research	22
6.1 Fiber Reinforced Rubber	22
6.2 New Mesh Designs	22
Chapter 7 Conclusions and Recommendations.....	23
Appendix and References.....	25

List of Figures

Figure 1. Schematic cross-sectional drawing of an element in a test fixture.....	7
Figure 2. Components of foldback ring element.....	8
Figure 3. Cross-section of gage ring with PEEK.....	9
Figure 4. Cross-section of end element with mesh ring.....	9
Figure 5. Chemical structure of an Aflas monomer.....	10
Figure 6. Cross-section of three-piece element with foldback ring.....	14
Figure 7. Cross-section of successful foldback ring design using PEEK rings under the gage ring.....	15
Figure 8. Cross-section of foldback ring element with anti-extrusion ring.....	16
Figure 9. Cross-section of an element with a mesh and split-ring backup.....	19
Figure 10. Cross-section of element with garter spring and mesh backup.....	19
Figure 11. Chemical Structure of PEEK.....	25
Figure 12. Chemical Structure of Viton®.....	25
Figure 13. Chemical Structure of Kalrez®.....	25
Figure 14. Chemical Structure of HNBR.....	25
Figure 15: Temperature Degradation of Aflas.....	25
Figure 16. Drawing of Element Test Fixture.....	26
Figure 17. Foldback Ring with contact markings from Test S-5.....	26
Figure 18. Extrusion markings on end element from Test S-11.....	26
Figure 19. Gas bubbles protrude from center element in test S-14.....	27
Figure 20. Foldback Ring from test S-15.....	27
Figure 21. Data from test S-9 (passed liquid test).....	27
Figure 22. Data from test S-9 (failed liquid test).....	28
Figure 23. Element setting test with acrylic tube.....	28
Figure 24. Element setting test using casing with windows	28
Figure 25. Element setting test fixture with acrylic tube.....	29
Figure 26. FEA of element from test S-5, S-11, and S-14.....	29
Figure 27. FEA of element from test S-2.....	29
Figure 28. FEA of element from test S-6.....	30
Figure 29. FEA of element from test S-12.....	30

List of Tables

Table 1. Typical properties of Aflas.....	10
Table 2. Critical Dimensions of Test Fixture.....	13
Table 3. Summary of Fixture Test Results.....	21
Table 4. Typical Mechanical Properties of Kalrez®.....	25

Chapter 1 Background

The goal of this project was to qualify an element for a 19.7 cm (7-3/4'') packer tool under high pressure and high temperature conditions. Secondary considerations include a low setting force to secure the element and the retrievability of the system. The section of the packer tool that is being examined is the portion shown in Figure 1. The gage rings are metal rings that surround the element on either side. The gage ring that applies force to the element is called the dynamic gage ring while the other is known as the static gage ring. In this particular packer the dynamic ring is on the downhole side, which is furthest from the surface. This positioning means that the element is set from below. Setting is the process of applying pressure from the dynamic gage ring to compress the element and form a seal. The seal forms between the mandrel and the casing, which is the outer tube that surrounds the mandrel. It is important to seal the space between the two tubes to create a pressure differential for the conveyance of oil through the mandrel. In this case the desired pressure differential is 103 MPa (15,000 psi) over a temperature range of 135°C (275°F) to 218°C (425°F). In order to qualify, the element must pass a test with a liquid media, and a gas media. These tests are known as V3 qualification and V0 qualification respectively.

In order to confirm that the elements pass V3 and V0 tests they must be tested in an environment that simulates the downhole conditions of the packer tool. The elements are tested in a test fixture such as those seen in Figure 16. The setting force, temperature, and differential pressure can be controlled and monitored through a software control program.

The process for qualifying a packer element begins with selecting the type of backup system. In this study several variations were examined such as foldback rings, mesh rings, garter springs, and combinations of these. The geometry and hardness of the rubber ring are critical to whether the element will seal. The hardness of rubber is called the durometer, which is measured on an increasing numerical scale. The term durometer refers to an instrument used to measure the indentation hardness of the rubber. The test is scientifically known as the Shore A hardness test. This value does not indicate other mechanical properties such as strength or wear resistance but it is often used to classify the rubber. The test is described in ASTM D2240 00 [1]. Some designs use only a one-piece center element while others have three pieces. Usually a three-

piece element will have the low durometer rubber ring in the center for sealing and the higher durometer rubber on the ends.

For testing the element is placed in a test fixture where it can be heated to the specified temperature. A setting force is applied from the dynamic gage ring, which presses the element against the static gage ring. The force causes the element to deform to the casing where it creates a seal. The backup system must completely contain the rubber so that the seal remains effective. A differential pressure of either liquid or gas is applied to the element to test the strength of the seal. A complete reversal involves testing the seal by applying pressure from both the dynamic and static sides. A schematic of the test fixture is shown below.

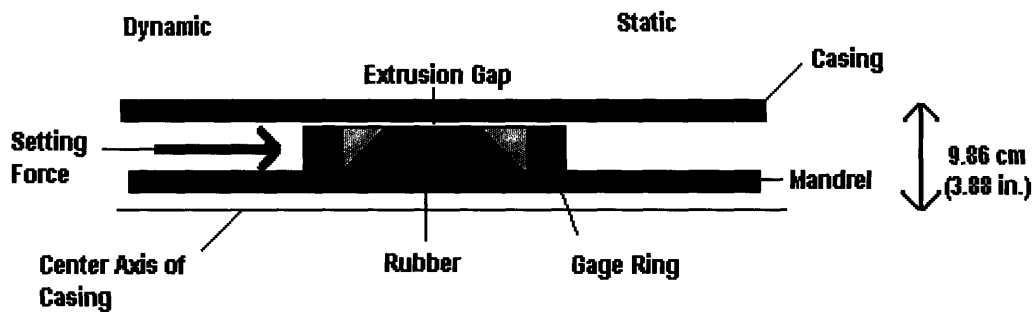


Figure 1. Schematic cross-sectional drawing of an element in a test fixture.

In order to be effective the rubber must completely fill the space between the mandrel and the casing. This dimension is referred to as the difference between the inner diameter (I.D) of the casing and the outer diameter (O.D.) of the mandrel. Another term for this space is the extrusion gap. A common problem with elements is that if the rubber extrusion is not contained to the space between the gage rings then it will flow through any leak path and there will be a loss of rubber volume over time. The loss of volume can cause the seal to leak. If leakage occurs the entire packer tool must be removed and replaced which is very costly and time-intensive. Extrusion can occur if there is any leak path available to the rubber. Therefore, it is important to have anti-extrusion devices, particularly with a rubber that tends to flow at high temperatures, such as Aflas.

Finite Element Analysis (FEA) is a theoretical mathematical simulation of certain material geometries under an applied load. In this study the ABAQUS[®] FEA code was used as a tool to analyze element deformation after the setting force is applied. The FEA could not be used to simulate the differential pressure and therefore the results were an approximation. The

theoretical results were compared to results of element fixture tests to see if the FEA software was capable of predicting the success or failure of certain element designs.

The goal of this project was to examine various element designs and determine which components lead to a successful element. Some problems that were encountered in the past were that the backup rings would not deform sufficiently, the rubber would extrude, or the center element would buckle. Buckling occurs when the element is too long and deforms inward instead of towards the casing. General knowledge about what causes certain designs to fail is not readily available. This project aimed to combine experimental testing and computer simulations to determine common causes of success and failure as well as what aspects should be considered when creating new designs.

Chapter 2 Seal Designs and Materials

2.1 Element Designs

The foldback ring design usually consists of a three piece rubber element with a low durometer center surrounded by higher durometer ends. The high durometer pieces serve to protect the center element and move it outwards to form a seal. The foldback rings are annealed carbon steel and deform under the pressure of the setting force. By contacting the casing they prevent extrusion of the rubber. Some of the problems associated with this design are that often a very high setting force is required and it can be difficult to retrieve the packer due to the strength of the steel foldback rings.

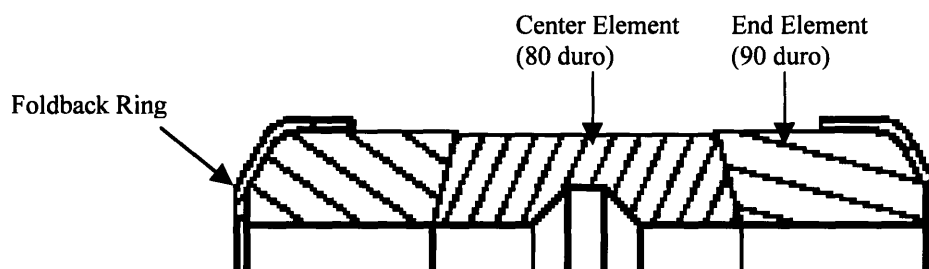


Figure 2. Components of foldback ring element.

Modifications to the basic design can be made to prevent extrusion. For example, small anti-extrusion rings can be placed underneath the end element or the gage ring, which is adjacent to the element. Examples of this can be seen in Figures 3 and 4. The PEEK ring will expand at high temperatures and fill any possible leak paths.

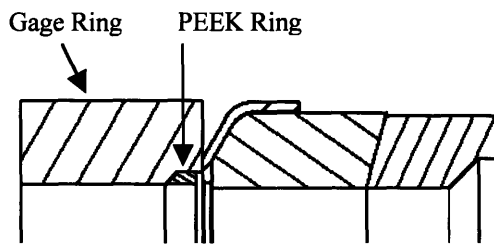


Figure 3. Cross-section of gage ring with PEEK.

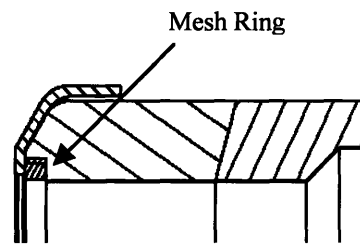


Figure 4. Cross-section of end element with mesh ring.

The mesh design usually contains a one piece rubber element of low durometer. One advantage of mesh rings is that they should theoretically require less force to deform because of the extra air volume. The disadvantage of the mesh design is that in reality it is difficult to deform the mesh rings so that they form a complete seal. Also the deformation of the mesh ring is not reversible so it cannot recover if the rubber contracts due to temperature changes.

The garter spring design is mainly used at lower pressures and temperatures because the spaces in the spring can create extrusion paths at high temperatures. The advantage is that the spring can expand and contract along with the rubber. This is important if there are large temperature fluctuations, which can affect the volume of the rubber.

2.2 Materials

2.2.1 Aflas®

The rubber used for all of the experiments was tetrafluoroethylene-propylene known by the trade name of Aflas, which is the standard material choice for high temperature downhole applications. This is due to the maintaining of rubbery mechanical properties at high temperatures, and high chemical resistance to the corrosive agents found in oil wells such as hydrogen sulfide (HS).

Aflas is a half-fluorinated elastomer made from the monomers tetrafluoroethylene (TFE) and propylene. TFE is a fully fluorinated ethylene and is the monomer for Teflon. The molecular chains of Aflas are stereoregular with an even ratio of TFE to propylene monomers. Because of the combined properties of the polar and hydrophobic groups the properties of Aflas are unique. The polar TFE provides resistance to oil, heat, oxidation, and flame. The hydrophobic propylene monomer provides good mechanical properties for molding as well as some resistance to water absorption. The stereoregularity of the chain provides stability and high

chemical resistance. Aflas has a glass transition temperature of 2.8°C (37°F) so it is not suitable for low temperature applications [2].

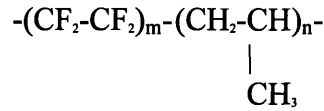


Figure 5. Chemical structure of an Aflas monomer [2]

<u>ASTM Method</u>	<u>Property</u>	<u>Avg. Value</u>
D412 Method A	Tensile Strength	20.7 MPa (3000 psi)
D412 Method A	Ultimate Elongation	229%
D412 Method A	Shear Modulus, G	4.28 MPa (621 psi)
D412 Method A	Young's Modulus E	12.8 MPa (1862 psi)
D746	Brittle Temperature	-40°C (-40°F)
D1329	Glass Transition	2.8°C (37°F)
D1329	Max. Operating Temperature	218°C (425°F)

Table 1. Typical properties of Aflas. [5]

2.2.2 Comparison of Fluoroelastomers

Other types of fluorinated elastomers, such as fluorocarbon rubber, known by the trade name of Viton®, contain vinylidene fluoride monomers that are prone to a dehydrofluorination reaction, which releases the toxic chemical HF. Viton also has less chemical resistance than Aflas. Totally fluorinated elastomers such as Kalrez®, a copolymer of perfluoromethyl vinyl ether and TFE, have superior heat and chemical resistance but have poor mechanical properties and are prohibitively difficult to mold. Also, due to the polarity of the monomers, these elastomers swell and absorb a lot of water. Since Aflas has both polar and nonpolar monomers the elastomer has only a slight affinity for both water and oil. Aflas contains 53 wt % fluorine while other fluoroelastomers contain over 70%. [6] However, the swelling of Aflas can be a problem and is one its negative features. It also does not store energy well because of high vibration dampening. Another problem is that at high temperatures the crosslinks weaken which results in extrusion problems from the flowing of Aflas. Despite this drawback Aflas can be used at temperatures much higher than hydrogenated nitrile rubber (HNBR), which is the

standard at lower operating temperatures. HNBR has longer chains and more cross-links so it is more elastic at low temperatures and has better mechanical properties than Aflas. At 204°C (400°F) Aflas can flow as cross-links weaken, but still maintain rubbery properties while HNBR becomes brittle from excessive cross-linking with H₂S when oxygen is present. Due to its heat and chemical resistance Aflas is the preferred material for HPHT and chemically corrosive applications. Aflas can be used in formulations ranging from 80 to 90 durometer. In this study the center elements were 80 durometer and the end elements were 90 durometer.

2.2.3 Carbon Steel

1018 carbon steel is a commonly used grade of steel in many component parts because it is easily machined. It can be annealed to increase ductility, which makes this a useful material for foldback rings that require both ductility and strength. Annealing is a process of controlled heating and cooling used to obtain a specific phase of material. The hardness of the foldback rings was about 72 HRb (63 UTS), which is in the desired range of 65-80 HRb. After machining was completed, the following annealing procedure was used under vacuum conditions:

1. Anneal for one hour at 857°C (1575°F) minimum to 899°C (1650°F) maximum.
2. Furnace cool from 857°C (1575°F) to 704°C (1300°F) at 10° C (50°F) per hour.
3. Continue cooling in furnace from 704°C (1300°F) to room temperature at any rate.

2.2.4 Wire Mesh

Stainless Steel 316 wire mesh is the standard material for mesh backup systems. A thin wire is woven into a mesh with approximately a 50% air vacancy so that it can be compressed when pressure is applied. After compression into a mold the mesh increases in strength and density as the wires are packed tightly. The mesh can be formed into a variety of geometries.

2.2.5 Polyetheretherketone (PEEK)

PEEK is a semicrystalline polymer and is normally used with glass fiber reinforcement, which provides better mechanical properties and higher temperature resistance. Because of its strong mechanical properties at high temperatures PEEK is often used as an anti-extrusion device, or backup ring, for elements and O-rings.

Chapter 3 Testing Procedure

3.1 Element Fixture Tests

3.1.1 Liquid Tests

The procedure specified by ISO 14310 was followed in all of the element tests. First the element is placed in the test fixture, which simulates the packer environment as seen in Figures 1 and 16. The test fixture used was part # 88634-000 from the Schlumberger database, except for tests with a differential pressure greater than 86 MPa (12.5k psi), which were run in the fixture with part #100056419. The critical dimensions of the fixture can be seen in Table 2. The fixture was heated overnight to 218°C (425°F) and then the element was set with an applied pressure from the dynamic gage ring with a specified force in the range of 178,000 N (40,000 lbs) to 311,376 N (70,000 lbs). After the setting force was removed a differential pressure was applied to the element using water as the test media. The pressure cycle at high temperature involved two pressure reversals, with a differential pressure of either 86 MPa (12,500 psi) or 103 MPa (15,000psi). Then the fixture was cooled to 135°C (275°F) for the low temperature portion of the test while maintaining a 34.5 MPa (5,000psi) to 48.3 MPa (7,000psi) differential pressure. The pressure test was run again from both sides in a single reversal cycle. To pass each reversal, a leak rate of less than 1% of the differential pressure over 15 minutes had to be recorded. All major dimensions of the element components were recorded before and after testing. After disassembly pictures were taken so that the element could be examined for failure analysis.

3.1.2 Gas Tests

The procedure for heating and setting the element is the same as in the liquid tests. In this case one side of the fixture is connected to a compressor supplying nitrogen gas under high pressure. The other side of the element is vented to atmosphere via a tube, the free end of which was submerged in a water bucket. Any gas present would travel through the tube and be observed as bubbles in the water. The differential pressure cycle is applied following the same procedure as the liquid tests except that in this case the test media is the nitrogen gas supplied by the compressor. Decreasing the pressure between cycles is a longer process than during the liquid tests. Gas pressure must be relieved slowly in order to avoid explosive decompression of any gas trapped inside the rubber element. The qualification for passing this test is that once the

pressure is stabilized the element must be bubble tight for fifteen minutes, meaning that no bubbles are observed for a given time period. The following is the procedure used for the rate of bleed down of the nitrogen gas pressure.

Bleed off the pressure to ambient pressure using the following steps:

- 1 Bleed off pressure from 87.6 MPa (12,700 psi) to 41.4 MPa (6,000 psi) at a rate of 4.1 MPa/min (600psi/min)
- 2 Hold 41.4 MPa (6,000 psi) for 10 minutes
- 3 Bleed off pressure from 41.4 MPa (6,000 psi) to 7.6 MPa (1,100 psi) at a rate of 0.69 MPa/min (100 psi/min)
- 4 Hold 7.6 MPa (1,100 psi) for 1 hour
- 5 Bleed off pressure from 7.6 MPa (1,100 psi) to 0.69 MPa (100 psi) at a rate of 0.069 MPa/min (10 psi/min)
- 6 Hold 0.69 MPa (100 psi) for 10 minutes
- 7 Bleed off pressure from 0.69 MPa (100 psi) to ambient at a rate of 0.034 MPa/min (5psi/min)

Casing I.D.	17cm (6.696 in.)
Gage Ring O.D.	16.36cm (6.440 in.)
Gage Ring I.D.	12.9 cm (5.065 in.)
Mandrel O.D.	12.85 cm (5.060 in.)

Table 2. Critical Dimensions of test fixture.

3.2 Element Setting Tests

A special fixture made of stainless steel was designed to observe an element during the setting process at room temperature. As seen in Figure 24 the casing has windows or slots through which the element can be viewed. A groove in the base was designed for an acrylic tube to fit inside the casing so that the element would not expand through the openings. The drawing of the entire fixture can be seen in Figure 25. The element was placed on the mandrel inside the fixture and then a controlled load was applied to the top of the gage ring, which applied force to the element. The loads for the tests were applied by a flat press machine. The force on the gage ring was displacement controlled and set at 0.127cm/min (0.05 in/min). The test was stopped when the acrylic tube fractured. Pictures were taken during the process and measurements of the mesh rings were taken before and after the test.

Chapter 4 Results

4.1 Summary

The results of the project are summarized in Table 3. The tests are grouped by category and the test report number indicates the sequence in which the tests run. The only design to successfully pass both V3 and V0 qualifications was the foldback ring design. The mesh design did not have a suitable center element geometry, which still needs to be found. The combination of a split shoe and mesh design was promising although not successful in these trials. The FEA results were generally consistent with the fixture test results, which were verified with experiment number S15.

4.2 Foldback Ring Design



Figure 6. Cross-section of three-piece element with foldback ring

The original design tested was modified from a successful element that had been qualified for a 19.4 cm (7-5/8'') packer. The only modifications were changing the rubber from HNBR to 80 duro Aflas for the center element, and 90 duro Aflas for the end elements. Aflas had to be used due to the required high temperature of 218°C (425°F). This design passed the fixture test with liquid media in test S1, but was near the maximum allowable leak rate. After testing there was evidence of significant rubber extrusion of the end element underneath the foldback rings and gage rings. From observing the groove around the surface of the foldback ring the point of contact with the casing could be determined as seen in Appendix Figure 17. It was possible to shorten the length of the shoe that covered the top of the element and not interfere with the point of contact with the casing. This was done to decrease the setting force needed to compress the element and to possibly reduce damage to the end element. Since the extrusion gap on the 19.7 cm (7-3/4'') packer is smaller than for 19.4 cm (7-5/8''), shortening the length of the ring was not expected to interfere with the sealing capability of this design.

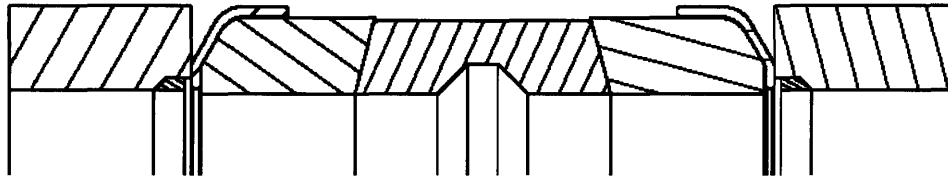


Figure 7. Cross-section of successful foldback ring design using PEEK rings under the gage ring.

The test S2 used shorter rings and end elements as well as a PEEK ring added under the gage ring to prevent extrusion. This test failed probably due to the shortening of the end elements, which decreased the stack length significantly. Damage could be seen on the center element and there was extrusion of the end elements under the PEEK ring. In this case the PEEK ring was unsuccessful at preventing extrusion.

In the most successful design, shown in Figure 7, taller peek rings with a larger O.D. were used in order to close the leak path under the gage ring. The shorter shoes, original length end elements and original center element were used so that the stack length was again the original height. The test S5 passed, although there were still some extrusion marks visible on the end elements similar to those seen in Figure 18. However, no pieces of rubber were found on the mandrel. This design passed at 103 MPa (15k psi) of differential pressure in liquid so it was tested again at 134 MPa (19.5k psi) differential pressure in test S11, which it also passed. The limit of the pressure lines in the test bay prevented testing at higher pressures. There was some extrusion under the static PEEK ring and in front of the dynamic PEEK ring. In the nitrogen gas test S14 this design passed at 86 MPa (12.5k psi) differential pressure. The equipment in the testing facility would not allow a higher differential gas pressure due to the limits of the compressor. The test had two holds at high temperature, 218°C (425°F) and one hold at low temperature, 135°C (275°F). There were some gas bubbles observed under the surface of the element as seen in Figure 19, but since there was no damage the element passed. In the next phase of testing this element should be tested at 103 MPa (15k psi) or greater in a gas test.

To further understand why some designs were more successful than others FEA simulations were run of each design. The successful design is shown in Figure 26 with an applied setting force of 244,652 N (55,000 lbs). The results show that the end elements protect the center element from the foldback ring and apply force to the O.D. side of the center element. In Figure 27 the simulation with shorter end elements shows that if they are not long enough than

they will not shield the center element and will be ineffective. This design was unable to hold a differential pressure.

Although the PEEK ring design was successful in tests S11 and S14 there was still a small amount of extrusion from the end elements similar to test S5, which was the same element at a lower test pressure. In order to correct this problem another design was tested with a small stainless steel 316 wire mesh ring on the I.D. of the end element, and the rest of the design remained the same since it had been successful overall. (Figure 8) However, this test S6 failed even though the mesh ring was successful in preventing extrusion of the end element. The center element was damaged and the contact markings on the dynamic ring were very uneven, indicating that the setting might have been off-center. After testing, the I.D. of the center element showed that it had not sealed around the mandrel. This design was also tried with PEEK rings instead of the mesh rings in test S13 but the result was still unsuccessful.

One hypothesis was that the decrease in length or volume of the end element due to the I.D. ring affected the sealing. To test the possibility longer end elements were designed. The test S9 with the longer end elements and the small mesh ring performed better but still was not successful. It passed the hot cycle but failed at cold temperature as seen in Figures 21 and 22. It is possible that the mesh was absorbing too much of the setting force and was therefore preventing the sealing mechanism from being effective. Since the center element was not damaged it is likely that the end elements were long enough and the problem was due to the small mesh I.D. ring. FEA results indicated that adding the small mesh ring prevented proper deformation of the center element as seen in Figure 28 compared to the successful design seen in Figure 26.

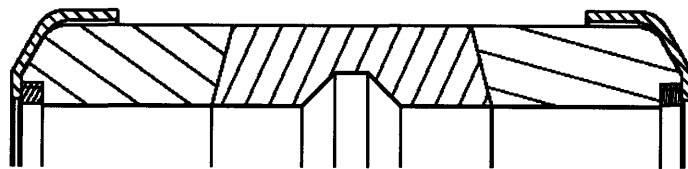


Figure 8. Cross-section of foldback ring element with anti-extrusion ring.

One test, number S15, was performed to verify the FEA results and determine the deformation that is caused by the setting force alone, and that which is caused by applying the differential pressure. The successful foldback ring design that passed the water and gas tests was used to find the effect of the setting force. The element was heated in the fixture to 218°C

(425°F) in air and a setting force of 245,000 N (55,000 lbs) was applied. The element was then released without applying a differential pressure. The deformation of the element was similar to those from tests in which pressure was applied, but the deformation of the foldback rings were significantly different as seen in Figure 20. The lip of the ring was bent outwards towards the casing instead of in towards the element as in the pressure tests. Also, there were no contact markings on the rings, indicating that they are normally caused by differential pressure. No extrusion was observed on these elements. When compared to Figure 26, the observed test results support FEA results. For example, the edge of the shoe extends to the casing in the same position during both experimental and theoretical tests.

4.3 Mesh Designs

4.3.1 Two-piece mesh backup

The two-piece mesh design was first tested with a modified version of the center element that passed on the 19.4 cm (7-5/8") size in test S3. Part of the goal of testing this design was to find a center element that could be used with the shoe and mesh combination backup system. The first design used an element that was shorter in length, 8.9 cm (3.5 in.), due to the smaller extrusion gap on the 19.7 cm (7-3/4") casing. A small metal ring was used underneath the center of the element on the I.D. side to prevent buckling. However, in the first test buckling of the center element was observed and the test failed which indicated that the element was still too long. After FEA analysis, a shorter center element was designed with a length of 7.6 cm (3 in.). Some of the other dimensions were changed such as the angles and the groove for the metal I.D. ring, which was redesigned for a closer fit to the rubber. However, this design did not pass element test S7 and performed just as poorly. Evidence of buckling was again seen on the center element. Both mesh rings had been deformed and were nearly flat on the side facing the gage ring. In the first test the dynamic ring had significantly more deformation than the static ring. This indicates that this design might require more than the maximum 311,000 N (70,000 lbs) of setting force. The next step would be to try a shorter element with a larger ID ring. If this does not work then it might mean either that a three-piece element is needed with this design or that the mesh is too thick for the applied setting force. If the mesh is not deforming completely to the casing at less than 311,000 N (70,000 lbs) of setting force then it is most likely too thick for this casing size.

The two-piece mesh design was also tested in the setting observation fixture to gain understanding of how the element deforms. In the first test of this mesh design the acrylic tube alone was used as a casing. The center element deformed to reach the acrylic casing first at the center and then eventually at the mesh rings. The acrylic tube broke at approximately 71,000 N (16,000 lbs) of setting force. The center element was completely deformed to the casing but the dynamic mesh ring had just begun to deform when the tube broke. It is likely that a thin section of the mesh was applying a large radial force that reached the maximum tensile stress of the acrylic tube. The test was useful overall because the results could be compared to the FEA results and the element fixture test results of the same design. The test was captured on video for further analysis.

The test which used the metal casing with windows, allowed a small increase of about 13,000N (3,000 lbs) of additional setting force before the tube broke. The tube was secured to the top of the casing with duct tape to prevent movement, which might have provided more support. The windows were not large enough to provide a clear view of the element. It was observed that the first contact between the rubber and the acrylic occurred more towards the dynamic ring than in the previous test, which did not use the metal casing. This trend is more similar to what was observed in the FEA model of setting. In the future a casing with a closer fit to the acrylic tube or a stronger plastic might help increase the setting force before failure. This would provide a view of the element that is closer to what occurs in the test fixture.

4.3.2 Triangular Mesh

Triangular-shaped mesh in which the mesh ring sits above an extension of the center element was also tried in test S4, but buckling was observed and the test failed. The length of the element was 8.9 cm (3.5 in.), which was too long for this casing size. FEA analysis has not yet been run for this design, which would be the next step to finding a more suitable center element geometry. Due to their similarities this design has difficulties consistent with the two-piece mesh design. Therefore the same center element geometry should be successful on both variations of these mesh backup systems.

4.4 Split Shoe with mesh

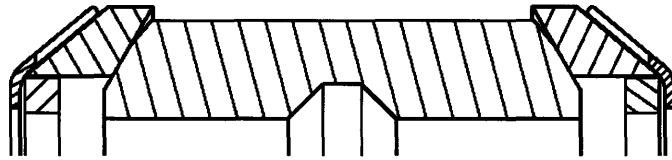


Figure 9. Cross-section of an element with a mesh and split-ring backup

The goal of the split shoe design was to combine the strengths of having both mesh and a foldback ring containing the element. By shortening the O.D. of the split ring, it should not reach the casing when compressed, but will support the mesh so that less mesh is needed. This should decrease the required setting force while also increasing retrievability. The cuts in the ring and the annealing process will also contribute to a lower setting force. However, a working center element for a mesh backup in the 19.7 cm (7-3/4'') casing size should be found to test with this design. The testing results were consistent with FEA trials of this design. The foldback rings and the mesh deform to the casing while the smaller mesh ring on the I.D. does not deform. The major concern is that the static foldback ring does not conform to the casing in the simulation seen in Figure 29. In the actual fixture test S12, the design failed but was able to support 34.5 MPa (5k psi) from the dynamic side and 75.8 MPa (11k psi) from the static side. The dynamic shoe and mesh rings were deformed to the casing while the static rings showed significantly less deformation. A 6.35 cm (2.5 in.) length center element was used which did not buckle, as did the longer center elements used with the mesh design. If the problem is only deformation of the split ring then this center element design might be successful with a mesh backup system. One possibility is that there is not enough rubber to gain an effective seal. If that is the case then most likely a three-piece element will have to be used with the split shoe backup system.

4.5 Garter Spring with Mesh

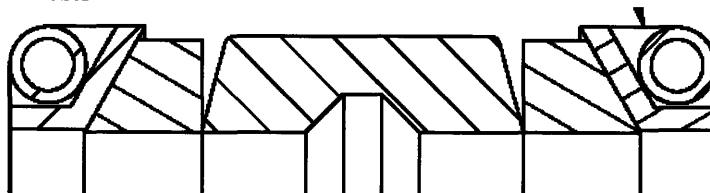


Figure 10. Cross-section of element with garter spring and mesh backup

The garter spring and mesh backup was designed to allow the benefits of a garter spring backup system without the extrusion of rubber through the spring. It has been shown that at high

temperatures Aflas will readily extrude through the gaps in a garter spring. The mesh is thin so that it will not add significantly to the setting force. In the first test S8, the center element geometry from the foldback ring design was used along with shorter end elements so that the total length of the end and the garter spring would be equal in length to the foldback ring end element. The test failed although the garter spring did not break. The failure was due to the mesh on the static end breaking in two opposite locations on the O.D. side. The rubber of the static end element and the static side of the center element were also broken in corresponding locations. The most likely failure mechanism is that the angle on the gage ring was not steep enough to allow the spring to move out to the casing. This would have subjected the mesh to all of the pressure and resulted in the observed blowout that occurred while applying pressure from the dynamic side. In the next test S10, the same element stack from the shoe design was used since longer end elements were needed to protect the center from damage. Gage rings with an angle of 30° instead of 15° were used to aid in spring deformation. The second test held less differential pressure than the first trial and buckling was observed on the center element. In this case there was damage to the mesh in two symmetrical points on the dynamic ring but it did not break so there were no holes in the rubber. The buckling is most likely due to the use of an element geometry that is not conventional for the garter spring, such as the longer end elements. In future tests the end elements will be shortened and the center modified to achieve a more effective element geometry.

The garter spring and mesh design was also tested using the acrylic tube as a casing. The setting force reached was 68,418 N (14,257 lbs), which was similar to the other tests run with the acrylic tube as a casing. The element behavior was consistent with the fixture test that failed for this design. The end elements were observed moving underneath the center element, which would explain the damage that was observed after the pressure test.

Element Type	Result	Test Report #	Comments
Foldback Ring	Passed	S1	Extrusion present
Foldback Ring	Failed	S2	End elements too long
Foldback Ring	Passed	S5	Some extrusion
Foldback Ring	Failed	S6	Tried small mesh ring
Foldback Ring	Failed	S9	Tried longer ends with mesh ring
Foldback Ring	Passed	S11	Small extrusion marks
Foldback Ring	Failed	S13	
Foldback Ring	Passed	S14	N ₂ Gas test
Foldback Ring	N/A	S15	Only setting force applied
Mesh	Failed	S3	Buckling of center
Mesh (triangular)	Failed	S4	Buckling of center
Mesh	Failed	S7	Buckling of center
Split shoe/mesh	Failed	S12	No buckling
Spring/mesh	Failed	S8	
Spring/Mesh	Failed	S10	

Table 3. Summary of Fixture Test Results.

Chapter 5 Discussion

5.1 Foldback Ring Design

The foldback ring design appears to be very sensitive to the length of the end elements. The ends need to be long enough to prevent damage to the center element from the foldback ring and short enough to prevent buckling. Figure 26 demonstrates how the end elements protect the center from being damaged by the foldback rings. In comparison, Figure 27 shows the same design with shorter end elements that are ineffective in protecting the center. The damage on the center element when the small mesh ring was present was similar to the test in which the end elements were too short. It is possible that the mesh ring interfered in the setting process, and therefore nothing besides the rubber can be in between the foldback rings. This result was supported with FEA, which showed a possible leak path on the I.D. of the element due to the movement of the mesh ring. The picture of the element with an applied setting force of 245,000 N (55,000 lbs) can be seen in Figure 28.

In order to further improve this design one possibility would involve adding a tapered edge to the foldback ring in order to prevent damage from the shoe pressing into the O.D. of the end element. A Teflon ring could also serve a similar purpose although it might not be approved for high temperatures. The Teflon ring or tapered edge idea could be applied either to prevent

damage on the O.D. or extrusion on the I.D. The Kevlar fiber reinforced end elements could also be a solution to the extrusion problem and should be tested with the successful foldback ring design. The length of the element might have to be adjusted if there is not enough rubber to seal effectively. As seen in the FEA result, the part of the end element that is reinforced will not deform in the same way as the rubber alone.

5.2 Mesh designs

The setting observation tests confirmed the validity of the FEA model for the two-piece mesh design. When the metal casing was used to reinforce the acrylic the added stiffness rendered the conditions closer to the actual casing, which would have no flexibility. Therefore it is logical that the deformation observed would more closely follow the FEA results. The bulging of the center element occurred more towards the dynamic ring, which indicates that the FEA results are realistic for this design because they showed the same trend. It was also confirmed that the dynamic mesh ring deforms before the static ring.

Overall the mesh designs were unsuccessful due to the geometry of the center element and the fact that the mesh did not deform correctly to prevent extrusion. From these experiments it can be determined that the one piece 80 duro center element is not sufficient to provide seal. Instead it might be possible to use a 90 duro center element or a three piece element similar to the mesh design. There are no clear advantages of this design over the foldback ring design at this time.

5.3 FEA study

Overall the FEA results were consistent with experimental test results, particularly with the foldback ring designs. It is important to note that the FEA only determined the effect of the setting force and not the differential pressure. This difference could affect whether FEA accurately predicts the quality of a design. As seen in test S-15 the deformation of the element from the setting force alone is significantly different than what is observed after the differential pressure is applied. However, it does confirm the accuracy of FEA when comparing only the deformation due to the setting force.

The most important observations from the FEA study are that a main function of the end elements is to protect the foldback ring from contacting the center element, and that any anti-extrusion device should be placed outside the rubber element so that it does not create an additional leak path or interfere with rubber deformation.

Chapter 6 Further Research

6.1 Fiber Reinforced Rubber

Another method to prevent extrusion is reinforcing the end elements with embedded Kevlar fibers in a weave pattern. The goal is to prevent extrusion without an exterior backup system. The benefits are that the rubber will contain itself, but by adding the fibers the properties of the end element will be changed. It might be necessary to increase the length of the end element so that enough of it will be free of fibers to deform and create a seal. This end element can also be used with the foldback ring design that successfully passed testing, with the goal of eliminating the need for extrusion prevention.

6.2 New Mesh Designs

In order for the mesh design to be effective new geometries must be tested both for the rubber and mesh components. Some possibilities are different density meshes and three-piece rubber elements. The combination of the mesh and shoe design was promising since it held more differential pressure and therefore should be considered in new designs. This design should also be easier to retrieve than the foldback ring design.

Chapter 7 Conclusions and Recommendations

The most promising element from this study is the foldback ring design with PEEK anti-extrusion rings under the gage ring. It passed at 134 MPa (19.5k psi) differential water pressure and 87.6 MPa (12.7k psi) differential nitrogen gas pressure with 245,000 N (55,000 lbs) of setting force. Variations on this design could still be explored in order to further prevent extrusion although it is successful in the current state. It was found that the end element length is critical in this design and if it is changed, the sealing mechanism is no longer successful. The ends need to be long enough to prevent damage to the center and they also need to create a seal on the I.D. of the element, which is prevented by the mesh anti-extrusion ring.

One-piece center element designs were difficult to pass for this casing size due to the small extrusion gap. The most successful attempt was the 6.35 cm (2.5 in.) center element used with the split ring and mesh backup. The center did not buckle in this case but it did not transfer

enough setting force to deform the static rings. This design was only tested once and could be passed with some modifications. It is possible that the mesh rings were too long and absorbed too much of the setting force. Also, a three-piece center might be needed even though they are normally not used with mesh backup designs.

FEA was a helpful tool in this study and it can be used to gain a greater understanding of element technology. In most cases the results from FEA were consistent with the results of testing and provided insight into the mechanisms of sealing and possible reasons for failure.

Chapter 8 Appendix

Physical Properties¹

Hardness ²	Shore A ± 5	82
100% Modulus ³	MPa	12,4
	psi	1800
TS at break ³	MPa	15,8
	psi	2700
Elongation at break ³	%	125
Compression set ⁴ , 70 h at 204°C	%	35

Table 4. Typical mechanical properties of Kalrez® (4)

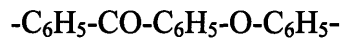


Figure 11. Chemical Structure of PEEK



Figure 12. Chemical Structure of Viton®



Figure 13. Chemical Structure of Kalrez®



Figure 14. Chemical Structure of HNBR

Typical thermogravimetric curves

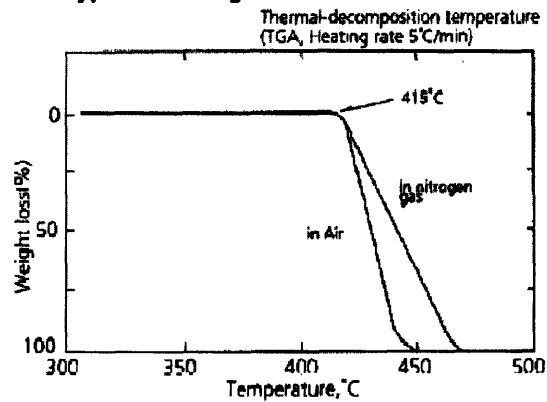


Figure 15: Temperature Degradation of Aflas. (3)

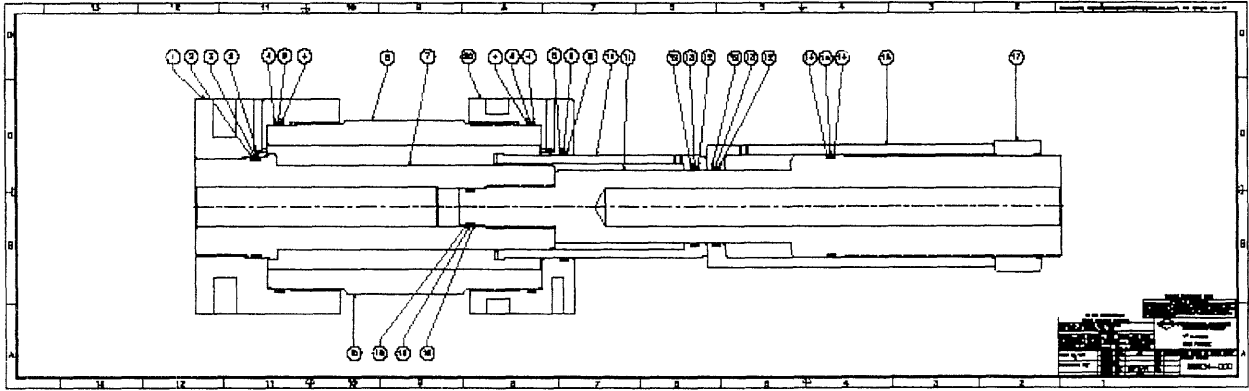


Figure 16. Drawing of Element Test Fixture.



Figure 17. Foldback Ring with contact markings from Test S-5.

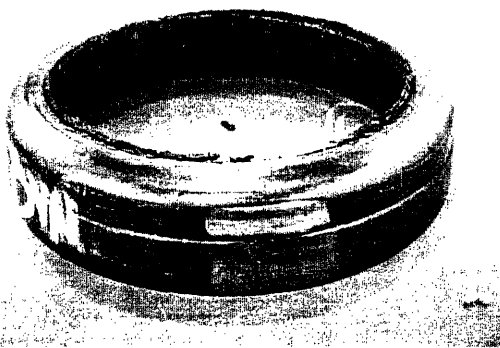


Figure 18. Extrusion markings on end element from Test S-11.



Figure 19. Gas bubbles protrude from center element in test S-14.

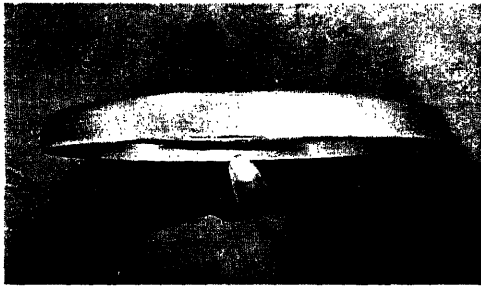


Figure 20. Foldback Ring from test S-15.

**PACKER ELEMENT FIXTURE TEST, AFLAS 90/80/90 WITH FOLDBACK RING,
7-3/4 (46.1#), 425F**

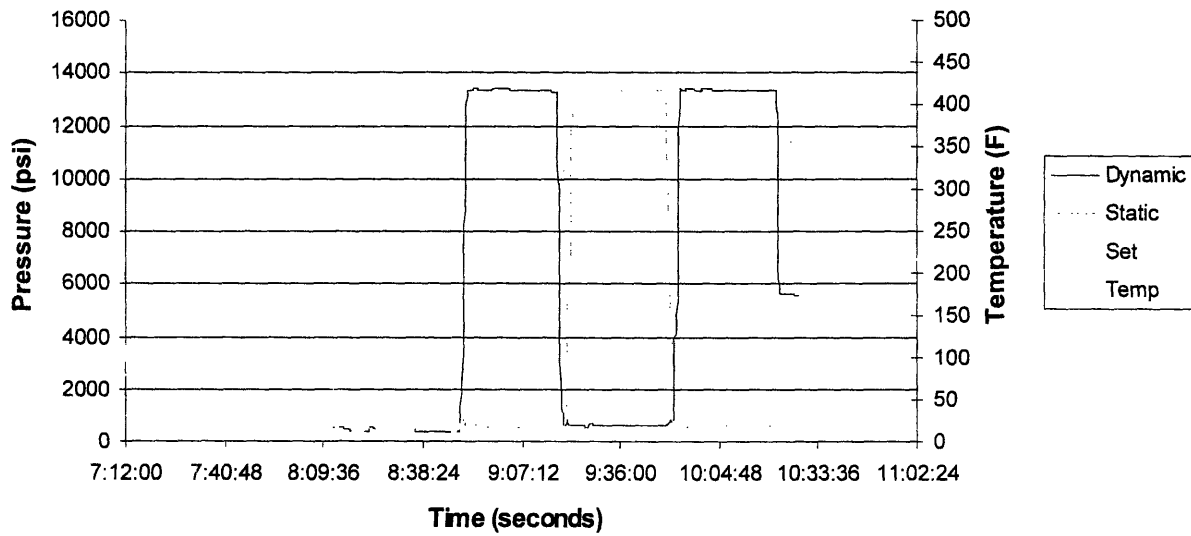


Figure 21. Data from test S-9 (passed liquid test).

PACKER ELEMENT FIXTURE TEST, AFLAS 90/80/90 WITH FOLDBACK RING,
7-3/4 (46.1#), 275 F

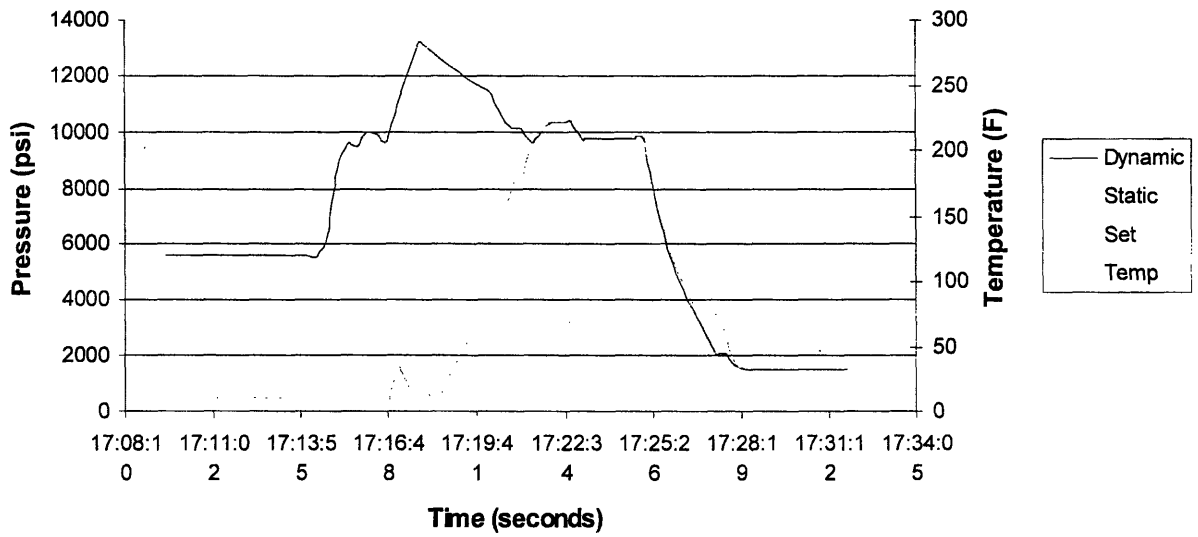


Figure 22. Data from test S-9 (failed liquid test).

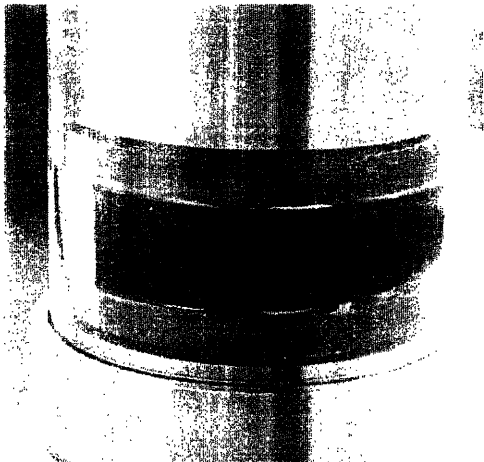


Figure 23. Element setting test with acrylic tube.



Figure 24. Element setting test using casing with windows.

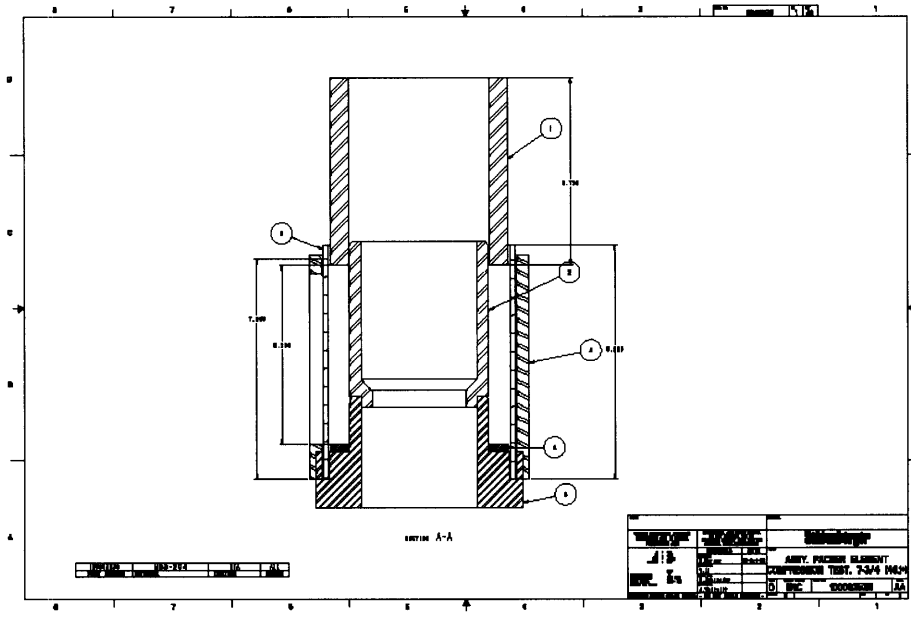


Figure 25. Element setting test fixture with acrylic tube.

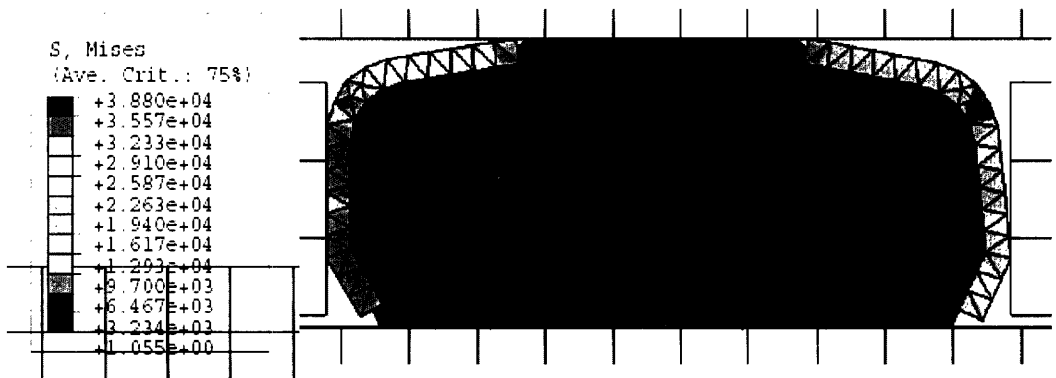


Figure 26. FEA of element from test S-5, S-11, and S-14.

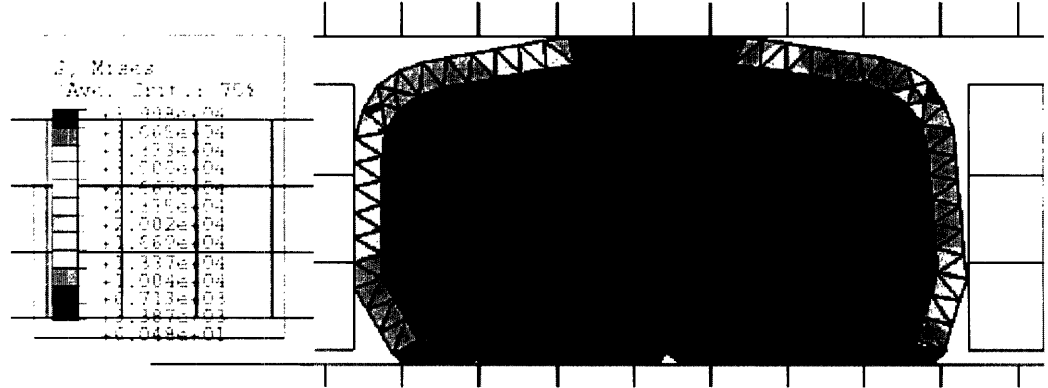


Figure 27. FEA of element from test S-2.

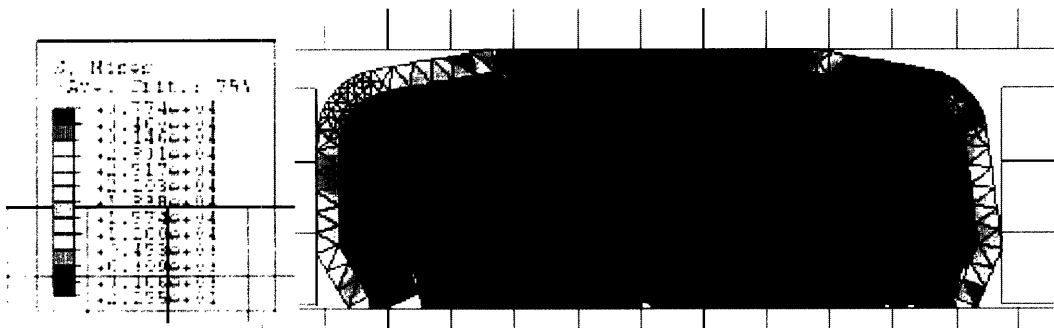


Figure 28. FEA of element from test S-6.

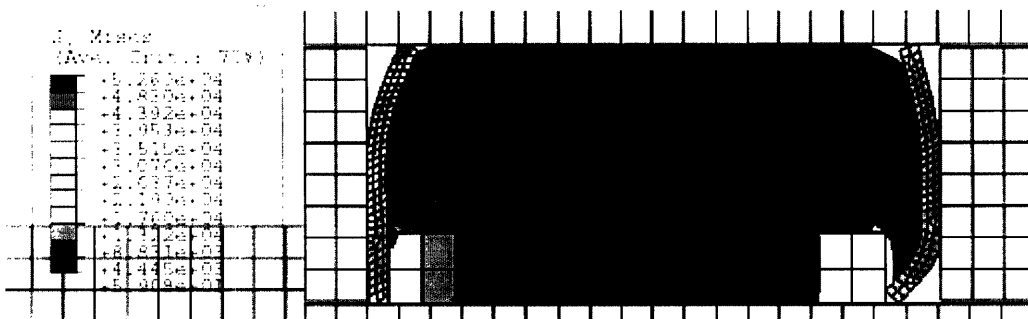


Figure 29. FEA of element from test S-12.

References

1. <http://www.matweb.com/reference/shore-hardness.asp>
2. <http://www.agc.co.jp/english/chemicals/gomu/aflas.htm>
3. <http://www.aflas.com/>
4. http://www.dupont-dow.com/Tech_Info/ViewProductDatasheetList.asp?product=Kalrez
5. <http://www.sealseastern.com/CompoundSpec.asp?cmpnd=7182D>
6. Ping Wang et al. Sorption and Diffusion of Organic Vapors in Two Fluoroelastomers. Journal of Applied Polymer Science, Vol. 71, 1525-1535 (1999).

Aflas® is a registered trademark of Asahi Glass Co., Ltd.

Viton® and Kalrez® are registered trademarks of Dupont Dow Elastomers L.L.C.