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BELLOWS SEALS FOR LIQUID METAL
SYSTEMS - LITERATURE SEARCH
FOR FABRICATION
AND OPERATIONAL EXPERIENCE

November 1968

AEC RESEARCH &
DEVELOPMENT REPORT

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BATTELLE MEMORIAL INSTITUTE

for the

UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

PRINTED BY/FOR THE U.S. ATOMIC ENERGY COMMISSION

54-1980-016 (11-67)

SEC-41 RICHLAND, WASH.

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BNWL-905

3 3679 00061 1915

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SUBMITTED TO AEC NOV 11'68

November 1968

BATTELLE MEMORIAL INSTITUTE
PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON

Printed in the United States of America

Available from

Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

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BELLOWS SEALS FOR LIQUID METAL
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INTRODUCTION

The conceptual design of the control system for the Fast Test Reactor (FTR) proposes a bellows seal to isolate the drive mechanism from the sodium. The seal separates the pure inert gas surrounding the drive mechanism from the mixture of sodium vapor and inert gas covering the 1200 °F sodium pool in the reactor vessel. Integrity of this seal is important to prevent mechanical and corrosion problems that would result from deposition of sodium or sodium oxide on the drive mechanism.

Seals of this type have been used in previous liquid metal systems. A search of the literature has been made to determine operating experience and point the way toward formulation of a specification for procurement of a metallic bellows seal to meet FTR criteria.

SUMMARY

A computerized literature search conducted by the Liquid Metals Information Center revealed 136 references relating to design and operating experience with bellows in liquid metal systems. These are all listed in Appendix B. Twenty-six of the references were relevant and were reviewed in detail (References). The additional references not reviewed are included under "Bibliography."

Designing and fabricating a bellows seal for the FTR control rod drive would appear to be within present "state

of the art." Specifications must be tight and quality control rigorous, however, to assure production of a long lasting component. A tentative specification for a bellows seal for the FTR is set forth in Appendix A. It is recommended that this specification not be considered final until input has been obtained from users and fabricators of bellows.

DISCUSSION

The Liquid Metals Information Center (LMIC) maintained by Atomics International for the AEC is the repository of virtually all information available on liquid metal systems. Therefore, LMIC was asked for a computer run to produce a bibliography covering operating experience on metallic bellows seals in sodium systems. The product of that run was a list of 136 reports with an abstract of each one. Twenty-six of these appeared relevant and were examined in detail. In addition, a number of catalogs from bellows fabricators were consulted. A summary of the information found on design, construction, testing, and operation of bellows seals follows.

DESIGN CONSIDERATIONS

The two most widely used types of metallic bellows are the hydraulically formed and the welded. The former is made from a length of seamless or welded tubing by hydraulically or mechanically corrugating the wall. This method of construction places practical limits on the depth of the corrugations and thus on the flexibility of the bellows. This limitation does not apply to the welded bellows which are formed by precision welding alternately on the inner and outer diameters of thin metallic discs. This construction allows greater flexibility, lower spring rate, more convolutions per inch and a greater maximum stroke. Hence, bellows requiring long stroke and/or low spring rate such as those being considered here for control drive seals are virtually always of the welded type.

Form and thickness (t) of the plates used for welded bellows have a strong effect on maximum stroke, spring rate, and pressure rating.⁽¹⁾ Stroke is proportional to $1/t$, spring rate to t^3 , and pressure rating to t^2 . For an application such as ours where pressure is low and a long, soft stroke is desired, there is incentive to keep thickness small. Some of the plate shapes available are shown in Figure 1. The vendor's recommendation should be obtained, but a pattern of concentric ripples like that labeled "corrugated (nesting)" seems favored for this type of service.

FIGURE 1. Typical Plate Shapes Available

The stress analysis of welded bellows using the nested-ripple diaphragm is limited mainly to empirical methods by the complexity of the geometry.⁽²⁾ These empirical methods have been developed by the bellows manufacturers for design applications, are considered proprietary, and are virtually

never disclosed to the user. A theoretical method based upon elastic beam theory has been used for design calculations in some applications. This method tends to yield conservative stress values about three times higher than the empirical method for operation within the elastic region. Test data confirm the empirical predictions more closely than they do the theoretical values. The theoretical elastic beam equation for welded bellows^(2,3) is:

$$S = \frac{3 EYt}{L^2} + \frac{PL^2}{2t^2}$$

where

S = Total stress (1st term deflection stress)
(2nd term pressure stress)

E = Modulus of elasticity

Y = Bellows deflection per convolution, in.

t = Diaphragm thickness, in.

L = Diaphragm width, in. [(OD - ID)/2]

P = Pressure, psi.

EXAMPLES OF BELLWS IN METALLIC LIQUIDS OR VAPORS

Examples were found of operating experience with metallic bellows in a molten metal environment in a number of reactors or reactor experiments. Several of these that may be relevant to FTR control rod drives are reviewed.

Fermi Reactor⁽⁴⁾

Approximately 35 stainless steel bellows are used in the fuel handling and control mechanisms of the Fermi reactor. These operate in liquid sodium vapor at temperatures from 250 to 1000 °F. In a year of operation following extensive

preliminary testing, there was only one failure. This was a latch rod bellows in a safety rod assembly. Seven such assemblies operate normally at 450 to 600 °F, but in special test runs had experienced 6 days at 750 °F, 5 hr at 700 °F, and 7 days at 1000 °F. One bellows leaked during a special run during which the argon pressure was raised to 10 psig from a normal pressure of only a few inches of water. It was removed into ambient atmosphere and steam cleaned. Inspection showed severe corrosion and many leaks of various size. Corrosion was intergranular and there was sensitization at the grain boundaries. The massive corrosion is ascribed to the subjection to air and steam upon withdrawal, since the other six units, withdrawn in argon and cleaned in alcohol, showed no corrosion. Original cause of leakage, probably mechanical, was undetermined since it was completely masked by the corrosion.

With the exception of this single failure, performance of all reciprocating bellows seals in the reactor fuel handling and control mechanisms has been trouble-free and satisfactory.

EBR-II⁽⁵⁾

In EBR-II, the entire reactor vessel is immersed in 700 °F bulk sodium contained in the primary tank. The bulk sodium pool is blanketed with argon. The only bellows seal on each of the 12 control rods is outside the primary tank, sealing the penetrations through the tank cover. Thus, the bellows do not see a high temperature, but are subjected on the inside to an atmosphere of argon and sodium vapor.

The control rod bellows seals are made of Type 347 stainless steel to minimize sensitization in the weld zones. They operate with a stroke ratio of 4 to 1 going from an

extended length of 19 7/8 in. to a retracted length of 5 in. The 99 convolutions of each bellows are fabricated from 198 discs 4 1/2 in. OD by 2 9/16 in. ID by 0.010 in. thick. Thus, extension of each element is about 0.150 in. Control speed is 4.76 in./min and scram speed 102 in./sec. The requirements for these bellows in size and performance are quite similar to the criteria for FTR. There was no indication of any problems with these bellows in over 2 yr of operation.

FARET⁽⁶⁾

FARET was designed as a test reactor in which the environment in the upper part of the reactor vessel was a mixture of argon gas and sodium vapor at 1150 °F. To seal the penetration of the control rod into this chamber, a welded metallic bellows was chosen because 1) the bellows were less complicated and more space-saving than other sealing methods, and 2) advancement in the art of fabricating metal bellows had made available extremely flexible and durable assemblies.

The bellows design used discs of Type 347 stainless steel identical in size to that of EBR-II drive shaft bellows seals. By the addition of a safety factor to the EBR-II design, it was assumed that a stroke of 0.125 in. could be expected from each convolution. With a nominal 25 in. travel, each bellows assembly comprised 200 convolutions or 400 discs. Each disc was impressed with concentric ripples to enhance the long-stroke characteristics and to reduce the spring rate. The free length of the assembly was made 60% of the extended length. This placed the null point of the bellows near the center of the shaft stroke, thus dividing the total force accumulation due to spring rate.

At the time of cancellation of the FARET project, a life expectancy test was in progress on a slightly modified

bellows assembly consisting of 246 convolutions. It was used to effect a seal between a simulated drive shaft and the nozzle of a resistance-heated vessel containing 1150 °F sodium blanketed with low-pressure argon. It was operated vertically at 11 in./min through a 36 in. reciprocating stroke, thus subjecting the test bellows to a 17% greater stroke per convolution than is expected in reactor service.

Normal life expectancy in such a test was 10,000 cycles. The bellows operated more than 17,400 cycles with no loss of gas pressure, no discernable deterioration of the bellows proper, and no impairment of performance due to sodium or oxide deposits on bellows or drive shaft. The intention at that point was to continue the test until there was sufficient evidence to warrant disassembly for inspection.

Liquid Metals Engineering Center (LMEC)⁽⁷⁾

A test program was scheduled to evaluate diaphragm type welded bellows for use in sodium vapor above a 1200 °F sodium pool. Two bellows each from two manufacturers were tested and reported as of February 1968. The fabrication specifications included the following:

- Helium leak test required leak rate not to exceed 1×10^{-7} STP cm³/sec.
- Bellows to be Type 347 stainless steel from the same heat.
- Stroke length 5.00 in., compression 2.5 in., extension 7.5 in., wall thickness 0.004 in., maximum OD 1 3/4 in., minimum ID 1/2 in., maximum solid length 1 1/4 in.

Manufacturer "A" (Belfab Corporation) supplied bellows with 50 convolutions, and manufacturer "B" (Belmetrics Corporation), 70 convolutions. The conditions of the test were as follows:

- Sodium pool maintained 30 in. below bottom of test bellows which was entirely inside the test chamber.

- Sodium temperature 1200 °F.
- Argon cover gas pressurized to 20 in. of water above atmospheric.
- Upper end of bellows maintained at 900 °F.
- Stroke 4 1/2 in. at 9 in./min.
- Proposed test duration 29,000 continuous cycles followed by 1000 cycles with a dwell of 1 hr between strokes.

The type "A" bellows completed 30,000 continuous cycles and 493 intermittent cycles at which point one of them failed. Both were removed, cleaned, and sectioned for examination. The failure appeared typical of stress fatigue in the heat affected zone of one of the inner welds. It was concluded that presence of sodium oxide in the crevice of weld junctions resulting from long term exposure probably will present the major obstacle to successful operation of welded bellows.

Both type "B" bellows failed in less than 1300 continuous cycles. Examination showed severe pitting on both surfaces associated with cracks in many locations in the region of the inner welds. The marked difference in performance between the "A" and "B" bellows is ascribed to differences in manufacturing techniques particularly as related to the difficult, small diameter inner weld.

The principle conclusion drawn from the test was that short term service in sodium vapor may be satisfactory, but that long term (1 to 20 yr) does not appear promising until methods are developed for minimizing sodium vapor deposition.

Advanced Sodium Cooled Reactor Program⁽⁸⁾

An effort was carried on for some time at Atomics International to develop a sodium-immersed control rod for the next large SGR. Before the program was discontinued about 1963, several tests were made on bellows seals. These tests

are not particularly applicable to our FTR design, but one test in particular indicates the resistance of Type 316 stainless steel welded bellows to operation in liquid sodium at 1200 °F, a very rigorous environment. This bellows, 18 convolution subjected to a 2.16 in. stroke, completed the following:

- 40,000 shim cycles (404% of design life) at the design stroke-to-compressed length ratio of 4 to 1
- 630 scram cycles (109% of design life) at design stroke with 1 hr dwell in the compressed position
- 640 scram cycles (110% of design life) with a two-hour dwell
- 3470 shim cycles (35% of design life) at 10% above normal stroke length.

Only after this complete program did the bellows finally rupture near the weld of an inner convolution.

Sodium Component Test Installation (SCTI)⁽⁹⁾

Three expansion joint bellows have failed in the main piping of the sodium heat transfer loops. These are massive 10 in. diam 2-ply hydraulically formed bellows of Type 304 stainless steel. They are completely unlike the bellows of concern to this study, but the circumstances of their failure are of interest. They had failed through heavy intergranular corrosion caused by sensitization of the material from a 1300 °F "bakeout" treatment specified in the fabrication. To eliminate future occurrences, the specification has been changed to 800 °F for this treatment. This incident points up the effects that fabrication techniques can exert on subsequent service performance.

Snap 10A Expansion Compensator^(2,10)

These reports describe the development, qualification, and flight system acceptance testing of expansion compensator

units for the Snap 10 A Nuclear Power Unit. These units incorporate welded metallic bellows. Their diameter and expected service differ considerably from that of the control rod seals. They use the same gage material (0.010 in.), but it is AM-350 steel and will see liquid NaK at 750 °F in service.

These reports are of value primarily for their detailing of the program on weld development and quality assurance. Because of variable weld quality early in the program, the following measures were taken:

- Welding process control by the manufacturer was reviewed and changes in equipment, instrumentation, and inspection were made.
- A weld bead specification applicable to thin foil TIG burndown welds was applied to bellows fabrication. It required a minimum penetration depth of $1.0t$ (see Figure 2) and laid down limits for porosity and inclusions.

FIGURE 2. Weld Dimensions

- Radiographic inspections of all convolution welds were made to implement the penetration and porosity specification.

Upward of 1000 welds were sectioned and examined metallographically. Figure 3 shows some typical welds as traced directly from 100X metallographs. From this study a statistical correlation was made between weld width and penetration. This provided an inspection technique for estimating penetration from easily accomplished weld bead width measurements. This experience should prove useful in developing bellows seals for FTR applications.

RECOMMENDATIONS

Study of the references on which this document is based has suggested the general content for a purchase specification for bellows seals for the FTR control drives. A tentative specification is outlined in Appendix A. It must be pointed out, however, that before it can be used for actual procurement it must be thoroughly reviewed, rounded out, and modified as required. Any or all parts of this suggested specification must be considered for possible modification, deletion, or amplification. The following steps are recommended, aimed at production of a final firm procurement specification:

- Visit the plants or laboratories shown to have had experience with bellows approximating our requirements. Interview the authors of the reference documents for their recommendations regarding specifications and competent manufacturers.
- Contact outstanding bellows producers to estimate their capabilities and limitations.
- Obtain input from FFTF project personnel and PNL materials, inspection, and fabrication specialists.
- With this background, produce finished drawings and specifications suitable for actual procurement.

a. Acceptable Weld Bead

b. Weld Bead with Large Pore
(unacceptable)

c. Unsymmetrical Weld Bead
(unacceptable)

d. Undersize Weld Bead
(unacceptable)

FIGURE 3. Bellows Weld Bead Cross-Sections

APPENDIX A

TENTATIVE SPECIFICATION FOR FTR CONTROL
DRIVE BELLOWS SEAL

APPENDIX A

TENTATIVE SPECIFICATION FOR FTR CONTROL
DRIVE BELLWS SEAL1.0 PURPOSE AND SCOPE

This specification states requirements for the procurement of the bellows seal for the control rod drive for the FTR.

2.0 APPLICABLE DOCUMENTS

The following documents of exact issue shown form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced here and detail within this specification, the detail requirements of this specification shall be considered a superceding requirement.

2.1 STANDARDS

ASTM-A167-63

ASTM-A370

ASTM-112

2.2 DRAWINGS

Drawing is yet to be issued.

3.0 REQUIREMENTS

The following physical, chemical, and metallurgical requirements shall be met.

3.1 CHEMICAL COMPOSITION

The steel used for these bellows shall conform to the chemical requirements for TP 347 as stipulated in ASTM-A167-63.

3.2 MECHANICAL PROPERTIES

Tensile properties of the sheet material used for the bellows discs shall be determined using methods described in ASTM-A370. Said material shall conform to the following requirements:

Tensile Strength, minimum psi	75000
Yield Strength, minimum psi	30000
Elongation, 2 in. gage, minimum %	40

The properties shall be reported for each lot of material used and each value reported shall be the average value obtained from three specimens.

3.3 DIMENSIONS

The exact dimensions and tolerances shall be as shown in drawing (final drawing not available at this time). Nominal dimensions are listed below:

Outside diameter, in.	4.0*
Inside diameter, in.	2.0*
Diaphragm thickness, in.	0.010
Length, in.	
Extended	52.0*
Free	35.0
Compressed	14.0*
Solid (assuming 0.030 in. weld bead)	10.0
Maximum excursions from free state	
Extension, in.	25.0
Compression, in.	25.0
Number of Convolutions	
Per inch of free length	9.6
Total	336

* Specified by FFTF project for this study

Total excursion per convolution

Working stroke, in.	0.125
Maximum allowable, in.	0.150

3.4 GRAIN SIZE

The maximum average grain size in the sheet material from which the diaphragms are made shall not exceed ASTM micrograin size No. 6 as determined by ASTM #112.

3.5 TEMPER

Bellows shall be furnished in the as-worked temper.

3.6 SURFACE CONDITION

Finished bellows shall be free from grease, oil, residual lubricant, weld spatter, and other extraneous materials. Diaphragms shall have a finish of No. 7 or better on both sides according to ASTM-A167-63.

3.7 WELDING

Welds shall be made in accordance with a specification applicable to thin foil burn-down welds. Specifically, the following criteria shall be met:

- Configuration of the welds shall conform generally to the figure below:

- Penetration shall be 1.3t minimum.
- Bead width (W) shall be 2.4t minimum. Average W of all welds in the assembly shall not exceed 3.0t.
- Symmetry of the weld bead shall be such that the minimum overhang on either side is $\frac{W-2t}{3}$.
- Welds shall be 100% radiographed for voids and inclusions. A minimum projected distance, as measured normal to the plane of the bellows diaphragm, of 1.5t is required between the root of the weld and the nearest edge of such a defect.
- Surface of welds shall be smooth and free of undercutting, cold laps, seams, cracks, crevices, or laminations.

3.8 STRUCTURAL INTEGRITY

Bellows shall pass a helium leak test at room temperature and 10 psig with a leak rate not to exceed 1×10^{-7} STP cm³/sec.

3.9 LOT REQUIREMENTS

A lot is defined as all material from a single heat.

4.0 TEST AND VERIFICATION

Certification will be required of chemical composition, mechanical properties, and grain size tests for each lot of material used.

The buyers inspector shall be provided the opportunity to witness and/or perform dimensional gaging and all other production and acceptance tests and inspections. He shall be notified in advance when components are ready for test or inspection, shall have free access to the necessary plant areas, and be provided reasonable facilities and assistance to perform this work.

4.1 PRODUCTION TESTING

Diaphragm Inspection

Individual diaphragms shall be gaged for dimensions. Surface finish (as required in Item 3.6) shall be verified including absence of nicks, scratches, dents, gouges, and abrasions.

Weld Inspection

Welds shall be inspected for conformance to all provisions of Item 3.7 above.

Pressure Test

Complete bellows shall be tested for conformance to Item 3.8 above.

4.2 ACCEPTANCE TEST REQUIREMENTS

Assurance must be provided to the buyers inspector that all bellows, before leaving the seller's plant, conform to Items 3.1 through 3.8 and 4.1 above. Witness or performance of tests and inspections by the buyers inspector does not relieve the seller of responsibility for such conformance.

4.3 RECEIVING INSPECTION REQUIREMENTS

Any or all of the acceptance tests referenced above may be repeated at the buyer's site within 90 days after delivery. Acceptance of the bellows will be contingent upon their passing this inspection.

5.0 PREPARATION FOR DELIVERY

Packaging and Marking

Bellows shall be suitably packaged in rigid wooden containers and individually separated in a manner to insure delivery of undamaged material. Each box shall be legibly and conspicuously marked with the following data:

- Purchase order number
- Name of manufacturer
- Material
- Size
- Lot number.

APPENDIX B

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AND BIBLIOGRAPHY

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