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TECHNICAL DATA RECORD

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DISTRIBUTION J. R. Cleveland J. J. Corugedo W. G. Dewart R. E. Fenton B. S. Pilling D. J. Zweng ETEC Library(10)		ABSTRACT: This report documents the results of the testing performed at Sandia National Laboratory, Albuquerque, New Mexico, on the applicability of a sodium freeze seal type valve stem in a molten salt environment. The freeze seal tests consisted of cycling the valve stem at set temperature intervals, checking the temperature distribution for freeze plug location, and verifying the actuator forces. In addition to the test results, this report also documents the engineering analysis and other tasks performed before testing to form a basis for predicted test conditions and recommendations for the test program. <u>External Distribution:</u> W. Cough, SNLA W. Delameter, SNLL (12) R. Dowling, B&W T. E. Fewell, B&W R. L. Johnson, SNLA M. E. Long, ETEC-PO, SSFL D. Smith, B&W L. Zurcher, B&W		
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I. INTRODUCTION

Babcock & Wilcox is the prime contractor of Sandia National Laboratories for a molten salt subsystem/component test experiment program. The objectives of this project are to resolve the present technical uncertainties relating to the plant subsystems/components, to provide a sound technological base for development of the molten salt solar industry, and to support the design and construction plans for the Saguaro (62-MW) and Solar 100 (100-MW) plants. One of the most critical elements of a molten salt solar thermal system is the valves.

This report documents the results of the testing performed at Sandia National Laboratory, Albuquerque, New Mexico, on the applicability of a sodium freeze seal type valve stem in a molten salt environment. The freeze seal valve stem is widely used in high temperature sodium systems. The stem design solidifies molten salt in the annulus between the valve stem and bonnet extension to provide a seal. This testing was performed under the above-mentioned contract.

Other than the sealing characteristics, a secondary objective of these tests was to determine the actuator forces necessary to operate the freeze seal by measuring actuator pressures. The freeze seal tests consisted of cycling the valve stem at set temperature intervals, checking the temperature distribution for freeze plug location, and verifying the actuator forces. Results demonstrated that the freeze seal stem did not leak at any temperature. Recorded actuator forces were moderate.

In addition to the test results, this report also documents the engineering analysis and other tasks performed before testing to form a basis for predicted test conditions and recommendations for the test program.

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II. PRE-TEST ENGINEERING ANALYSIS

The main tool for evaluating the freeze seal stem and actuator for molten salt service was a computer program that had been developed and used by ETEC for designing freeze seal stems for sodium and lithium valves (References 1 and 2).

The engineering analysis consisted of two aspects, preliminary shear tests and computer modeling analysis, described in the following sections.

A. PRELIMINARY SHEAR TESTS

In order to model actuator forces, some estimate of the shear force in molten salt was necessary. A literature search was done to try to gain some information. Since molten salt shear information was not readily available, a shear test was conducted.

A test specimen (Figure 1), consisting of a hollow shaft inside a hollow cylinder, was fabricated to simulate the shear stress mode encountered during stem operation. Molten salt was melted and allowed to solidify in the annulus between the shaft and concentric cylinder.

A compression test was performed on the tensile test machine at room temperature. Results demonstrated a shear stress of 22 psi with the fracture occurring at the simulated stem surface (400 grid paper surface finish). Figure 2 is the load vs deflection plot obtained from these tests. Figure 1 is a picture of the test specimen after the shear stress test.

Figure 1. Test Specimen after Shear Stress Test on Tensile Machine

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Figure 2. Shear Stress Test Load vs Deflection

B. COMPUTER MODELING ANALYSIS

The computer model used for evaluating the molten salt freeze seal valve stem was based on the design method for sodium valves described in References 1 and 2. Physical property data for the 60% sodium nitrate, 40% potassium nitrate (Reference 3), molten salt were incorporated into the freeze seal modeling computer program along with the shear stress data from the shear test.

Required input consisted of valve dimensions, fin dimensions, and operating conditions. Table 1a is a listing of the required data input for the case of a bulk temperature of 650°F and a pressure of 325 psig.

Output results from the model provided a temperature profile along the stem and fins, freeze stem length, and actuation force. Table 1b shows the design freeze seal stem length of 7.35 in. Table 1c lists the actuator force requirement of 731 lb and the temperature distribution along the stem (X) and fins (Y).

Figures 3 and 4 summarize the results of this analysis. Figure 3 shows the predicted temperature distribution along the stem, while Figure 4 shows the calculated stem length as a function of salt temperature for three different valve stroke lengths.

The operating characteristics for the stem in the molten salt environment were determined to be as follows:

- 1) For loop temperatures up to 1050°F, the stem temperature should be less than 100°F at the stem height of 13 in. (zero elevation is at the base of the valve, the beginning of the molten salt annulus (Figure 3)).
- 2) For a valve with a 6-in. stroke and a molten salt bulk temperature of 1050°F, the freeze stem length should be 12 in. long (Figure 4).
- 3) The maximum actuator force required to operate the valve should be 1000 lb, based on a fluid temperature of 1050°F, a pressure of 325 psig (no cover gas), and a shear stress value of 22 psi.

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Table 1a. Data Input for Computer Modeling of Freeze Seal Stem

FREEZE SEAL ANALYSIS PROGRAM

Stem Material: Stainless Steel
Fluid Material: Molten Salt -60% NaNO₃, 40 % KNO₃

STEM DIMENSIONS

D1	Stem Shaft OD	1.750 inch
D2	Sleeve ID	1.875 inch
D3	Sleeve OD at Stem Height	2.625 inch
D4	Sleeve OD at Base	8.512 inch
Lb	Length - Base to Insulation	3.000 inch
Lb2	Insulation Height on Stem	1.000 inch
Lt	Stem Travel	3.000 inch

FIN DIMENSIONS

N	Number of Fins	6.000 ----
fL	Fin Span	6.000 inch
fT	Fin Thickness	.375 inch

DESIGN CONDITIONS

P	Operating Pressure - Fluid	325. psig
Pg	Cover Gas Pressure	0. psig
Ts	Temperature at Base - Fluid	650. deg F
Tinf	Air Temperature	83. deg F

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Table 1b. Modeling Results - Heat Transfer Parameters and Stem Dimensions
650°F Bulk Temperature, 325 psig

FREEZE SEAL ANALYSIS PROGRAM

Stem Material: Stainless Steel
Fluid Material: Molten Salt -60% NaNO₃, 40 % KNO₃

HEAT TRANSFER PARAMETERS

e	Surface Emissivity	.80
Fr	Rad Factor - Stem	.52
Fr _f	Rad Factor - Fin	.26
Ld/Lth	% Unplugged Stem	.25
Sp	Shear Stress-Plug	22.30 PSI

NODAL TEMPERATURES

T _s	Temp at Bonnet Base	650.0 deg F
T _b	Temp at Stem Redctn	629.8 deg F
T _o	Temp at Insul End	514.9 deg F
T _l	Temp at Plug (x=L)	470.0 deg F

COEFFS FOR BARE REGION OF FINNED STEM (@T_xBAR)

T _x BAR	Stem Reprnt. Temp	481.3 deg F
H _c	Convective Coeff	1.95 Btu/hr-sq.ft.-deg F
H _r	Radiative Coeff	1.37 Btu/hr-sq.ft.-deg F
H	Ave. Coeff (H _c +H _r)	3.32 Btu/hr-sq.ft.-deg F
m	Stem Const Eq.5/6	4.563 1/FT
m _l	Stem Const xlength	.895 ---

COEFFS FOR FINNED SECTION OF STEM (@ T_yBAR)

T _y BAR	Ave Temp Fin End	216. deg F
T _y BAR	Rep Temp for Fin	282. deg F
F _{Hc}	Convective Coeff	1.64 Btu/hr-sq.ft.-deg F
F _{Hr}	Radiative Coeff	.46 Btu/hr-sq.ft.-deg F
F _{Hf}	Ave. Coeff (F _{Hc} +F _{Hr})	2.09 Btu/hr-sq.ft.-deg F

OVERALL COEFFS - FINS & STEM

m _f	Fin Const Eq. 22	3.52 1/FT
H _{fs}	Efctv Cf Finned Region	35.9 Btu/hr-sq.ft.-deg F
B	Constant Eq. 27	.3 ----
H _e	Efctv Coef Finned Stem	12.2 Btu/hr-sq.ft.-deg F

STEM DIMENSIONS

L _d	Length added as margin	.59 in
L _t	Stem Shaft Travel	3.00 in
L _s	Freeze Seal Plug Len.	.41 in
DL	Delta on Length Calcd	.00 in
L _{th}	Stem Len. Insul to Plug	2.35 in
L _{b2}	Len.- Intrfc. to Insult.	1.00 in
L _{b1}	Len.- Base to Intrfc.	2.00 in
L _{tot}	Total Frz Stem Length	7.35 in

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Table 1c. Modeling Results - Actuator Force and Temperature Distribution
650°F Bulk Temperature, 325 psig

LINEAR MOTION

MIN FORCE= 433. LB
MAX FORCE= 731. LB, FOR PLUG= 5.76 IN, SHEAR= 22.30 LB/SQIN,
RDT FORCE= 2194. LB, AND AVE STEM TEMP= 135.0 F

TEMPERATURE PROFILE ALONG SHAFT LENGTH
X=0 at Insulation Surface and Y=0 at Shaft Surface

X dist	Temperature						
-3.0 IN	650. F						
-1.0 IN	630. F						
X dist	Temperature						
.0 IN	515. F						
Y dist	deg F	Y dist	deg F	Y dist	deg F	Y dist	deg F
1.5	373.	3.0	287.	4.5	242.	6.0	228.
X dist	Temperature						
1.0 IN	381. F						
Y dist	deg F	Y dist	deg F	Y dist	deg F	Y dist	deg F
1.5	283.	3.0	224.	4.5	193.	6.0	183.
X dist	Temperature						
2.0 IN	291. F						
Y dist	deg F	Y dist	deg F	Y dist	deg F	Y dist	deg F
1.5	222.	3.0	181.	4.5	159.	6.0	153.
X dist	Temperature						
3.0 IN	231. F						
Y dist	deg F	Y dist	deg F	Y dist	deg F	Y dist	deg F
1.5	182.	3.0	153.	4.5	137.	6.0	132.
X dist	Temperature						
4.0 IN	192. F						
Y dist	deg F	Y dist	deg F	Y dist	deg F	Y dist	deg F
1.5	156.	3.0	135.	4.5	123.	6.0	120.
X dist	Temperature						
5.0 IN	170. F						
Y dist	deg F	Y dist	deg F	Y dist	deg F	Y dist	deg F
1.5	141.	3.0	124.	4.5	115.	6.0	112.
X dist	Temperature						
6.0 IN	160. F						
Y dist	deg F	Y dist	deg F	Y dist	deg F	Y dist	deg F
1.5	135.	3.0	120.	4.5	111.	6.0	109.

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Figure 3. Predicted Temperature Distribution as a Function of Stem Height

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Figure 4. Freeze Seal Stem Length as a Function of Temperature

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III. TEST DESCRIPTION

A. TEST ARTICLE DESCRIPTION

The test article consisted of the freeze seal stem and actuator from a 6-in. sodium gate valve which had been removed from one of ETEC's facilities. The stainless steel valve stem was modified to include a 6-in. standard, 1500-lb welded neck, raised-face flange (Schedule 80, type 304 stainless steel) for adapting to the Bench Test Experiment Loop at Sandia National Laboratories in Albuquerque, New Mexico.

Some of the overall physical characteristics of this test article were as follows:

Stem Shaft OD	1.750 in.
Sleeve ID	1.875 in.
Sleeve OD	2.625 in.

Number of Fins	6
Fin Span	6 in.
Fin Thickness	0.375 in.
Fin Overall Length	20 in.

Overall Length - Stem Assembly	40 in.
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The valve stem had a design stem travel of 6 in.; however, valve cycling testing was based on a valve stroke of 3 in. in order to be consistent with other valve tests.

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B. TEST FACILITY

Testing was performed at Sandia National Laboratory's Central Receiver Test Facility, Albuquerque, New Mexico in the Solar Molten Salt Bench Test Experiment Loop. On-site test followup was provided by Babcock & Wilcox and ETEC. The design maximum conditions of this loop for this test were:

Design Pressure	400 psig
Design Temperature	1075°F

Figure 5 is an isometric of the test loop. The test location of the freeze seal stem can be seen in Figure 5.

C. TEST DEFINITION AND INSTRUMENTATION

1. Definition

The test program consisted of two types of tests. The first type simulated the conditions encountered by a shutoff valve; the valve was cycled from full open to full closed position. This cycle was repeated at a 5- to 10-minute rest interval. The second type simulated a throttle valve test consisting of 10 cycling series of one full open-close cycle and approximately 8 to 10 consecutive $\frac{1}{4}$ -stroke open-close cycles.

In Figures 7 through 12, whenever an event number is used as one of the axis, it represents the open-close position of the valve stem in the cycling previously described. For example, Events 1 and 2 represent the result of cycling the valve the full 3-in. stroke, from open-to-close and close-to-open, respectively. Events 3 and 4, and so on, represent the $\frac{1}{4}$ -stroke cycling with valve position going from open-to-close and close-to-open, respectively. Events 21 and 22 would represent the last opening and closing of each series, but only data up to Event 18 were reduced for consistency in the data plots.

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Figure 5. Babcock & Wilcox Solar Molten Salt Bench Test Experiment Loop

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Tests were performed at a pressure of 325 psig and temperatures of 550, 650, 700, 750, 780, and 800°F.

2. Instrumentation

The instrumentation was divided into two groups: (1) The first group was used to obtain the temperature distribution on the valve stem to establish the location of the freeze plug, and (2) the second provided actuator force requirements at the different operating temperatures.

Table 2 is a list of the instrumentation including both range and frequency of the measurements.

Table 2. Test Instrumentation

Parameter	Quantity	Frequency of Measurement
TEMPERATURE DISTRIBUTION INSTRUMENTATION		
Stem Temperature	100-1100°F	18 One sample every 2 minutes
Stem Base Temperature	100-1100°F	1 One sample every 2 minutes
Bonnet Temperature	100-1100°F	1 One sample every 2 minutes
Ambient Air Temperature	0-100°F	1 One sample every 2 minutes
ACTUATOR FORCE INSTRUMENTATION		
Actuator Line Pressure	0-100 psig	2 Continuously
Valve Position Indicator	0-3 in.	1 Continuously

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IV. TEST DATA ANALYSIS AND RESULTS

A. DATA REDUCTION

Data reduction was divided into two groups. The first group consisted of compiling for each test the temperature distribution as a function of stem location and time. The second group consisted of measuring at the actuator pressures.

Figure 6 is a sketch showing the forces acting on the stem; the shear force includes the drag against the molten salt. The drag force from the packing was determined from the 550°F dry test (no salt). The hydraulic imbalance force was determined by multiplying the system pressure (325 psig) by the stem cross-sectional area (2.4 in.²). The total actuator force was calculated by taking the differential pressure across the actuator and multiplying it by the actuator area (221.5 in.²). The shear force was calculated using the formula shown in Figure 6.

B. TEST RESULTS

To demonstrate the seal performance, open/close cycle testing of the freeze seal stem was performed in a pressurized stagnant molten salt environment. A flowing system was not a requirement.

Table 3 provides a summary of the testing performed and the observed valve operation, in terms of the smoothness of the stroking. Tests a) through d) at 550°F showed overall valve motion to be relatively smooth with some jerkiness during full close-to-open cycling. At 650°F, valve motion was initially jerky, thereafter becoming smooth as stroking continued, tests a) through e). The last two 650°F tests, f) and g) were performed after the 800°F test to verify the repeatability of smooth operation after the higher temperature tests; both tests confirmed similar valve stem motion characteristics. Valve stroking at 750°F demonstrated the smoothness of stroking to have some relationship with the type of stroke. Full strokes were usually jerky, small increments in position ($\frac{1}{4}$ -strokes) were easier to control. Valve stroking at 800°F was very jerky.

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$$F_{thrust} = F_{shear} + (-)F_{hp} + F_{df}$$

$$F_{shear} = F_{thrust} + (-)F_{hp} - F_{df}$$

$$F_{hp} = 780 \text{ lbs}$$

$$F_{df} = 590 \text{ lbs}$$

Figure 6. Force Diagram on Freeze Seal Stem

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Table 3. Valve Operation Summary

Date	Test Description	Observed Valve Operation
<u>Temperature - 550°F</u>		
05/23/85	a) Dry test - no salt in system	Smooth operation
05/23/85	b) Test 1 (full open/close cycling)	O/C** - smooth C/O** - jerky
05/23/85	c) Test 2A*	Smooth
05/23/85	d) Test 2B*	Smooth
<u>Temperature - 650°F</u>		
05/24/85	a) Test 1	Smooth
05/24/85	b) Test 2A*	Smooth initially - slightly jerky latest cycles (O/C)
05/24/85	c) Test 2B*	Slightly jerky initially - smooth later
05/24/85	d) Test 2C*	Very smooth
05/28/85	e) Test 2D* (no pressure)	Jerky initially - smooth later
05/31/85	f) Long endurance	Jerky initially - then smooth
05/30/85	g) Test 2E* (700°F)	Jerky initially - smooth later
<u>Temperature - 750°F</u>		
05/29/85	a) Test 1	Very jerky
05/29/85	b) Test 2A*	Full strokes very jerky - ½ strokes smooth
05/29/85	c) Test 2B*	Full strokes very jerky - ½ strokes smooth
05/29/85	d) Temperature 780°F	Smooth
<u>Temperature - 800°F</u>		
05/30/85	a) Test 2A*	Very jerky

*Letter represents number of times that test was repeated; i.e., B=2, C=3, etc.

**O/C = open-close cycle; C/O = close-open cycle.

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Shear forces for the open-close stem cycling were noted to vary with no particular pattern. Forces for the close-open $\frac{1}{4}$ -stroke cycling were found to be fairly consistent for all temperature tests with values in the range of 1000 to 2000 lb. Predicted shear force for the 650°F test was 731 lb, and 929 lb for the 1050°F test

The actuator pressure recorder was readable only to a 2 psi increment; with a plenum area of 221.5 in.², this resulted in an accuracy on the shear force of 450 lb.

It should be emphasized that at no time throughout the testing was a leak observed.

1. Tests at 550°F

Results from the dry test at this temperature were used to estimate the drag caused by the packing. An average value of 590 lb was calculated for this force.

Figures 7a and 7b provide the stem temperature profile recorded. The history of this profile can be seen in Figure 7a where the upward movement of the salt can be deduced as a function of time. Figure 7b locates the melting region (430 to 470°F) of the salt and therefore the start of the molten salt plug.

Figures 8a and 8b are a summary of the resultant force (shear and drag) that was required to cycle the valve stem. The average force to operate the stem for $\frac{1}{4}$ -stroke cycling (Events 3 to 18) can be seen to average between 2000 to 4000 lb. Data for events 19-22 are not shown for consistency since several of the cycles did not include these events.

2. Tests at 650°F

Figures 9a and 9b present the stem temperature profile. The predicted temperature profile can be seen in Figure 9b.

In Figures 10a through 10d, shear forces are plotted showing an average value for the $\frac{1}{4}$ -stroke (Events 3 to 18) of approximately 3000 lb.

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Figure 7a. Temperature Profile as a Function of Time for Test at 550°F

Figure 7b. Temperature Profile as a Function of Location on Stem for Test at 550°F

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Figure 8a. Shear Force as a Function of Event for Test 2A at 550°F

Figure 8b. Shear Force as a Function of Event for Test 2B at 550°F

Figure 9a. Temperature Profile as a Function of Time for Test at 650°F

Figure 9b. Temperature Profile as a Function of Location on Stem for Test at 650°F

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Figure 10a. Shear Force as a Function of Event for Test 2A at 650°F

Figure 10b. Shear Force as a Function of Event for Test 2B at 650°F

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Figure 10c. Shear Force as a Function of Event for Test 2C at 650°F

Figure 10d. Shear Force as a Function of Event Comparing Tests 2A, B, and C at 650°F

A test was conducted to investigate the effects of pressure (test 2D). The pressure was reduced from 325 to 0 psig. Figure 11a shows these results with no significant difference except that the average value is fairly close to the predicted value of 731 lb.

The effects of long endurance cycling (see Table 3 for chronological order) are shown in Figure 11b, where it can be seen that the temperature profile stabilized after approximately 50 minutes of operation.

The last test under this temperature category (test 2E) (see Table 3 for chronological order) consisted of type 2 testing with a 700°F bulk temperature. Temperature distribution can be seen in Figure 12a and shear forces can be seen in Figure 12b.

3. Tests at 750°F

In order to reach this temperature (750°F), 3 in. of insulation were added up the stem. The new insulation level became the old 3-in. mark.

Figures 12a and 12b denote the stem temperature profile. Comparison of the results shown in Figures 12b and 9b show how the addition of insulation increased the salt level 3 in. up the stem. Figure 12c shows the shear forces comparing close to the previous values.

4. Test at 800°F

At this temperature (800°F), open/close cycling of the stem was very jerky. Due to the jerky motion observed, the data was inconclusive and therefore not included in the test results.

Due to restrictions on time and the fact that the heat trace system could not raise the temperature any higher than 800°F, no higher temperature tests were performed.

5. Post-Test Inspection

Post-test inspection of the freeze seal stem revealed scoring or wear marks up to 3 in. long on approximately half of the stem diameter. Inspection of the lower guide bushing also revealed it to have some damage. Inspection was unable to verify whether the damage to the stem and bushing occurred during testing or during subsequent disassembly. If damage did occur during testing, it could possibly explain some of the jerky motion. Salt was found 19 in. up the stem.

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Figure 11a. Shear Force as a Function of Event for Test 2D at 650°F and no Pressure (0 psig)

Figure 11b. Temperature Profile as a Function of Time for Long Endurance Test at 650°F

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Figure 12a. Temperature Profile as a Function of Time for Test at 750°F

Figure 12b. Temperature Profile as a Function of Location on Stem for Test at 750°F

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Figure 12c. Shear Forces as a Function of Event for Test at 750°F

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The results, both observational and measurable, demonstrate that the freeze seal stem provided adequate sealing for all temperatures without any leaks. Measured temperature profile demonstrated that the solid-liquid interface location predictions were conservative.

Valve motion behavior (smoothness of stroking), outlined in Table 3, indicated increased friction between the stem and salt, or the presence of other mechanical friction. Further evaluation to determine the cause of this behaviour is needed.

Measured shear-drag force had an average value for full-open cycling of 6000 lb. Values ranged from 9000 lb to 1000 lb where the lowest was usually for the close-open stroke. The average shear-drag force for the 1/4-stroke cycling had an average value of 3000 lb with a minimum value of less than 1000 lb and a maximum of 6000 lb.

The minimum value of 1000 lb obtained for this shear force was very close to the maximum predicted value of 929 lb.

B. RECOMMENDATIONS

An additional test program is recommended to further define the motion characteristic behavior of a molten salt freeze seal valve as a function of temperature and pressure. Testing should be oriented to determine the effects of temperature, pressure, freeze seal dimensions and surface finishes, shear/creep strength, and fin dimensions and tolerances.

Results should be used to design and fabricate a new prototypic freeze seal stem for key feature testing.

VI. REFERENCES

1. "Valve Freeze Seal Design Method," by S.M. Cho, ETEC Document No. TI-00-LME-015.
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3. "Physical Properties Data Compilations Relevant to Energy Storage - II Molten Salts: Data on Single and Multi-Component Salt Systems," NSRDS-NBS 61, Part II.