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FUSION TEST REACTOR

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Author

Haughian, J.

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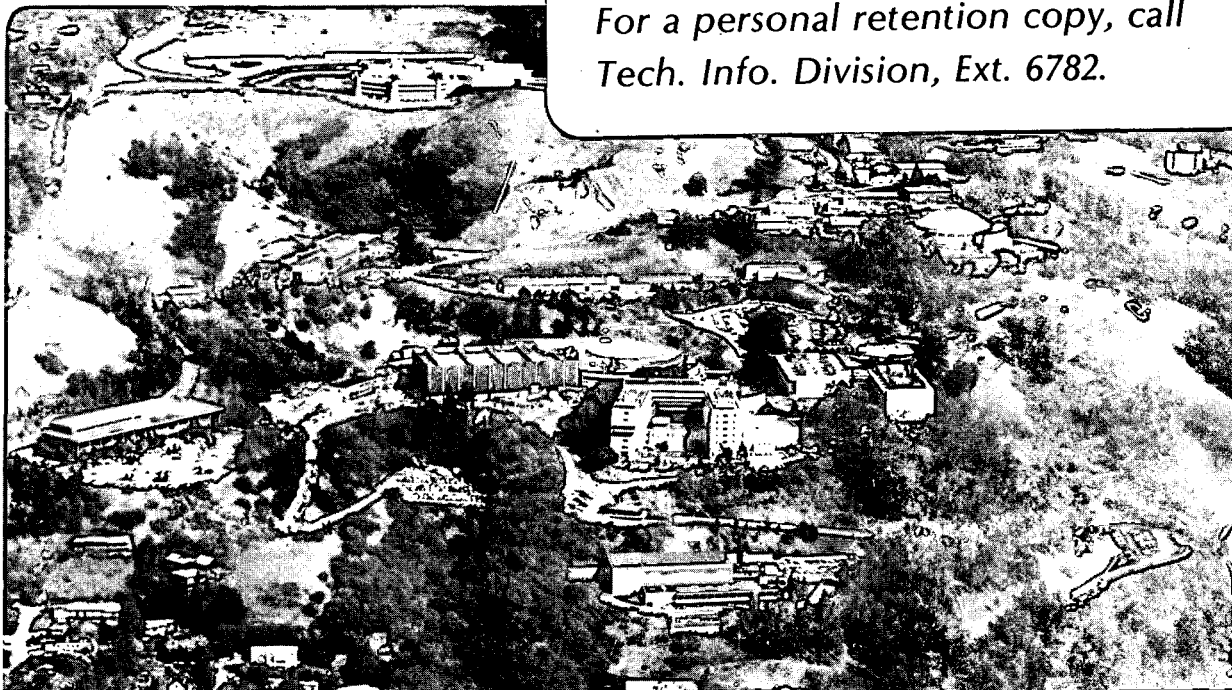
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J. Haughian, K. Lou, J. Greer, M. Fong,
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THE TESTING OF THE RECTANGULAR PIVOT-POINT BELLOWS
FOR THE
PPPL TOKAMAK FUSION TEST REACTOR

J. Haughian, K. Lou, J. Greer, M. Fong and D.T. Scalise
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

1. Role of Bellows in TFTR

The Neutral Beam Pivot Point Bellows (PPB) is installed in the duct which connects the Neutral Beam Enclosure to the Torus. This bellows, located at the pivot point, must fit the severely limited space available at the pivot-point location. Consequently, it has to be made rectangular in cross section with a large inside area for beam access. This leads to small convolutions with high stress concentrations. The function of the bellows is to permit change in the angular positioning of the neutral beam line with respect to the Tokamak, to isolate the Neutral Beam Line from the deflection of the Torus during bake out, and to allow for all misalignments. Internally the bellows will have a vacuum along with such gases such as hydrogen or deuterium. Externally, air or nitrogen gas will be present. The bellows is shown in Figures 1, 2, 3 and 4. It is constructed of Inconel 718 convolutions welded together to provide a clear rectangular opening of 23.4 by 32.2 inches, joined to a 625 Inconel flange at each end.

2. Role of LBL and Bellows Test Parameters

The Princeton Physics Laboratory (PPL) supplied five welded bellows (fabricated to PPL specifications) to the Lawrence Berkeley Laboratory (LBL) for testing and analysis. The basic objectives of the LBL testing and analysis included leak checking, determination of structural strength, bake out stresses, and life cycling, as follows:

- a. Perform leak tests on bellows to determine if leak rate is acceptable and to seal excessive leaks where possible.
- b. Perform strain gage tests at various surface locations on bellows to give working stresses under various loads.
- c. Perform stress analysis for various surface locations on bellows to determine stresses under various loads and to determine ultimate strength of bellows.
- d. Perform axial-deflection and angular-rotation cycling tests to determine effect of repetitive loading on the leak rates.
- e. Perform test at elevated temperature to determine effect of temperature on the leak rate.

Test a. above was performed on all five bellows.

Tests b. through e above are to be performed on only one bellows, which is designated as a "prototype" bellows.

A summary of the test parameters is given in Table 1.

3. Status of Test Program, Overview of Current Test Results, Scope of Paper

As of the writing of this paper, the test program described above is still in progress. An overview of the current results is given in this section. In other sections of this paper, a more detailed description of current results will be given as well as plans to solve the bellows problem.

For the four production bellows, an overview of the current test results follows:

- a. All four production bellows leaked excessively.
- b. Leaks on only one bellows, successfully repaired after numerous attempts, passed the leak test. It has been installed at PPL.
- c. Leaks on two bellows could not be repaired. Despite repeated attempts, total leak rate increased and new leaks appeared as old leaks were sealed. Leaks were 2×10^{-7} TL/sec⁻¹, and 5×10^{-6} TL/sec⁻¹, respectively.
- d. Leak repair attempts on the fourth bellows were cancelled when tests on the prototype bellows showed that leak rates increased excessively with life-cycling tests.

For the prototype bellows, an overview of the strain gage and life cycling tests follows:

- a. Axial Deflection. Stresses versus axial deflection were measured at various locations of the center and end convolutions both with and without vacuum loads. Typical results are shown in Figure 5, 6 and 7.
- b. Life Cycling Tests. With vacuum inside the bellows, leak rates and stresses were measured as the axial deflection was cycled between +1.5 to -1.4 inches. It was found that the leak rate increased significantly after 20 cycles, so this test was discontinued.

As of the writing of this paper, other strain gage tests are still in progress. These tests included measurements of stresses versus rotational deflection (± 10 degrees easyway ± 3 degrees hardway). The purpose of these rotational tests is to furnish data to permit validation of the theoretical model.

4. TFTR - Bellows Test Equipment

The test setup consists of a rectangular test box with its associated hydraulic system, vacuum system, and data acquisition system. The bellows is installed on the bottom of the test box with a cover closing off the top flange. The test box walls provide for the mounting of the hydraulic cylinders, travel limit switches, feedthrus for electrical and hydraulic lines. This test box is designed for two psig external pressure on the bellows. The extension and compression of the bellows is permitted by use of a splined shaft inside the bellows on its axial centerline. This shaft is replaced with a universal-joint shaft during rotational testing. The universal joint simulates the pivot point of the bellows during actual use. Two viewports in the box allow for observation of the bellows during testing. An overview of the equipment is shown in Figure 8. Details of the bellows and actuating cylinders are shown in Figure 9.

The vacuum system consists of a mechanical pump for roughing the bellows and for backing the diffusion pump. The bellows is pumped down through the bottom of the test box. Leak rate is monitored by a mass spectrometer leak detector when the test box is flooded with helium. Vacuum is monitored by an ion gage and a thermocouple gage. A chart recorder tracks the leak rate and vacuum during the cycling testing.

Test Equipment

Three hydraulic cylinders provide the extension, compression, and rotational motions. The hydraulic system consists of a one hp power unit and three four-way solenoid valves, each directing flow to a hydraulic cylinder. One cylinder provides for the extension and compression of the bellows. The other two cylinders provide for X and Y rotations. Two normally-closed two-way solenoid valves hold the pressure in each cylinder to maintain the bellows' position. Overtravel is prevented by limit switches which are backed up by mechanical stops. These same limit switches are also part of the computer controls during the cycling tests.

The data acquisition system, Figure 10, for the 37 strain gage rosettes consists of a Hewlett Packard 9845 computer, an HP3456A digital multimeter, two HP3496A channel selectors, and a terminal can housing the electrical circuitry. Figure 11 shows the four-wire ohms method of measuring the unbalanced quarter bridge circuits. The measurement of gage resistance with the four-wire ohms method limits the system speed to 130 channels per minute. However, the use of a one milliamp constant-current source eliminates the lead wire error. The resolution of this system is 4.2 microstrains for the 120 ohm rosettes and 1.4 microstrains for the 350 ohm rosettes. A reference gage is mounted inside the test box to monitor temperature variation and its effects.

5. Overview of Theoretical Analysis

LBL entered into a subcontract with Structural Mechanics Associates (SMA) to provide assistance in the theoretical analysis of the bellows. A finite-element analysis was made. This analysis used thin plate and shell elements to model behavior of the bellows as membranes in bending. Approximately

800 elements were used in the finite-element model. The boundary conditions corresponded to either symmetric or asymmetric loads. The underlying governing equations are based on stress tensor formulations. Linearized theory was used.

The numerical analysis was done on the computer using computer programs SAP4, SAPSTAT, and GEMINI. Approximately one hour of CRAY computer time was required.

A brief summary of the results are given in Table 2. This table indicates the Bellows Load Conditions vs. Calculated Peak Stresses.

A more detailed description of the SMA finite element analysis will be given as a separate paper in this Symposium by SMA.

6. Comparison of Theory and Experiment

A preliminary comparison of stresses measured during the tests with those calculated by theoretical analysis has shown mixed results. For the typical center convolution, measured and calculated stresses compare well. For the end convolution, measured and calculated stresses differ substantially.

The comparison between experiment and theoretical results is continuing.

7. The Engineering Design Challenge

The engineering design challenge presented by the pivot-point bellows is due to the following unique combination of requirements:

- a. Non-symmetrical shape (rectangular rather than circular).
- b. Large size (23.4 x 32.1 inch clear opening x 9.1 inch long).
- c. Severe space restrictions prevent the reduction of stress through use of deeper convolutions.
- d. High degree of vacuum-tightness, required to prevent the leak of tritium into the test cell during later phases of operation.
- e. Inconel 718 bellows material to provide high strength at elevated temperature makes weldability difficult.
- f. Severe operational deflection and rotational loading on the bellows.

The proper solution to this challenging problem and the production of satisfactory bellows passing the severe operational tests will push the state-of-art for the design, fabrication technology and stress analysis of this class of large, severely-loaded ultra-vacuum tight, rectangular bellows.

8. Future R & D Objectives and Production Requirements

PPL has indicated their intention to pursue the following course of action to solve the above-described bellows problems:

- a. Interim Solution. As an interim solution, a special box made of stainless steel with one or two flexible convolutions will be used in place of the original pivot-point bellows. This will be adequate to meet the interim requirements of the TFTR during the interim period of operation of about one year beginning in January 1984.
- b. New Load Requirements. With the more accurate TFTR torus data that is now available, more realistic loading requirements for the future pivot-point bellows now can and will be made by PPL.
- c. Research and Development Objectives. A two-pronged R & D program will be followed which has a theoretical branch and a welding-technique branch.

The objectives of the theoretical branch are as follows:

- i. To validate or reconcile the theoretical results from the finite-element analysis with the results from stress measurements for the first prototype bellows.
- ii. To use the validated theoretical model with the new load requirements to seek a design solution which will minimize the stresses in the bellows material.
- iii. If possible in step ii, reduce stresses to point where the bellows material can be stainless steel rather than Inconel. This would greatly facilitate the welding problem and the meeting of the vacuum tightness requirements.

The objectives of welding technique studies are as follows:

- i. Determine techniques to produce vacuum-tight welds; e.g., section a number of weld samples of a joint between corrugations. Control certain sample parameters such as:
 - Edge-surface preparation
 - Cleaning techniques
 - Weld bead size
 - Welding environment (e.g., air, argon)

Vacuum test these samples and try to correlate techniques with results.
- ii. Determine techniques to satisfactorily repair leaking bellows by using control samples, such as in a above.

- d. Production Bellows. Using the design solution found in c above, fabricate four production bellows by fall of 1984.

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Table 1. Bellows Test Parameters-Excerpts from Test Specifications

1. Configuration (See Figures 1 and 2)
2. Bellows Material (Inconel 718 convolutions, Inconel 625 end flanges)
3. Bellows Total Leak Rate, maximum allowed 1×10^{-9} Torr liters sec^{-1}
4. Strain Gage Locations on Bellows laminations

4 corners	-Air side	4 locations
	-Vacuum side	4
2 edges	-Air side	2
	-Vacuum side	2
Total per lamination		12
Total for 3 laminations		
(1 center, 2 ends)		36
5. Axial Deflection Cycling
 - a. 100 cycles of stress-limited a/ extension-compression cycles with and without vacuum inside bellows.
 - b. 10,000 cycles at ± 0.5 inch extension-compression cycles with vacuum inside bellows.
 - If at any time total leak rate exceeds 10^{-9} Torr liters sec^{-1} , deflection cycling is to be stopped.
6. Angular Rotation Cycling
 - a. 100 cycles at ± 10 degrees easy way rotation and ± 3 degrees hardway rotation with (1) no vacuum loads and (2) vacuum inside and 2 psig pressure outside bellows.
 - Record 20 sets of strain gage readings.
 - b. 1000 cycles for above rotations with above internal vacuum and external pressure loads.
 - Record 40 sets of strain gage readings.
 - Measure leak rate. Stop tests if leak rate exceeds 10^{-9} Torr liters sec^{-1} .
7. Thermal Tests

Maximum bake out temperature of temperature cycle 270°C

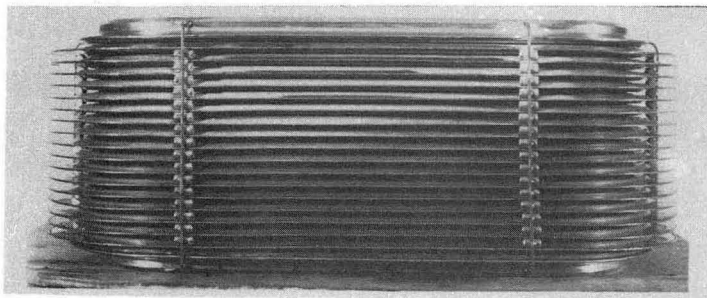
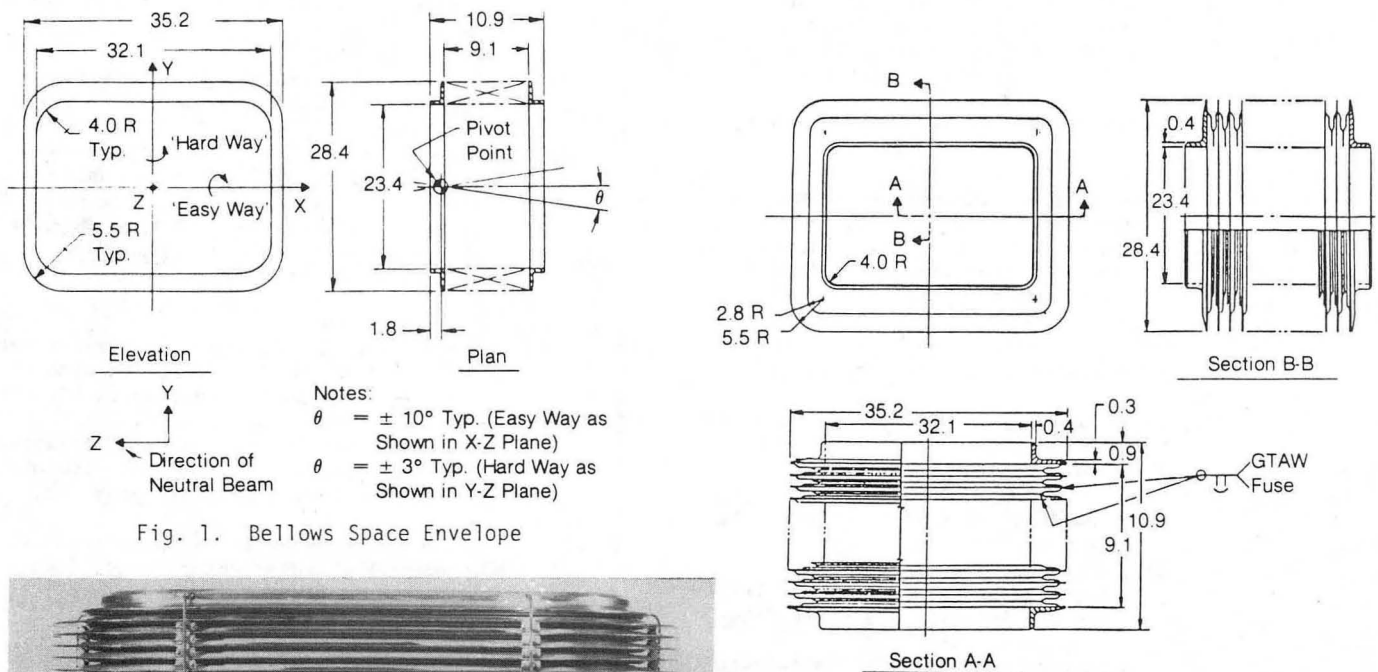
 - Measure leak rate during temperature cycle

- a/ Axial deflections limited to strain-gage measurement of maximum stress equal to 66 percent of yield strength of bellows material; i.e., 120 KSI.

Table 2. Bellows Load Conditions vs. Calculated Peak Stresses

Load Description			Load Condition Name										
			A	B	C	D	E	F	G	H	I	J	K
Vacuum			X	X	X	X		X	X				
+ 2 psi			X						X				
+ Extension Stroke				X		X							
+ Compression Stroke					X								
+ Thermal						X							
+ Extension to 120 psi							X	X	X				
3° Rotation about x-axis										X		X	
10° Rotation about Y-axis											X		X
+ 16.7 psi												X	X
Convolution Location	Stress Type	Direction (σ_1, σ_2)	Calculated Peak Principal Stresses (ksi) ^{1/}										
Center	Tensile	σ_1	12	31	31	32	131	125	126	43	95	49	85
		σ_2	9	11	13	17	26	44	44	11	23	11	17
	Compressive (-)	σ_1	2	-10	-6	-4	-52	-38	-34	-16	-37	-20	-37
		σ_2	-12	-32	-31	-33	-132	-133	-133	-42	-95	-49	-85
End	Tensile	σ_1	7	7	13	26	113	115	115	22	41	29	48
		σ_2	2	2	4	17	77	76	76	15	27	17	30
	Compressive (-)	σ_1	-2	-2	-4	-15	7	5	5	1	2	-1	0
		σ_2	-7	-7	-13	-20	-112	-114	-114	-22	-41	-29	-47

^{1/} From SMA finite-element stress analysis.



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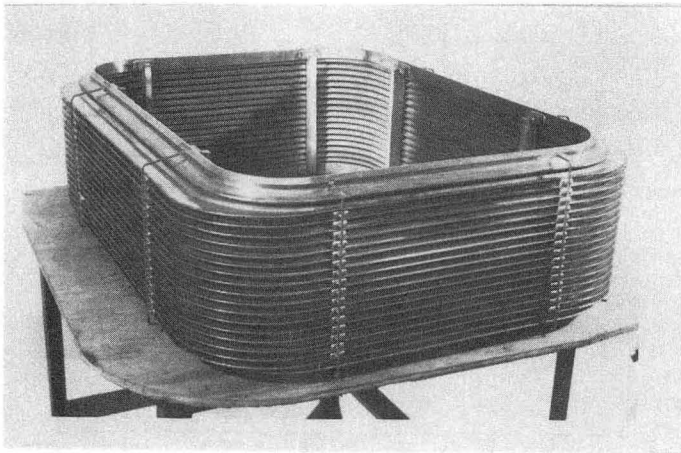


Fig. 4. Pivot Point Bellows

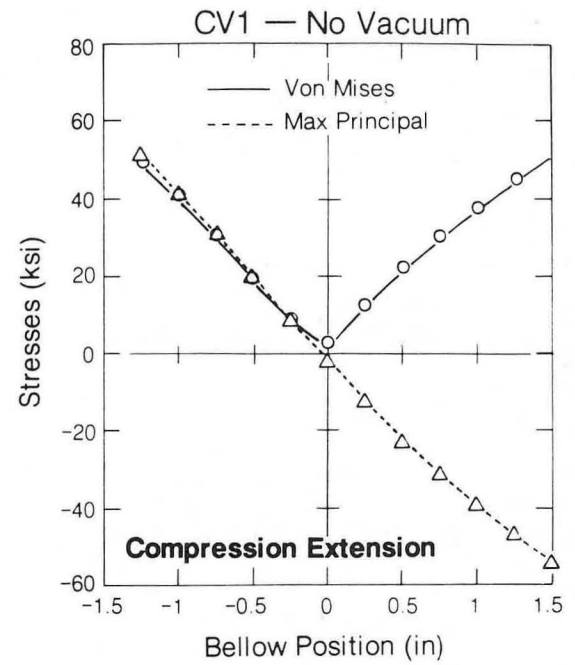


Fig. 6. Stresses at Air

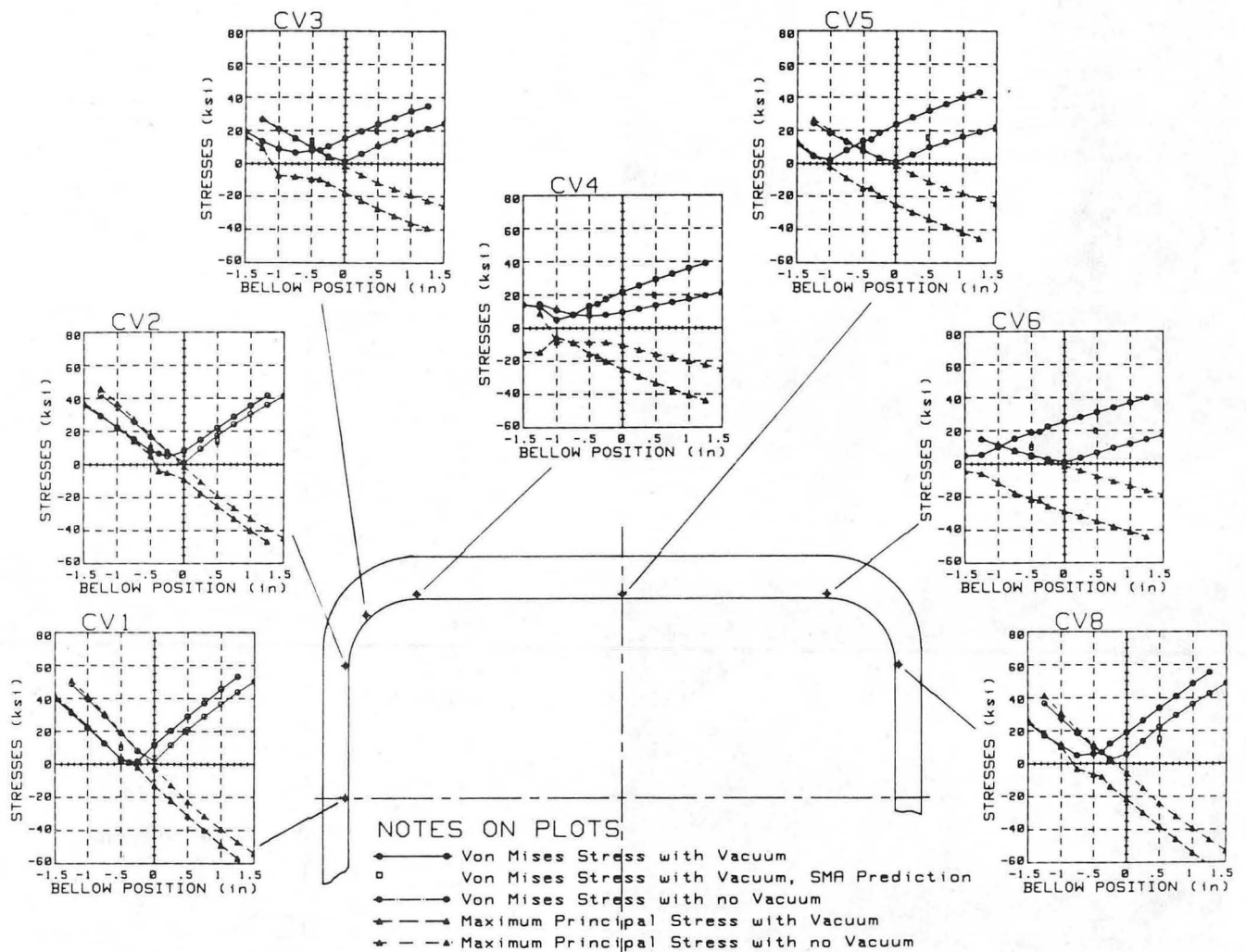


Fig. 5. Stresses vs. Deflection
Center Convolution, Vacuum Side

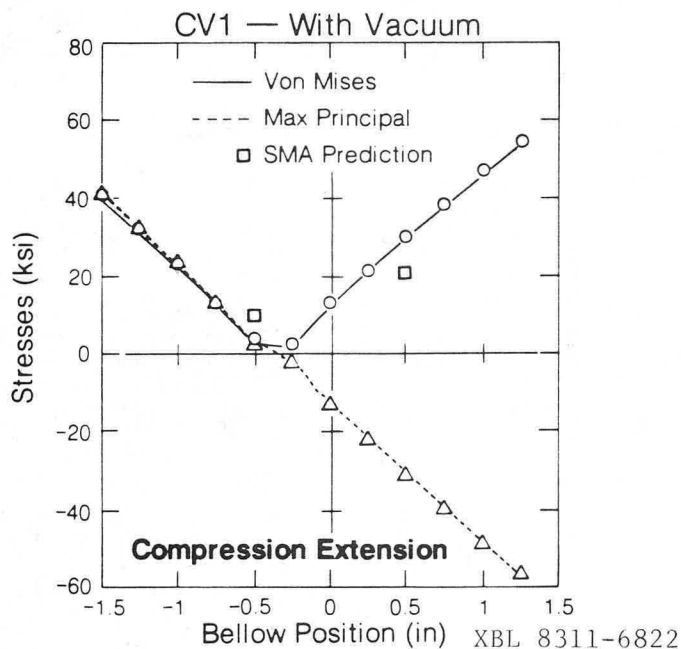


Fig. 7. Stresses at Vacuum

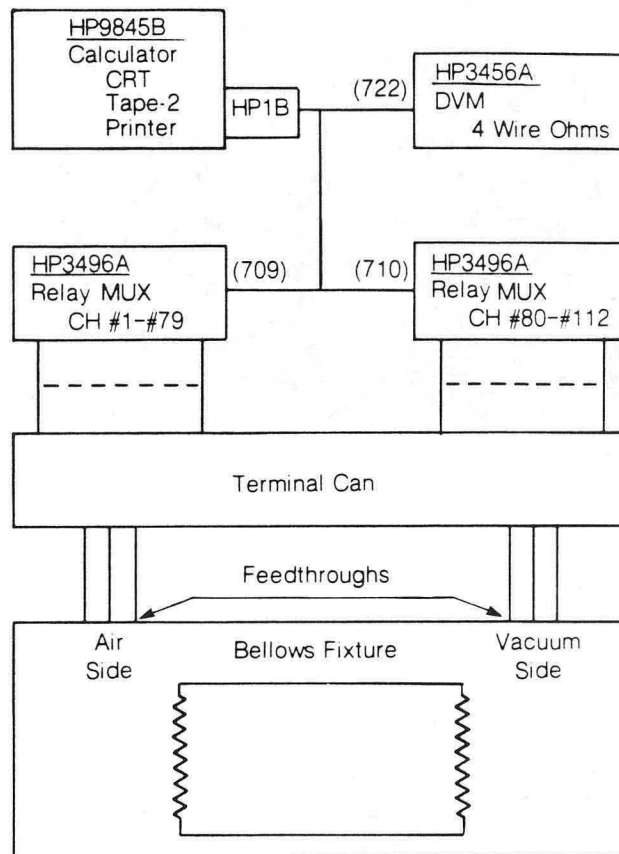


Fig. 10. The Data Acquisition System

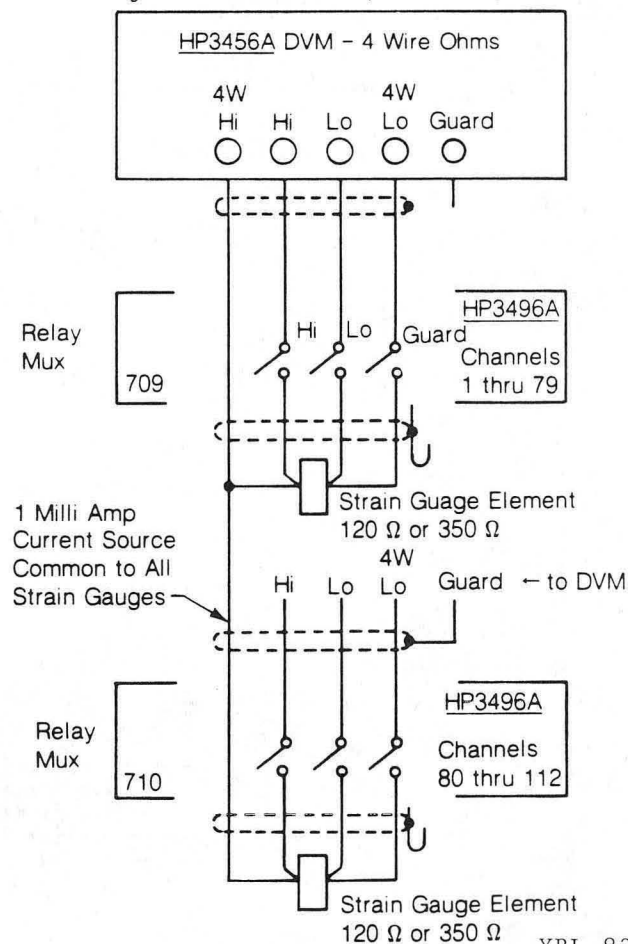


Fig. 11. Wiring Diagram for the Strain Gauges

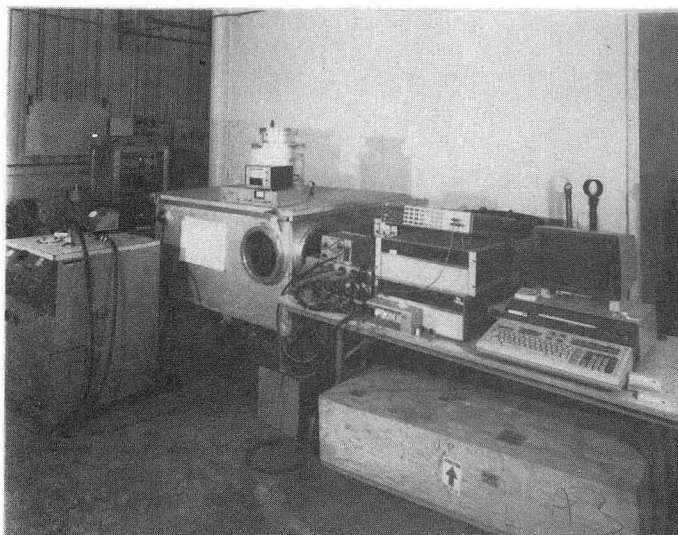


Fig. 8. An overview of the test setup showing (L - R) the vacuum system, the test box containing the bellows & the actuating cylinders, & the data acquisition system

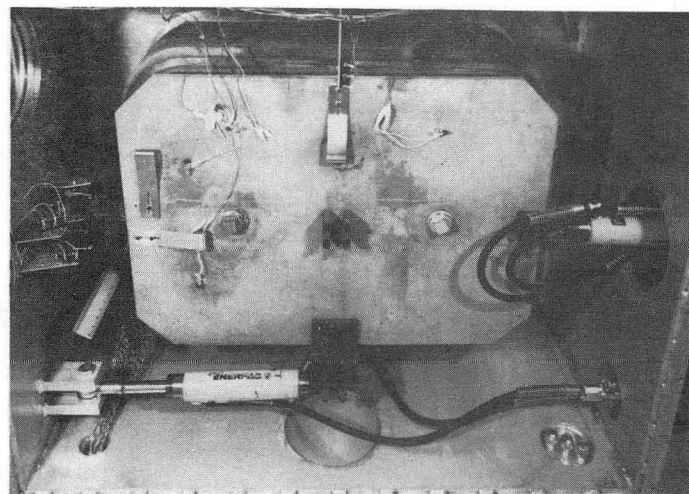


Fig. 9. Details of Test Box, Bellows, and Actuating Cylinders

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