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SNAP 10A
EXPANSION COMPENSATOR

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ATOMICS INTERNATIONAL
A DIVISION OF NORTH AMERICAN AVIATION, INC.

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SNAP 10A

EXPANSION COMPENSATOR

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ABSTRACT

The SNAP 10A Nuclear Power Unit (NPU) utilizes two expansion compensator units (ECU) as follows: (1) to absorb the volumetric increase of NaK due to thermal expansion, (2) to provide a void-free NaK system, and (3) to regulate the NaK system pressure.

In order to fulfill these system operation requirements, an ECU has been developed which utilizes a welded bellows fabricated from AM-350 (SCT-850) precipitation hardening steel foil. For increased reliability, the ECU has a secondary NaK containment housing which permits continued system operation at design power in the event of a bellows failure.

An extensive development test program was conducted on separate bellows capsules and ECU's to evaluate fatigue life, pressure capability, and endurance performance in a high temperature-liquid metal (NaK-78) environment. The parameters affecting welded bellows quality — the material cleaning, welding and heat treating — have been thoroughly investigated. Extensive statistical regression and correlation studies have been performed to establish a suitable weld bead width versus penetration ratio and the size control limits of the bellows welding process.

The secondary containment ECU design is presently in the 90-day endurance phase of the Qualification Test Program. Expansion compensators have been installed in all SNAP 10A Ground Test and Flight Systems and the performances of all units to date have been satisfactory.

I. INTRODUCTION

The SNAP 10A Nuclear Power Unit (S10A-NPU) is a compact, reflector-controlled, nuclear heat source utilizing thermoelectric conversion to produce 500 watts of electrical power continuously for one year. This SNAP system is being developed by Atomics International, a Division of North American Aviation, Inc., under contract to the Atomic Energy Commission.

The S10A-NPU is illustrated in Figure 1; the principal components are a nuclear reactor, thermoelectric converter, thermoelectro-magnetic pump, heat-rejection space radiator, expansion compensator units (ECU), and an interconnecting dynamic liquid-metal heat transfer piping system. Thermal energy produced in the nuclear reactor is transferred by liquid metal, NaK (binary eutectic 22% sodium — 78% potassium alloy), circulated by a thermoelectric pump through the reactor to the converter.

This report describes the development, qualification, and flight system acceptance testing of expansion compensator units for the S10A-NPU. Two expansion compensators are needed to accommodate the volumetric thermal expansion of NaK as the NPU is raised to operating temperature. The ECU's also serve as system pressure regulators and are designed to maintain a void free system.

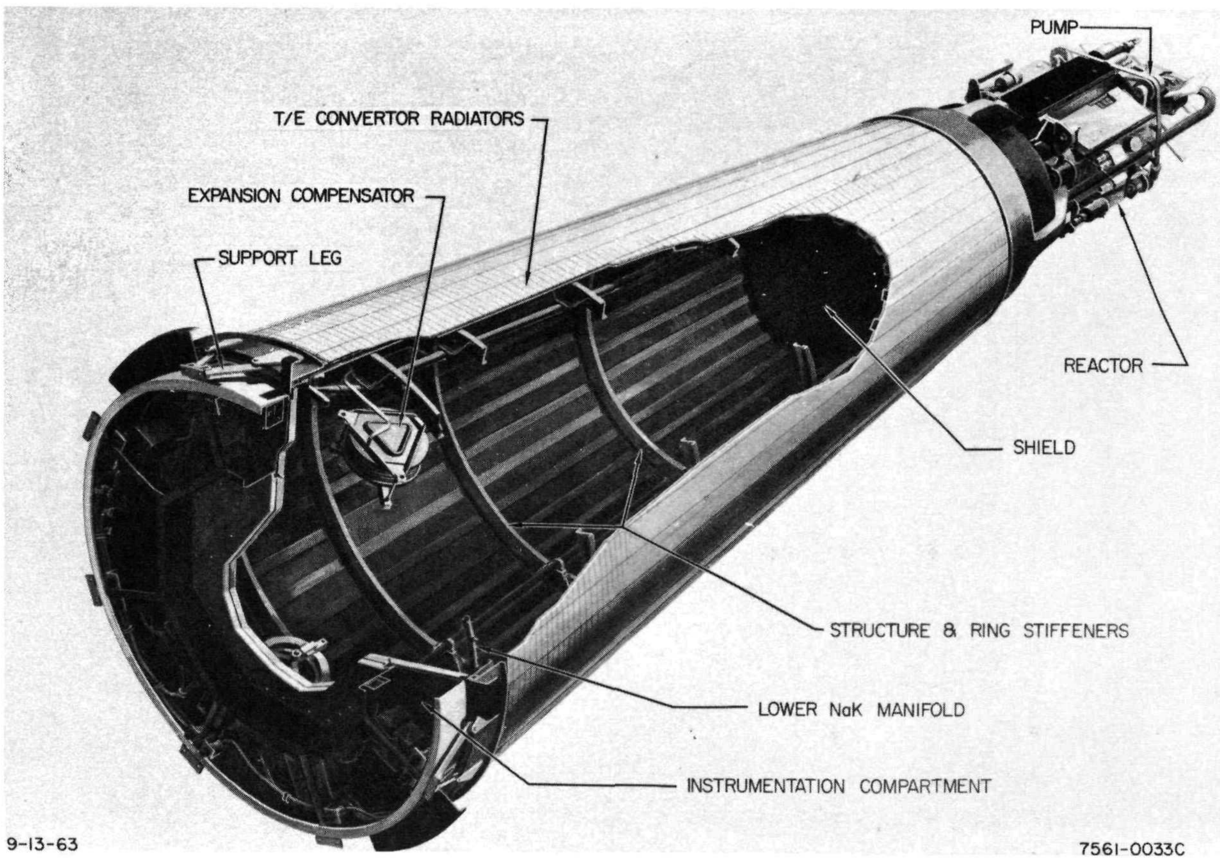

Figure 1. SNAP 10A Nuclear Power Unit (NPU)

TABLE 1

SNAP 10A EXPANSION COMPENSATOR
PERFORMANCE REQUIREMENTS

Volume Change per ECU:	
Normal Operation	60 in.^{3}
Abnormal Operation	120 in.^{3} (maximum)
Design Temperatures:	
Launch	70 to 150°F
Operating	700 to 750°F
Design Pressures:	
Launch and Startup	0.90 psia (minimum)
	34 psia (maximum)
Operating	5 psia (minimum-initial)
	20 psia (maximum, 120 in.^{3} condition)
	4 psia (minimum, after 1 yr)
Operating Life:	1 yr at operating design point
	10 thermal cycles

TABLE 2

SNAP 10A EXPANSION COMPENSATOR
ENVIRONMENTAL LOADS

1. Vibration

Longitudinal and Lateral (x, y, and z)

Frequency, cps	Peak Magnitude
5 to 20	0.25 in. D.A.
20 to 400	5.0 g
400 to 2000	7.5 g

To be applied in a single sinusoidal sweep proceeding from low to high frequency in 25 min.

2. Shock

Axis	Peak Magnitude
NPU longitudinal (x)	±20 g
NPU lateral (y and z)	±10 g

Two impact shocks shall be applied in each direction along each of the three NPU axes for a total of 12 shocks. The shock wave form shall be an approximate half-sine wave with a time duration of 6 msec.

3. Acceleration

Axis	Load
NPU longitudinal (x)	+10 g, -5 g
NPU lateral (y and z)	+6.3 g, -6.3 g

The loads shall be applied for 10 min in each direction.

II. COMPONENT REQUIREMENTS

A. DESIGN REQUIREMENTS

The function of the S10A-NPU expansion compensator is to accommodate the net volume expansion of the NaK that occurs between vehicle launch and full power orbital operation. Concurrently, the compensator unit is to pressurize the NPU NaK system within a specified range to ensure that neither cavitation nor boiling occurs. These functions are to be accomplished in a void-free system and are to be performed by two identical compensator units which are located in the system on branch lines connected to each of the two NaK return lines. The compensators are supported by the NPU structural shell assembly.

The reference expansion compensator design utilizes a bellows assembly. To prevent overstressing of the bellows during launch acceleration it is necessary to restrain the movement of the bellows with a locking device. The locking device must be released after launch for normal design operation. In the event of lock release failure of one unit, the bellows assembly of the second unit must be capable of absorbing the full net expansion of the NaK without exceeding the maximum allowable pressure.

Instrumentation is required to (1) provide positive indication of release of the bellows assembly, and (2) provide determination of system pressure by means of a continuous bellows position indicator.

Additional design requirements are that the total weight of one expansion compensator shall not exceed 18 lb and that a ground test adapter shall be provided for use during ground thermal tests of the NPU. The ground test adapter cancels out the effect of the static head of NaK over the expansion compensator during acceptance testing of NPU's and during operation of qualification systems.

B. PERFORMANCE REQUIREMENTS

The major performance requirements are shown in Table 1.

C. ENVIRONMENTAL REQUIREMENTS

1) Vibration, shock, and acceleration loads equivalent to structural qualification test levels are shown in Table 2. The bellows is to be constrained in the launch position during environmental testing since the launch environment causes the most severe loading of the compensator.

2) Space vacuum: $\sim 10^{-12}$ torr

3) A one-year nuclear radiation dosage of 2×10^{15} nvt (fast neutrons) and gamma rays totalling 1×10^{8} R.

D. RELIABILITY

The ECU design must fulfill the component reliability objectives of:

1) The probability for successful bellows release must be 0.9995.

2) The probability that no malfunction of either ECU will occur which would result in a mission abort during a 90-day period must be 0.995.

3) The probability that no malfunction of either ECU will occur which would result in a mission abort during 1-yr must be 0.990.

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III. COMPONENT DESCRIPTION

A. FINAL ECU DESIGN

The S10A expansion compensator unit (ECU) utilizes a welded metal bellows assembly, the interior of which is directly connected to the circulating NaK system of the NPU. This primary bellows is in series with a secondary bellows which, together with a metal housing that surrounds both bellows assemblies, provides secondary NaK containment in the event of a primary bellows failure. The major parts of the ECU are presented in Table 3. The ECU is illustrated in Figure 2.

The description and function of each major part of the ECU are explained in the following paragraphs.

TABLE 3

S10A ECU — MAJOR PARTS

1. Primary Bellows Assembly
2. Secondary Bellows Assembly
3. Containment Housing
4. Top Support
5. Helical Compression Spring
6. Position Transducer and Demodulator
7. Position Switch
8. Actuator Assembly

1. Primary Bellows Assembly

The primary bellows assembly accommodates the volume expansion of the NaK as the NPU reactor outlet temperature is increased from ~70°F system launch temperature to ~1010°F system design temperature. The average NaK system temperature at design operation is ~945°F. In addition to absorbing the fluid volume increase of the NPU, the primary bellows provides a force to pressurize the NaK system. The design volume expansion of the

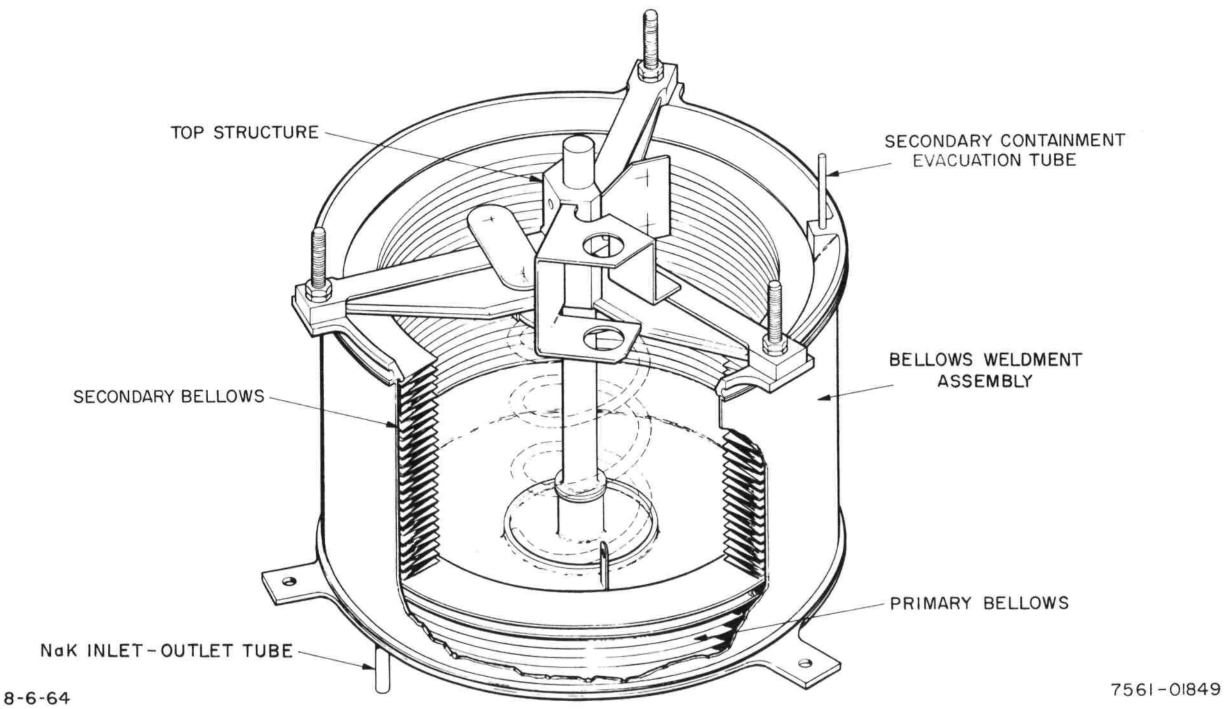


Figure 2. SNAP 10A Expansion Compensator Unit (ECU)

NaK system, 120 $in.^3$, is accommodated by a deflection of each of the ECU bellows to ~1.42 in.

The bellows assembly is of the welded metal diaphragm type. It is made up of 26 nesting ripple diaphragms, 8 in. OD and 6.4 in. ID, which are TIG welded at the inner and outer perimeters to form a bellows capsule. The diaphragm material is AM-350 precipitation hardened stainless steel. Twenty-four of the diaphragms are 0.009 in. thick. The two end diaphragms are 0.015 in. thick. The completed bellows capsule is heat-treated to the SCT-850 condition to provide increased yield and tensile strength. After heat treatment the bellows capsule is welded to end sections which completes the primary bellows assembly. The additional thickness of the end diaphragms provides the required decrease in stresses at the end section welds to compensate for the loss in weld joint strength caused by the annealing effect of post heat-treat welding.

The top end section of the primary bellows assembly forms the inner wall of the ECU NaK primary containment, provides the preloading of the bellows assembly, and contains the helical compression spring retainer and center post guide support. This member is made of machined 347 CRES stainless steel.

Figure 3 illustrates the primary bellows, secondary bellows, top and bottom plates, and center post configuration. The preload of the primary bellows is accomplished by heat-treating the bellows in its fully collapsed height, 0.625 in. (maximum) and expanding it to a height of 1 in. nominal in its installed position, as governed by the depth of the top end section. The pertinent dimensions of this section are OD of inner wall — 6.324 in. and wall thickness — 0.100 in. The OD of the flanged section is machined to fit the bellows OD after heat treatment within ±0.001 in. Special care is given to machining of the weld preparation for attachment of both the primary and secondary bellows to ensure proper fit-up for the maximum reliability of weld joints.

The bottom flange of the primary bellows forms the bottom wall of the ECU NaK containments, contains the NaK inlet tube, provides three outer tabs for installation to the NPU structure, and has machined weld preparations for the primary bellows and the secondary containment housing. All ECU weld preparations, except for the top support structure, are of the burn-down fusion type similar to that of the bellows diaphragm weld joint. The bottom flange is made of 347 CRES stainless steel. This section has machined reinforcement ribs in its bottom surface to provide a minimum weight member adequate for the design loads. The pertinent dimensions of the bottom flange are: plate diameter — 8.600 to 8.625 in., bolt hole circle radius — 5.054 in., minimum wall thickness — 0.075 in., and NaK inlet tube ID — 0.325 in.

2. Secondary Bellows Assembly

The secondary bellows in conjunction with the outer cylindrical housing provides for NaK secondary containment. It also contributes to the pressurization of the NaK system. This bellows is identical to the primary bellows except that it contains 18 convolutions instead of 13 and that it is heat-treated in an extended position.

The free, post heat-treat length of the bellows is 4.00 in., its installed length is 3.82 in. nominal. The secondary bellows is stroked in compression as compared to the expansion stroking of the primary bellows. The secondary bellows is welded at its bottom end to the top section of the primary bellows. At its top end the bellows is welded to a 347 stainless steel

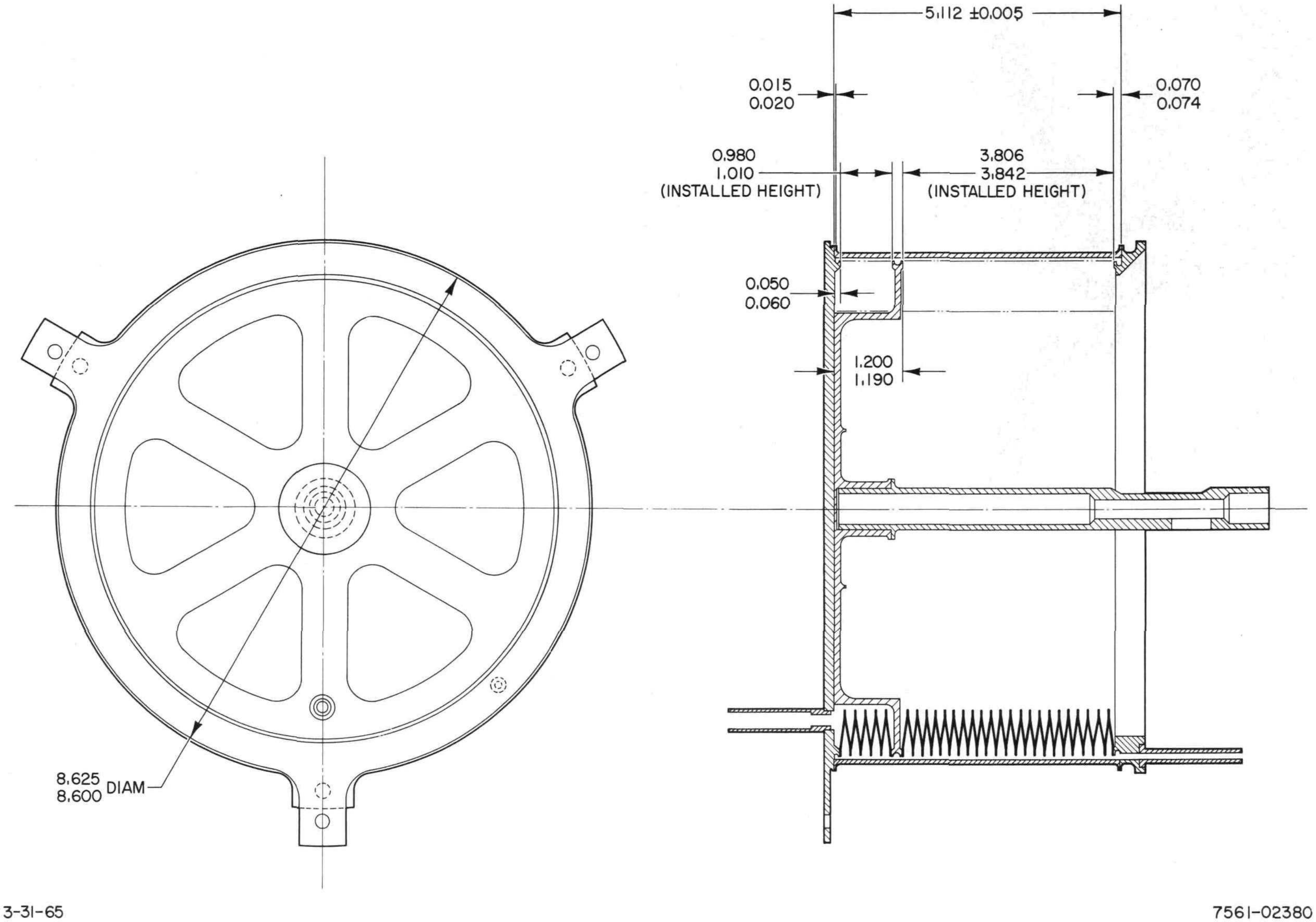


Figure 3. Expansion Compensator Bellows Assembly Schematic

ring subassembly. This ring contains the secondary containment evacuation tube, weld preparations for the secondary containment cylinder and bellows, and mounting tabs for the top support structure.

3. Containment Housing

The containment housing is a 347 stainless steel cylinder with flanged end weld preparations which are joined to the ECU bottom flange and to the ring subassembly. The clearance between the outer diameter of the bellows and the housing is maintained small, ~0.080 in., in order to minimize loss of NaK from the primary bellows in event of a bellows failure. The pertinent dimensions of the housing are 8.180 in. ID, 0.052 in. wall, and 5.10 in. long.

4. Top Support

The functions of the top support, shown in Figure 4, are as follows:

1) to support the pin-puller actuator assembly, position switch, and position transducer

2) to restrain the auxiliary, helical compression spring

3) to guide the center post during primary bellows expansion.

The top support is fabricated of Inconel-X alloy and designed to withstand the launch loads and the force of the auxiliary spring at the maximum possible primary bellows volume displacement of 120 $in.^3$ The center post guide hole in the hub of the top support is coated with a molybdenum disulfide dry film lubricant to assure free movement of the center post under the space vacuum operating environment.

5. Helical Compression Spring

The helical compression spring augments the pressure contribution of the bellows in order to meet system requirements. The spring is

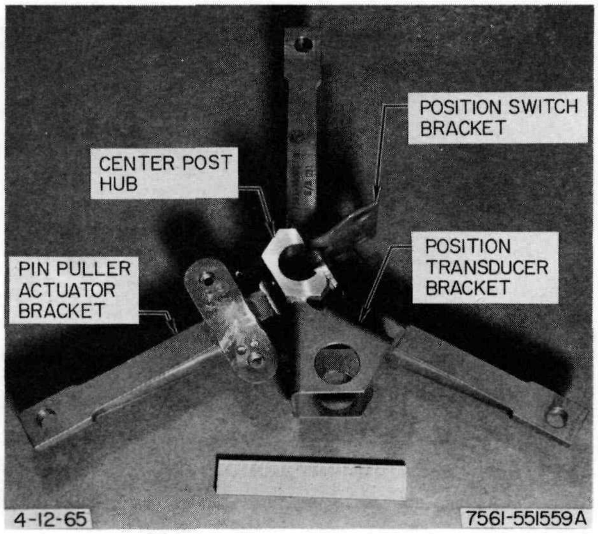


Figure 4. Top Support Structure (Top View)

compressed between the top plate of the expanding bellows and the top support structure. The pressure contribution of the spring at design bellows deflection is 2.5 psi. The design features of the spring are listed below.

Material	Rene' 41 wire
Mean coil diameter	2.42 in.
Wire coil diameter	0.196 in.
Free length	4.798 in.
Number of active coils	3
Spring rate at 80°F	70 lb/in.
Spring rate at 750°F	61.8 lb/in.

6. Position Transducer and Demodulator

The position transducer and demodulator (Figure 5) are designed to convert the mechanical expansion of the bellows into an electrical voltage proportional to the displacement. Transducer readout is achieved by a variable reluctance principle whereby a movable magnetic core (armature) is displaced in an ac excited magnetic field. The signal is transferred to a demodulator unit which converts and conditions the information to a linear 0 to 50 millivolt dc output. The armature, an iron

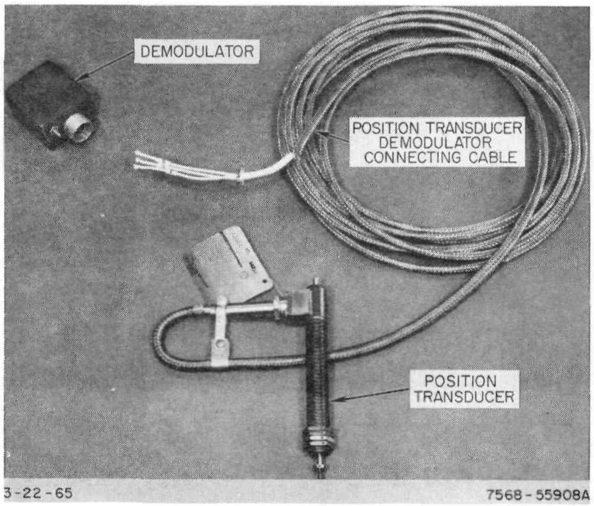


Figure 5. Position Transducer/Demodulator

rod, is attached to a clevis which is integral to the top plate of the primary bellows assembly. The demodulator is physically separated from the transducer and housed in the NPU instrument compartment due to its low operating temperature limitation.

7. Position Switch

The purpose of this switch is to sense a contraction of the bellows from the normal operating deflection of 1.42 in. to a nominal 0.20 in. deflection, which will be indicative of a leak in the NaK system plumbing. Since a leak will cause failure of the system, it is important that certain failure mode data be recorded prior to loss of the system; thus the activation of the position switch effects "turn-on" of an in-flight recorder to monitor specific diagnostic instruments.

The position switch is an ON-OFF microswitch actuated by a leaf spring that rides on the center post, which has an attached cam to deflect the spring as required during bellows expansion and contraction. This switch is shown in Figure 6.

8. Pin-Puller Actuator Assembly

To prevent overstressing of the bellows due to acceleration loads during vehicle launch, the bellows assembly is locked by means of a pin inserted through the bellows center post in the region of the top support hub. This pin is extracted after launching by means of a pin-puller which is actuated by remote control firing of the two squibs which are bolted into the actuator assembly. The pin-puller assembly is shown in Figure 7. When the squibs are fired, a force of about 438 lb is applied on the locking pin, extracting it from the bellows center post, thereby allowing the bellows to expand in a normal manner. Figure 8 shows a fully instrumented expansion compensator unit.

B. DEVELOPMENTAL ECU DESIGN

The final S10A ECU design evolved from a single welded bellows assembly, no secondary containment design. That design satisfied performance and initial weight requirements but did not meet the reliability requirements. The developmental single bellows ECU is pictured in Figure 9. The bellows diaphragm design has remained essentially constant throughout the development program as have the position indicator, position switch, top support, helical spring, and pin-puller assembly. The final ECU design comprised essentially the single bellows design with a secondary containment consisting of the secondary bellows and the outer housing. However, the fixture utilized to attach the ECU to the NPU, the "A" frame, shown in Figure 9, was eliminated in the final ECU design in order to minimize the required weldments and to simplify fabrication.

In addition to the major ECU design change of adding secondary containment, minor modifications to ECU design were made as a consequence of developmental test results, system requirement changes, and fabrication difficulties. Design changes resulting from developmental test results are presented in the Development Test Program section of this report.

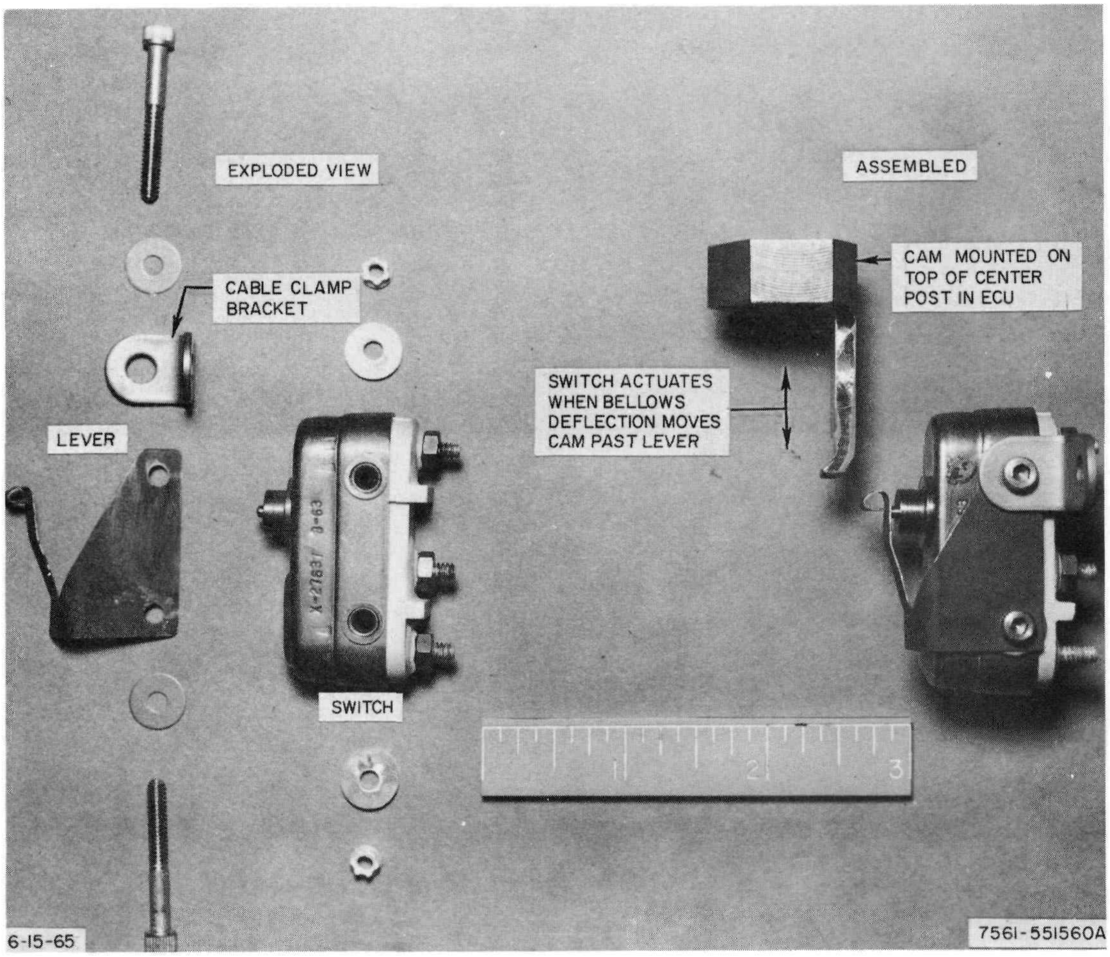


Figure 6. Position Switch

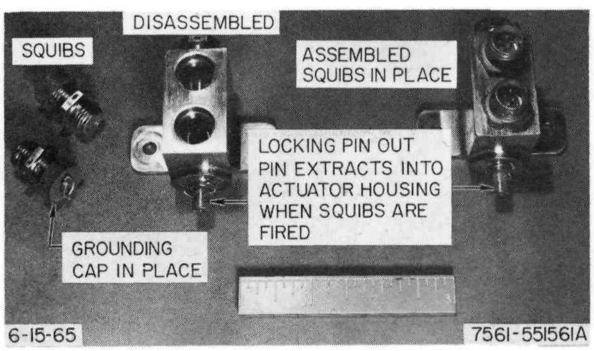


Figure 7. Pin-Puller Actuator and Squibs

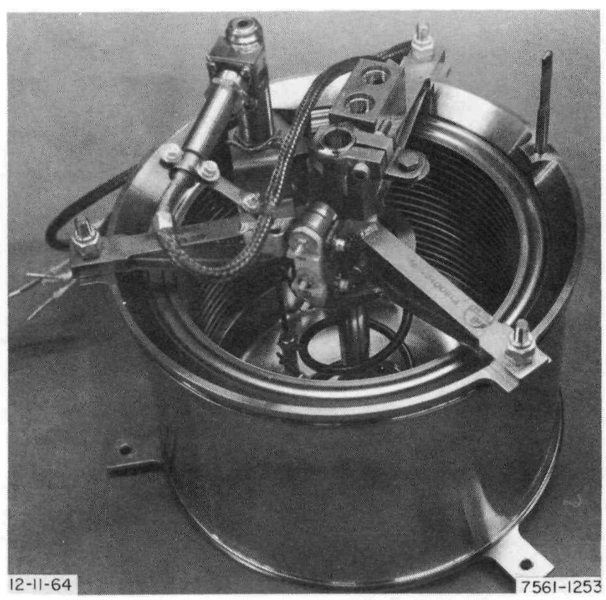


Figure 8. Fully Instrumented ECU

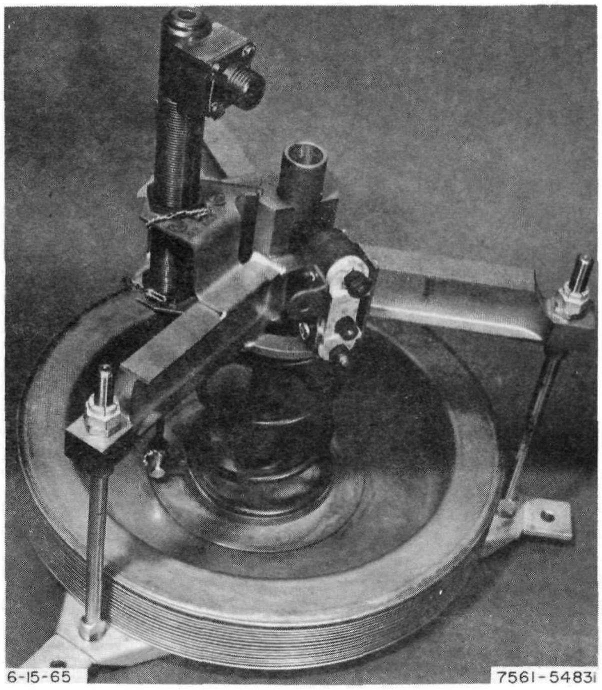


Figure 9. ECU 10FS-34001 (Single Bellows)

The original ECU design contained a 30-diaphragm bellows assembly: diaphragm dimensions were 8-in. OD, 6.4-in. ID, and 0.010 in. thick. The material selected, on the basis of NaK compatibility and high strength-to-weight ratio, was PH 15-7 Mo alloy. Prototype bellows assemblies were successfully fabricated; however, fabrication problems were encountered in production. The diaphragm welds repeatedly failed a mass spectrometer helium leak check. The bellows material was changed to AM-350 alloy, which eventually eliminated the fabrication problem.

A change in the initial system volume requirement from 75 $in.^3$ of NaK per ECU to 60 $in.^3$ permitted a reduction in the number of diaphragms from 30 to 28. Upon recommendation of an alternate bellows manufacturer, the bellows design was further modified to the use of 26 diaphragms, each diaphragm, except for the end pieces, being 0.009 in. thick.

IV. DESIGN ANALYSIS

A. STRESS ANALYSIS

The stress analysis of welded bellows utilized in the S10A compensators is limited mainly to empirical methods because of the complexity of the nested-ripple diaphragm geometry. These empirical methods have been developed by bellows manufacturers for design application and are considered proprietary. They have not been made available for use at AI. A theoretical method based upon elastic beam theory* has been used for design calculation on SNAP 10A expansion compensators. Test data have shown this method yields conservative stress values within the elastic region of operation. Some stress values have been supplied by bellows manufacturers for the specific S10A bellows design and operating conditions. In these instances, comparison of the theoretically obtained results indicate the latter can be ~300% too high. The theoretical equations are presented in Appendix A.

1. Operating Stress Levels

The calculated operating stress levels for the S10A compensator bellows are presented for both room temperature and system operating temperature conditions in Appendix B. One design criterion for the S10A compensator was that the bellows normal operating stresses be within the elastic limit as defined by the 0.2% offset yield point. This criterion has been met on the basis of calculated stresses, and with an adequate margin of safety on the basis of the 33% correction factor applicable according to empirical stress determinations.

2. Material Properties

The significant material properties of AM-350 in the SCT-850 heat-treated condition are presented in Appendix C.

3. Discussion of Operating Stresses

The maximum programmed deflection of the bellows assembly at room temperature is 1.77 in. beyond the initial preload deflection. The maximum programmed deflection at 750°F is 1.5 in. In the event of one compensator unit not being released, the other unit would then absorb the entire NaK volume increase of 120 in.^{3} and, therefore, it would expand ~3.0 in.

According to the table of AM-350 – SCT-850 mechanical properties, the room temperature operation is within the elastic range. A deflection of 1.90 in. and greater can produce plastic deformation. It must be noted, however, that the calculated stress levels at conditions causing plastic deformation are incorrect since the analytical method assumes elastic deformation and does not take into account stress relieving as a result of plastic flow. The ultimate strength of the bellows should be exceeded at the 3.0-in. deflection at 18 psi pressure, according to the calculated stress. However, tests have shown that pressures in excess of 50 psi are required to burst the primary bellows at 3.0-in. deflection.

At the 750°F operating temperature the design deflection of 1.5 in. is still within the elastic stress region if the material exhibits typical properties of ~127,000 psi yield stress. The minimum yield stress at 750°F of the heat-treated AM-350 is considered to be ~100,000 psi. Applying a 33% correction factor to the calculated stress assures that the 1.5-in. operating point is in the elastic region.

The ductility of the heat-treated AM-350 as reported in the literature is in the 4 to 10% range, which is considered sufficient to classify the material as ductile and capable of undergoing stress relief via plastic deformation.

*F.J. Feeley, Jr. and W.M. Goryl, "Stress Studies on Piping Expansion Bellows," ASME, National Meeting of Applied Mechanics (June 1949)

V. DEVELOPMENT TEST PROGRAM

A. TEST OBJECTIVES

The objectives of the development tests are as follows:

1) To verify that environmental and performance requirements are satisfied.

2) To determine mode of failure of the ECU.

3) To determine relaxation rate of the ECU at operating conditions.

4) To determine that the final design of the ECU will meet successfully all system performance objectives.

B. DEVELOPMENT TESTS

The following types of developmental tests were performed upon bellows assemblies and/or complete ECU's:

1) Burst Pressure Tests

2) Cyclic Fatigue Tests

3) Thermal Endurance Tests

4) Vibration, Shock, and Acceleration Tests

5) System Operational Sequence Tests

Failure analyses, utilizing metallographic techniques, were made of all failed units to determine cause and to provide bases for corrective action.

C. TEST APPARATUS

Various sets of test apparatus have been utilized for ECU testing. The following descriptions of the presently available test rigs are representative of the major types.

1. Inert Gas Test Rigs

Inert gas has been used as the ECU bellows pressurizing fluid in the three major types of test rigs: Fatigue Cycling Rig, Burst Test Rig, and Acceptance Test Rig.

a. Fatigue Cycling Rig

The Fatigue Cycling Rig is shown in Figure 10.

The function of the rig is to cyclically pressurize the ECU bellows through its design deflection range at room ambient external pressure and temperature. The rig operates unmonitored and continues to cycle a bellows until the bellows ruptures. The rupture allows the pressurizing gas to escape in such a way that the pressure required to force the bellows to a switch actuating deflection can no longer be generated in the bellows. Thus, no further cycles occur and the cycles-to-failure are accurately counted. The cycling rate between zero and 60 $in.^3$ bellows displacement can be varied from ~1 to 12 cpm. The rig, as shown in Figure 10, has been modified for testing of secondary containment ECU's. The modification consists of an inert gas line connected to the ECU secondary containment inlet. A pressure switch is installed in this line which acts to break the circuit to an electrical cycle counter upon loss of pressure in the secondary. Thus, cycles-to-rupture on the secondary are determined on an unmonitored test if the secondary ruptures before the primary containment.

The rig consists of four testing stations on an angle iron and steel plate mobile framework. Each testing station (two on the upper level, shown in Figure 10; and two on the lower level, not shown) is equipped with ECU mounting rods, bellows deflection actuated switch and fixture, and swagelocked copper tube inert gas inlet line. The following instrumentation and equipment are provided for each test station:

1) High pressure inert gas tank and associated pressure and flow regulators. (Multiple tanks are used for extended unattended operation.)

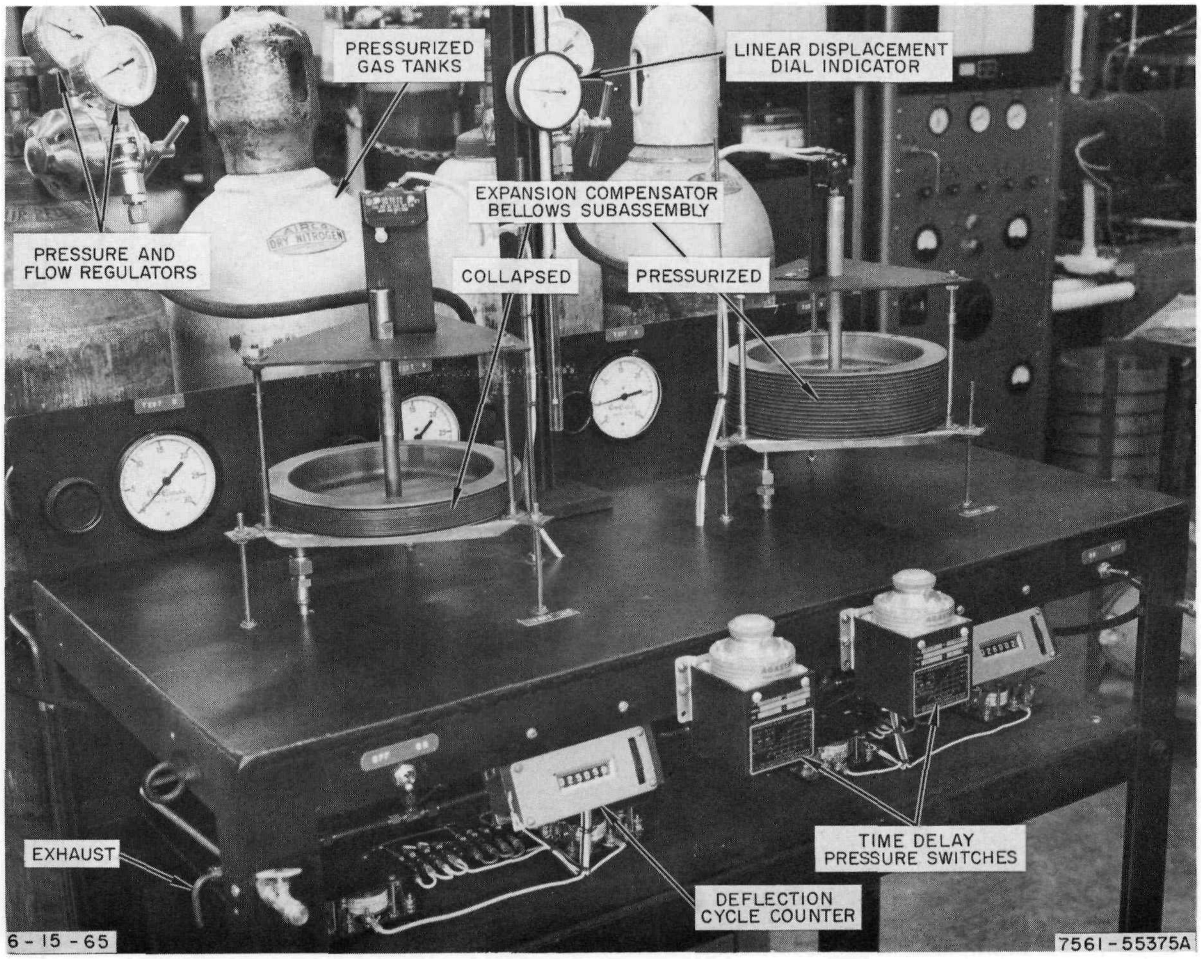


Figure 10. Fatigue Cycling Test Rig

2) A 0 to 30 psig panel-mounted gas pressure gauge.

3) An Agastat time delay pressure switch.

4) A deflection cycle counter actuated by an electromechanical switch. (Two counters are used when testing primary and secondary containment.)

A 3-in. travel, 0.001-in. accuracy, dial-indicating deflection gauge is used to originally set and periodically reset the bellows deflection limit required to actuate the electromechanical switch which triggers the exhaust phase of each cycle.

b. Burst Test Rig

The Burst Test Rig is shown in Figure 11. This rig and its revised counterpart have been and will be used for high pressure proof testing of ECU's and bellows assemblies. The primary components of the rig are:

1) A test station with mounting rods and a gas pressure inlet line with removable fitting.

2) A high pressure gas supply which is a standard high pressure inert gas bottle.

3) Pressure and flow regulators for the gas supply.

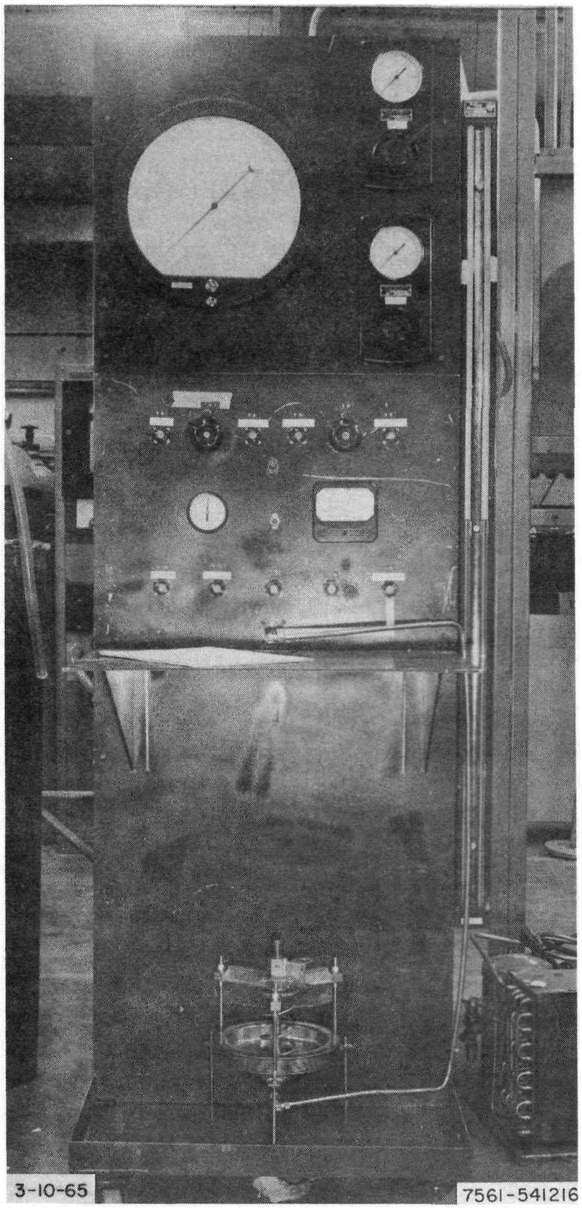


Figure 11. Burst Test Rig

4) A high pressure, laboratory precision, Bourdon tube, gas pressure gauge.

5) A 50-in. mercury manometer for more accurate pressure readings at low pressures.

6) Associated tubing and manual valves.

c. Acceptance Test Rig

Two views of the Acceptance Test Rig (in its present configuration) are shown in Figure 12. There are two such rigs at present which are utilized to perform the acceptance tests required on flight system units. In addition, they are used for high-temperature, inert-gas developmental tests on ECU's and bellows assemblies. The distinguishing capability of these rigs is the conduction of high-temperature (to 1000°F) tests in a vacuum environment. They also have the capability for bellows deflection cycle testing at high-temperature in vacuum at a rate of 4 cpm between zero and 60 in.^{3} bellows displacement.

The following paragraphs list the equipment and instrumentation which comprise an acceptance Test Rig.

(1) Vacuum Test Chamber

The vacuum test chamber consists of an upright, water-cooled, stainless steel cylinder with a flat head. It has a water-cooled floor plate fitted with an elastomer O-ring. The jar is fitted with a vacuum line, lift rings, a Philips vacuum pressure gauge head, and a glass tube on the top plate. The glass tube is O-ring sealed and has a steel protection sleeve. The tube acts as the measurement station for the bellows deflection indicator rods and has a steel rule set within for measurement reference.

The floor plate is fitted with ECU mounting rods, a multiple Swagelok fitting for sheathed thermocouple penetration, a hermetic multipin connector for transducer and switch lead penetration, and a bellows supported ECU inlet line. It is also fitted with eight Swagelok fittings for electrical resistance tubular heater element penetrations. It supports the ECU and surrounding aluminum foil and stainless steel thermal energy shields.

(2) Refrigeration Unit

This is a standard 3/4-ton capacity, industrial type refrigeration unit which employs a

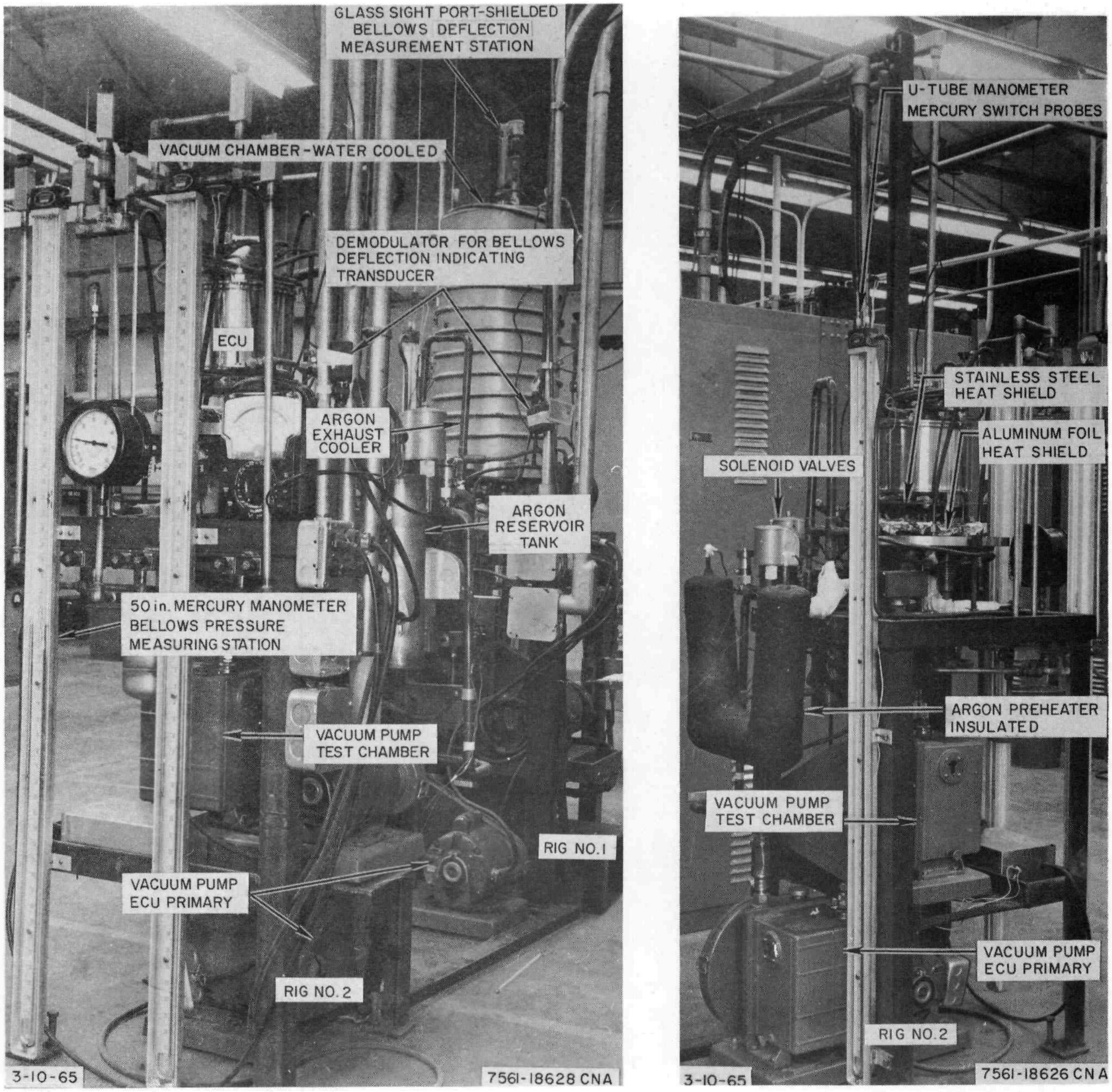


Figure 12. Acceptance Test Rig (2 Views)

recirculating Freon system with ambient forced air convection heat rejection. The unit functions to cool the cold finger on the reservoir tank and the vacuum system vapor cold traps.

(3) Two Mechanical Vacuum Pumps

The rotary pumps have a maximum vacuum pressure capacity of less than 5×10^{-4} torr when coupled with this test system. One pump is connected to the ECU primary, the other to the chamber. The chamber pump is used in conjunction with a Freon-cooled, pump-oil-vapor trap. The argon exhaust cooler acts as a trap on the ECU primary pump line.

(4) Pressurized Argon Supply Tank

A standard industrial pressurized gas cylinder, fitted with pressure and flow regulators, is used to supply argon pressure.

(5) Variable Power Supply

The heaters used to maintain the test chamber at design operating temperature are supplied with electrical current through a variable voltage transformer from a 60-cps source line. Voltage and current are monitored on standard panel meters.

(6) Transducer/Demodulator Power Supply

An Elin 400 cps, 115 volt ac power supply is utilized for transducer/demodulator input.

(7) Argon Reservoir

An all-welded stainless steel tank provides the proper sized argon gas charge required during each cycle on the 200 high-temperature cycle phase of the acceptance test.

(8) Argon Exhaust Cooler

The argon exhaust copper tubing is passed through a section of water coolant copper tubing, forming a single tube-in-tube counter flow heat exchanger. Its function is to cool the exhaust gas sufficiently to allow proper operation of the downstream exhaust gas solenoid valve.

(9) Argon Preheater

The argon supply line to the ECU primary is fitted with a stainless steel sheathed tubular heater. The heater's function is to preheat the argon entering the ECU primary to a sufficient temperature necessary for essentially constant ECU temperature during cycling.

(10) Valves

The gas/vacuum system contains a number of small manually operated valves. A number of solenoid valves provide for automatic cycling.

(11) Time-Delay Pressure Switch

An Agastat time delay pressure switch triggers the solenoid valves during high temperature cycling.

(12) U-tube Manometer Pressure Switch

A 50-in. U-tube mercury manometer has been fitted with two emersion probes in such a manner that, upon loss of pressure in the argon reservoir during each high temperature cycle, the mercury contacts both probes and completes an electrical circuit. The circuit energizes the argon supply solenoid which provides a fresh argon charge in the reservoir. Once charged to sufficient pressure, the mercury probe contact is broken and the solenoid is de-energized, isolating the line from the argon supply bottle. The cycling is thus repeated until manually overridden.

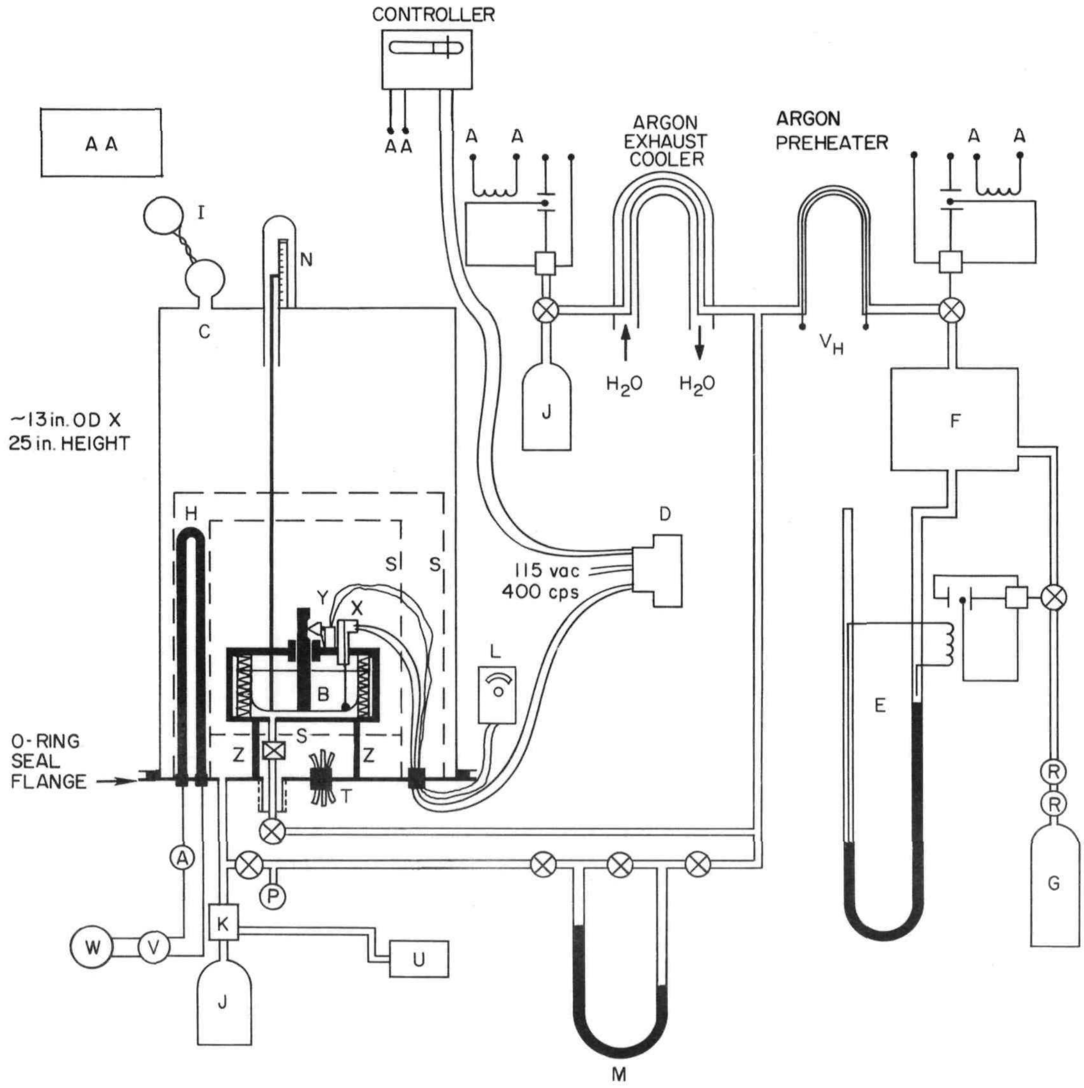
(13) Instrumentation

Temperature Recorder — multipoint "K" type records ECU temperatures.

Millivolt Recorder — single-pen — 0 to 50 mv records transducer/demodulator output signal.

Voltmeter — laboratory precision ac voltmeter indicates 115 vac transducer/demodulator power supply voltage.

U-tube Manometer — Mercury-in-glass 50-in. manometer indicates differential ECU pressures.



⊗ - valve (manual)
⊠ - nonwelded, mechanically sealed connector
⊗ - valve (solenoid)
A - ammeter
B - expansion compensator bellows
C - test chamber
D - demodulator for bellows deflection indicating transducer
E - mercury manometer pressure switch
F - argon reservoir tank
G - pressurized argon supply tank
H - heater-tubular
I - cold-cathode, ionization, vacuum gauge and meter
J - vacuum pump
K - vacuum vapor-cold-trap
L - voltohmmeter registers microswitch actuation
M - mercury filled U-tube manometer
N - glass sight port, bellows deflection measuring station
P - pressure gauge — Bourdon tube type
R - gas pressure and flow regulators
S - heat shields
T - thermocouple fitting
U - refrigeration unit
V - voltmeter
W - variable voltage transformer
X - expansion compensator transducer
Y - expansion compensator microswitch
Z - expansion compensator support rods
AA - Agastat time-delay pressure switch

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Figure 13. Schematic Diagram of Acceptance Test Rig

Compound Pressure Gauge — 30-in. Hg to 0 to 60 psig compound Bourdon tube indicates ECU and system gauge pressures.

Philips Vacuum Gauge and Four Channel Readout — measures absolute vacuum pressure in chamber.

Temperature Controller-Indicator — provides for automatic over-temperature shutdown of test heater power.

Bellows Deflection Gauge — provides for measurement of deflection of ECU bellows. A stainless steel rod rides on the ECU bellows top plate, and protrudes through a guide hole in the vacuum chamber top plate. An attached pointer rides past the ruler in the glass tube providing for visual monitoring of deflection.

Liquid-in-Glass Thermometer — A laboratory standard mercury-in-glass thermometer is used to measure room ambient temperatures.

Voltohmmeter — A laboratory standard VOM is used to monitor ECU position switch actuation and deactuation.

Resistance Bridge — A precision bridge is used to measure transducer circuit resistances.

Figure 13 is a schematic diagram of the Acceptance Test Rig.

2. NaK Test Rigs

There are nine test rigs which may be used to test ECU's and bellows assemblies in vacuum, at high temperature, with a NaK charge in the ECU. These rigs vary slightly in their composition and capabilities, but are basically as shown in the schematic diagram, Figure 14. Figure 15 shows a view of two qualification test rigs housing ECU's S/N-023 and -026 prior to start of endurance qualification testing. Figure 16 is a closeup view of the ECU S/N-026 in its test rig.

The test rig is comprised of the following:

a. Vacuum Test Chamber

The chamber is essentially the same as that used on the Acceptance Test Rig.

b. Auxiliary Equipment

The rig has one each of the following components which are identical to those of the Acceptance Test Rig:

Refrigeration Unit

Mechanical Vacuum Pump

Pressurized Argon Supply

Variable Power Supply

Transducer/Demodulator Power Supply

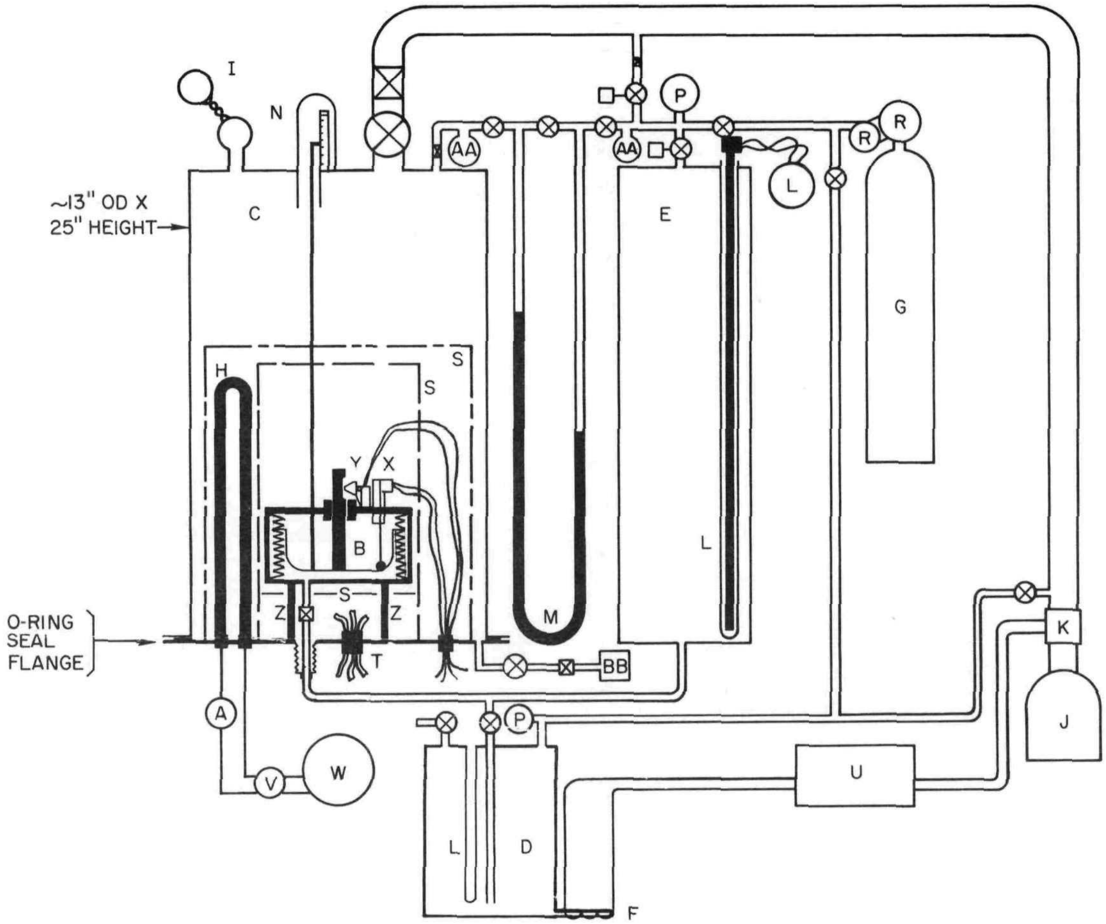
It does not have the argon reservoir, exhaust cooler, preheater, time-delay pressure switch, or U-tube manometer switch of the Acceptance Test Rig. It contains a number of small gas/vacuum valves. The solenoid valves perform emergency isolation duty during periods of unattended operation, rather than the automatic cycling functions of those in the Acceptance Test Rig. The rig has a small stainless steel all-welded tank connected to either arm of the manometer, which serve as mercury overflow traps.

c. NaK Reservoir Tank

The NaK reservoir tank acts as the system fill and dump tank. It is an all-welded, stainless steel pipe, upright cylindrical tank with a fill line, pressure line, and liquid level probe well. It has a refrigerated cold trap for NaK oxide and is fitted with a compound Bourdon tube pressure gauge. This tank is isolated from the test NaK system during testing.

d. NaK Pressure Tank

The NaK pressure tank acts as the operating NaK reservoir and pressure head counter balance, It is an all-welded, stainless steel pipe, upright cylindrical tank with a gas pressure



⊗ - valve (manual)
⊠ - nonwelded, mechanically sealed connectors
□⊗ - valve (solenoid)
A - ammeter
B - expansion compensator bellows
C - test chamber
D - NaK reservoir tank
E - NaK pressure tank
F - cold finger
G - pressurized argon supply tank
H - heater-tubular
I - cold-cathode, ionization, vacuum gauge and meter
J - vacuum pump
K - vacuum vapor-cold-trap
L - level probe and wells
M - mercury filled U-tube manometer
N - glass sight port, bellows deflection measuring station
P - pressure gauge — Bourdon tube type
R - gas pressure and flow regulators
S - heat shields
T - thermocouple fitting
U - refrigeration unit
V - voltmeter
W - variable voltage transformer
X - expansion compensator transducer
Y - expansion compensator switch
Z - expansion compensator support rods
AA - manometer mercury traps
BB - mass spectrometer leak detector station

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Figure 14. Schematic Diagram of NaK Test Rig

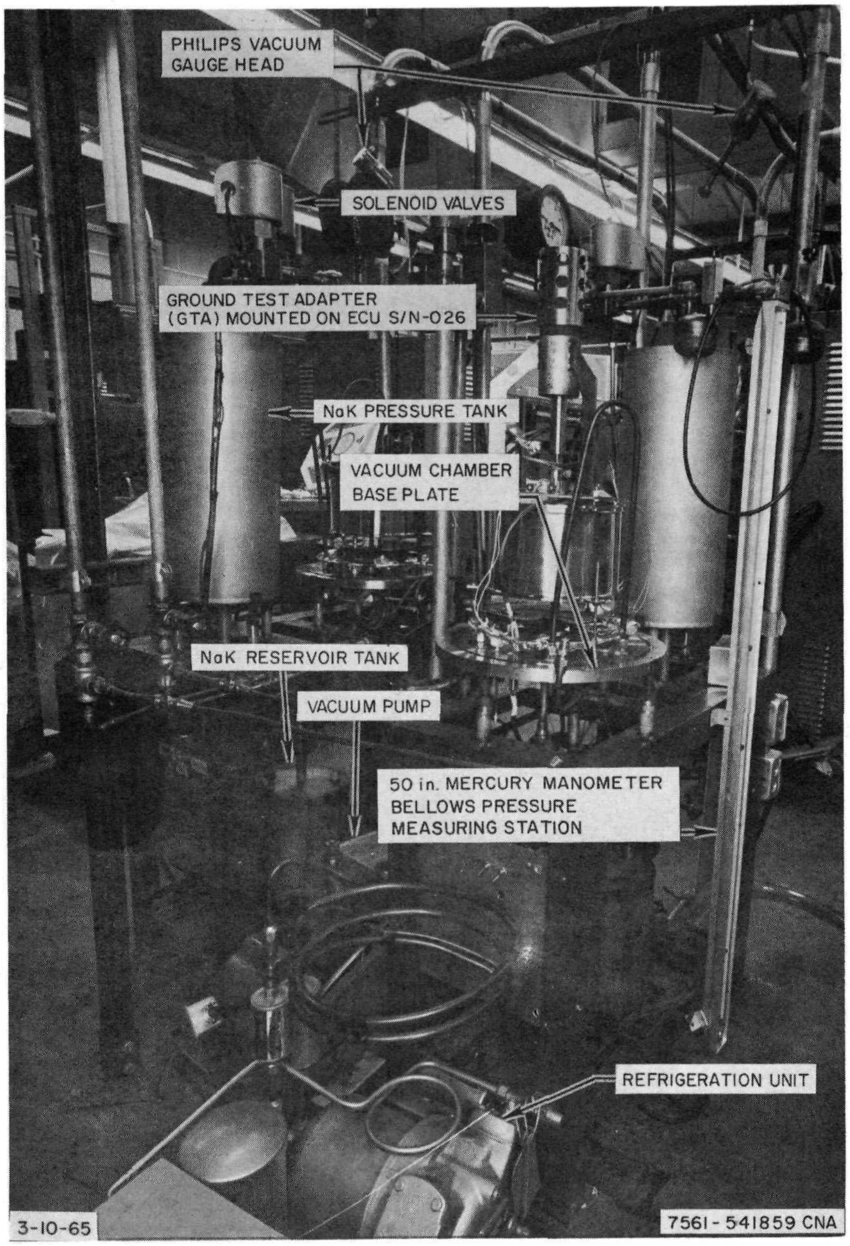


Figure 15. Qualification Test Rig

inlet and liquid level probe well in the top plate. The ECU bellows are deflected by pressurizing the argon gas head in this tank.

e. NaK Valve and Piping

The NaK system is of all-welded stainless steel tube and pipe construction. The drain valve is the bellows sealed type.

f. Instrumentation

The instrumentation is the same as for the Acceptance Test Rig with the addition of a differential type liquid level probe used to detect NaK levels in the NaK reservoir and pressure tanks.

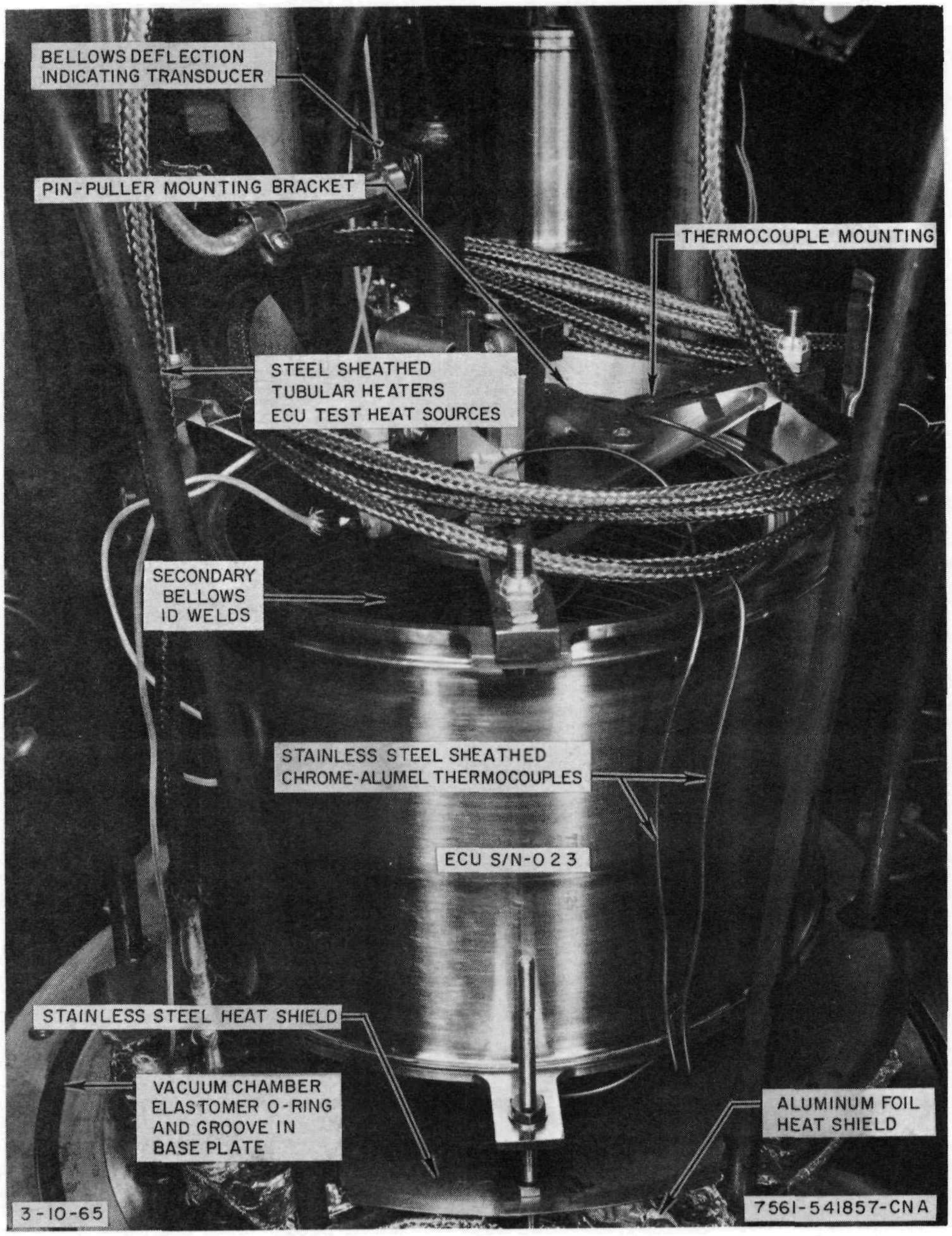


Figure 16. Closeup of Qualification Test Rig

3. Environmental Test Rigs

a. Acceleration Test Rig

The acceleration testing of ECU's is conducted in a 100-lb capacity Trio-Tech model G-338-3 centrifuge. Figure 17 presents a typical test setup in this rig. A right angle fixture is used in conjunction with the 9° offset fixture when conducting the radial axis (zz) acceleration runs.

The centrifuge vendor's calibration chart of acceleration as a function of centrifuge arm length and rpm is used to set test loads. The rpm is monitored on a continuous digital readout. A television camera, mounted on the centrifuge arm, is available for visually monitoring the test.

b. Shock and Vibration Test Rig

The ECU shock and vibration testing is conducted on a 7500-lb capacity Ling Model A-246 electromagnetic induction shaker system and associated microslip table. A typical test setup in this rig is depicted in Figure 18. The following list of equipment and instrumentation comprises that utilized during shock and vibration testing of ECU's and bellows assemblies.

(1) Shaker System

The Ling A-246 head is mounted in a steel cradle and is shown in the vertical oscillation configuration in Figure 18. It is manually rotated, and connected to the microslip table to provide for oscillation in the horizontal plane.

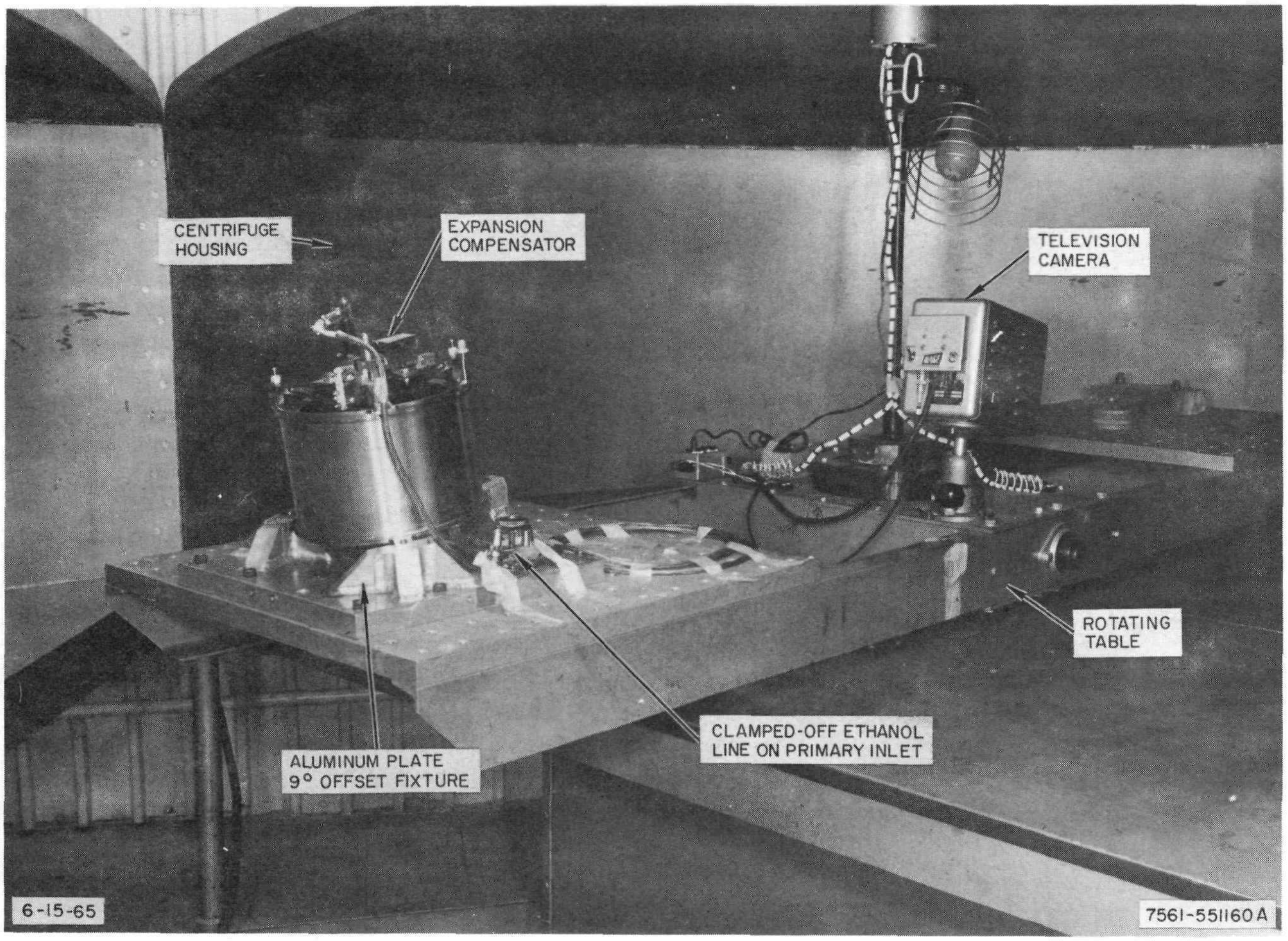


Figure 17. Centrifuge Setup — Environmental Test Rig

The head is used in conjunction with a Ling R-1003 or R-1003A console and a Ling PP20-24C power amplifier.

(2) Microslip Table

In two vibration test axes the shaker head is in the horizontal oscillation configuration and the armature head is connected to a 3- by 40- by 48-in. magnesium slip table weighing 330 lb. The table rides on an oil film on a polished granite block. Both the head cradle and granite block are secured to a seismic mass.

(3) 9° Offset Fixture

During vibration and shock testing the ECU is mounted on an aluminum plate fixture, the first resonance of which is at greater than 500 cps. The fixture has three ECU supports to which the ECU is bolted. These supports provide for a 9° tilt of the ECU forward support leg up from the horizontal plane of the fixture or vibration plane to which it is bolted. This 9° is the offset mounting angle of the ECU in the SNAP 10A system.

The fixture has a bolting station for attachment of the hose cock clamp which seals the ECU alcohol fill Tygon line.

(4) Alcohol Filling Rig

A piece of apparatus is used which facilitates evacuation of an ECU bellows, subsequent void-free ethyl alcohol fill, and pressurization of the ECU alcohol charge through a length of transparent Tygon plastic hose. This filling rig contains an alcohol reservoir (stainless steel

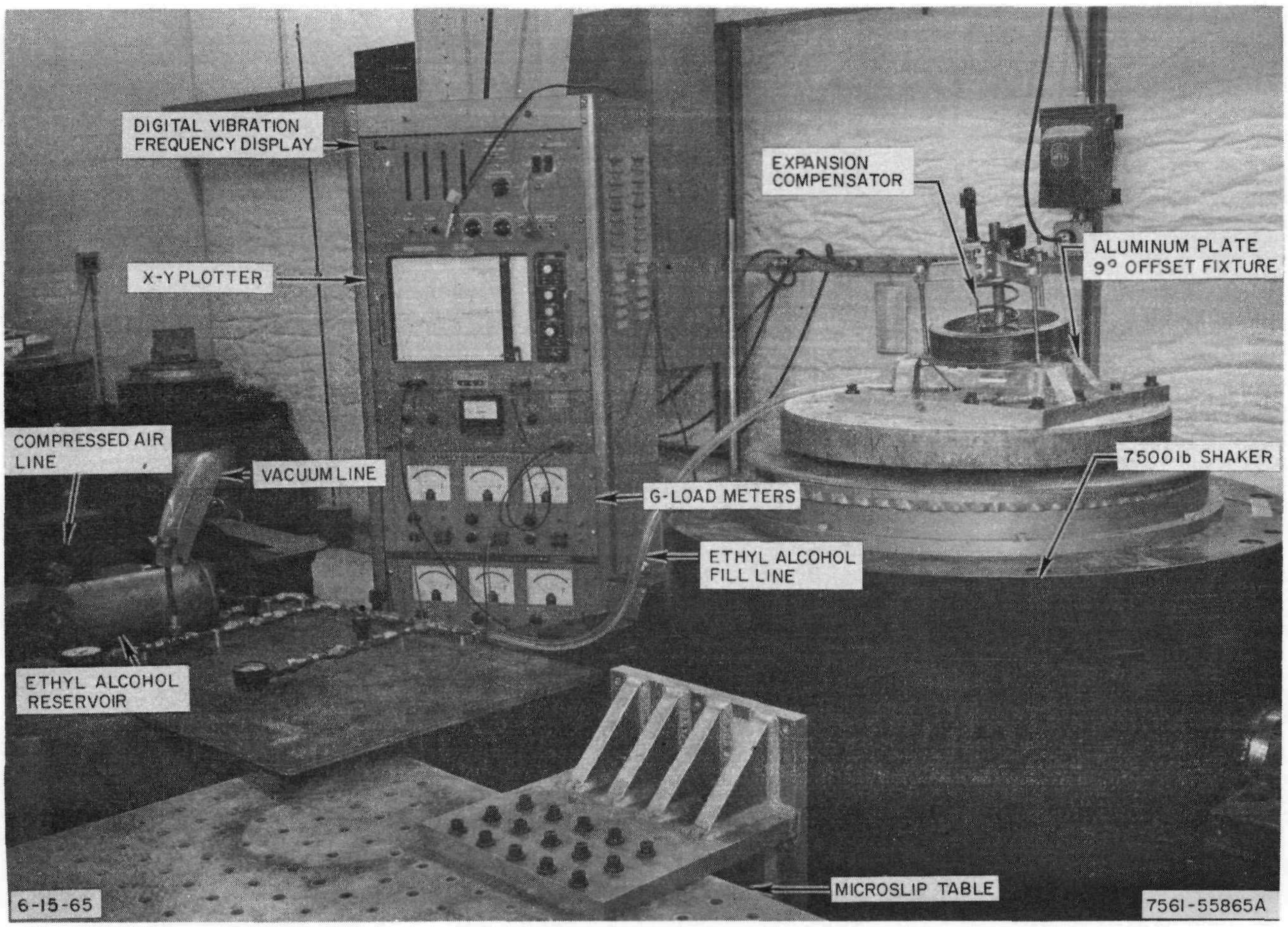


Figure 18. Shock and Vibration Test Rig

tank) and a mechanical vacuum pump of better than 5 x 10^{-4} torr blank-off pressure capacity. It is fitted with a 0 to 30 psig Bourdon tube pressure gauge, a thermocouple type vacuum pressure gauge head and readout, and has copper tubing and manifolds with brazed joints. Rig valves are the brass Veeco vacuum type. A standard industrial mobile air compressor provides alcohol pressurization.

(5) Auxiliary Equipment and Instrumentation

The vibration and shock tests are conducted utilizing the following equipment or a part thereof:

- Accelerometer Transducers and Signal Meters
- X-Y Recorders
- Magnetic Tape Recorders
- Tracking and Bandpass Filters
- Oscillograph Recorders
- Strobe Lights
- Motion Picture Camera and Strobe Synchronizer
- Oscilloscope and Polaroid Camera
- VOM — monitors ECU switch actuation during testing.

D. TEST RESULTS

1. Single Bellows ECU

Fifty-four single bellows assemblies were subjected to developmental tests to determine design and off-design performance characteristics. Tables 4 and 5 are summaries of the single bellows test program, delineating the pertinent design configurations, type of test, and test results. Test units normally consisted of bellows assemblies plus helical compression springs. Where bellows only was tested without the spring, the configuration column of Tables 4 and 5 indicates no spring. The two tables represent test results of bellows units furnished by two different bellows manufacturers.

The test results given in Table 5 are of bellows assemblies obtained for the purpose of establishing a backup source.

The following conclusions were reached from the test results summarized in Table 4.

The single bellows ECU design satisfied the launch environmental performance requirements as evidenced by successful testing of fourteen units at qualification load levels.

The design analysis of the bellows assembly was conservative and an adequate margin of safety existed. This was verified by the results of the burst and cyclic fatigue tests. The burst tests indicated that failures occurred at calculated stresses ranging from 207,900 psi to 309,400 psi, the higher value being well in excess of the ultimate strength of materials tested, PH15-7 Mo alloy (RH 950) and AM-350 alloy (SCT 850). The calculated stresses are, of course, approximate since they are based upon elastic deformation whereas the ruptured bellows assemblies yielded prior to failure. The cyclic tests conducted at room temperature and those conducted at temperatures in excess of design temperature (750°F) indicated the adequacy of the bellows design for the approximate 10 cycles operational requirement.

The endurance tests of units 012, 013, 017, 018, and 019 substantiated the adequacy of the design to meet the pressure requirement of 4 psi minimum after 1 yr operation. Relaxation curves of units 017, 018, and 019 are shown in Figure 19. The FSM-1 system test revealed that the ECU operating temperature requirement was ~725°F as opposed to previous analytical determination of 800°F maximum. This finding greatly increased the reliability of AM-350 alloy heat treated to the SCT 850 condition for the bellows application requiring low relaxation. An endurance test temperature of 750°F was used subsequent to the FSM-1 test except for accelerated relaxation tests.

The structural reliability of welded bellows assemblies was questionable as borne out by the early failure of unit 105 in the FS-1 system test. Although this was the only unit to fail structurally of the numerous units tested at S10A design conditions, this type of failure cannot be tolerated since structural failure of the single bellows with accompanying gross NaK leakage can result in complete system loss.

The test results of the alternate supplier's bellows assemblies presented in Table 5 indicated that these units would also meet the bellows relaxation requirements and had superior cyclic fatigue characteristics as exhibited by the performance of unit 010. This assembly was cycled 100,000 times with no structural damage at thermal conditions where the ductility of AM-350 (SCT 850) approached its minimum of ~5% elongation. No detrimental effects due to thinner diaphragm material or reduced number of convolutions was observed. The combination of the bellows spring rate characteristics and the auxiliary compression spring produced the requisite prestress and steady-state design condition pressures.

As a consequence of the single bellows expansion compensator development test program the basic compensator design was modified, as previously described in Section 3, Part B, to incorporate secondary containment of the NaK fluid. Failure analyses and post-operational metallurgical examination of test bellows assemblies revealed the need for improvement in the quality of the bellows weld joints.

Generally, a large variation in the size and shape of the convolution weld beads was noted. Measurements were made of the width and penetration depth of numerous weld bead specimens. The widths for the outer diameter welds ranged from 2.05 to 3.0 t (t = diaphragm thickness); the depths varied from 1.1 to 3.1 t. Figure 20(a and b) shows the crack that occurred in the weld bead of the bellows assembly S/N-105, which failed during startup of the S10A-FS1 nuclear test system. This crack propagated through the weld bead; the anticipated failure site is the heat affected zone at the root of the weld bead due to its reduced strength. Figure 21 shows the crack that occurred in the weld beads of the S/N-013 bellows assembly which was utilized successfully in the 90-day qualification test of the nonnuclear S10A-FSM1 system. The crack extends from the bead root to within 0.002 in. of the outer edge of the bead.

A program to provide greater quality assurance of fabricated compensator assemblies was instituted concurrently with the development of the secondary containment expansion compensator design. This program comprised material studies, manufacturing process control development and refinement of nondestructive test methods to verify quality of product.

2. Quality Assurance Program

As previously stated metallurgical examination of single bellows test units revealed the need for improvement in the quality of convolution weld beads. This problem had been noted in the initial phase of compensator development; however, the recommended solution proved inadequate as evidenced by the failure of bellows S/N-105. Examples of weld bead defects found in the first few developmental bellows assemblies are shown in Figures 22 and 23. A microphotograph of an acceptable weld bead is included for comparison. As a result of this variation in weld bead quality, three measures were taken:

a) Welding process control by the manufacturer was reviewed and changes in equipment, instrumentation, and inspection were made.

Serial Number	Bellows Assembly Material and Configuration	Environmental Tests: Vibration, Shock, and Acceleration	Expansion Compensator Pressures: Preload (psi)	Expansion Compensator Pressures: 33 psi – Launch Restrained	Expansion Compensator Pressures: 60 in.³ Displacement	Burst Pressure	Fatigue Cycles Pressure/Deflection (Room Temperature)	Thermomechanical Cycles	Operating Endurance (NaK-Vacuum Environment)
A	15-7 Mo, 0.010 in. thick 15 convolutions No spring	Qualification level, vibration only-1 psig glycerine fill to 10 in.^{3}	*	*	*	Rupture at 7.5 psi, 195 in.^{3} displacement	10 cycles, 0 to 75 in.^{3} displacement	*	*
B	15-7 Mo, 0.010 in. thick 15 convolutions No spring	Qualification level, vibration only-1 psig glycerine fill to 10 in.^{3}	*	*	*	Rupture at 52 psi, launch restrained	10 cycles, 0 to 75 in.^{3} displacement	*	*
C	AM 350, 0.010 in. thick 15 convolutions No spring	Qualification level, 33 psig alcohol fill to 10 in.^{3}		0.030 in. to 0.050 in. deflection of top bottom plates	*	Rupture at 68 psi, launch restrained	10 cycles, 0 to 75 in.^{3} displacement	2 cycles, 0 to 60 in.^{3}, R. T. to 800°F	*
D	AM 350, 0.010 in. thick 14 convolutions No spring	*	*	*	*	Rupture at 12 psi, 214 in.^{3} displacement	*	*	*
1	↓	*	*	*	*	*	2 cycles, 0 to 75 in.^{3} displacement	6 cycles, 0 to 75 in.^{3}, R. T. to 800°F	*
2	↓	*	*	*	*	*	2 cycles, 0 to 75 in.^{3} displacement	6 cycles, 0 to 75 in.^{3}, R. T. to 800°F	*
3	↓	*	0.30 psi at 800°F	Leak in OD weld	1.9 psi at 800°F		Rupture after 33,940 cycles, 0 to 62 in.^{3}	*	*
4	↓	*	0.39 psi at 800°F	Leak in OD weld	1.95 psi at 800°F	*	Failure after 44,508 cycles, 0 to 62 in.^{3}		*
5	AM 350, 0.010 in. thick 14 convolutions No spring	*			*	*	*	*	*
001	AM 350, 0.010 in. thick 14 convolutions	*	0.95 psi at R. T.	No damage	6.15 psi at R. T.	*	*	3 cycles, 0 to 75 in.^{3}, R. T. to 800°F	*
002	AM 350, 0.010 in. thick 14 convolutions No spring	*	0.65 psi at R. T.	↓	3.82 psi at R. T.	No failure 34 psi, 123 in.^{3} displacement at 800°F	*	*	*
003	AM 350, 0.010 in. thick 14 convolutions No spring	*	0.60 psi at R. T.	↓	3.75 psi at R. T.	Rupture at 9.9 psi, 135 in.^{3}	*	*	*
004	AM 350, 0.010 in. thick 14 convolutions	Qualification level, vibration only-5 psig alcohol fill to 10 in.^{3}	0.87 psi at R. T.	↓	5.9 psi at R. T., 5.2 psi at 800°F	*	Rupture after 3 cycles, 0 to 90 in.^{3} + 150 previous cycles, 0 to 62 in.^{3}	*	*
005	AM 350, 0.010 in. thick 14 convolutions	*	0.57 psi at R. T.	↓	5.25 psi at R. T.	*	Rupture after 17,810 cycles, 0 to 62 in.^{3}	*	*
006	AM 350, 0.010 in. thick 14 convolutions		0.427 psi at R. T	No damage	5.33 psi at R. T.	*	Rupture after 5,311 cycles, 0 to 62 in.^{3} displacement	*	*

*No test performed.

Note R. T. – room temperature

All pressures shown are gauge pressures.

Table 4. Single Bellows Assembly Test Summary (Sheet 1 of 3)

Serial Number	Bellows Assembly Material and Configuration	Environmental Tests	Expansion Compensator Pressures			Burst Pressure	Fatigue Cycles Pressure/Deflection (Room Temperature)	Thermomechanical Cycles	Operating Endurance (NaK-Vacuum Environment)
		Vibration, Shock, and Acceleration	Preload (psi)	33 psi – Launch Restrained	60 in.^{3} Displacement				
007	AM 350, 0.010 in. thick 14 convolutions	Qualification level, 5 psig alcohol fill to 10 in.^{3}	0.62 psi at R.T.	*	5.45 psi at R.T.	No failure - 11 psi at 120 in.^{3} displacement	*	20 cycles, 0 to 60 in.^{3} at R.T. to 800°F	1538 hr at 60 in.^{3}, 800°F Final pressure = 3.65 psi High relaxation-test discontinued
008			0.5 psi at R.T.	No damage	5.22 psi at R.T. 4.4 psi at 800°F	*	*	2 cycles, 0 to 75 in.^{3} at R.T. to 800°F	*
009			0.6 psi at R.T.		5.47 psi at R.T. 4.85 psi at 800°F	*	*	2 cycles, 0 to 75 in.^{3}, R.T. to 950°F	70 hr at 60 in.^{3}, 950°F Stacked height = 2.15 in., Original 1.07 in. High relaxation-test discontinued
010		Qualification level, 5 psig alcohol fill to 10 in.^{3}	0.65 psi at R.T. 0.50 psi at 800°F		5.75 psi at R.T.	*	*	9 cycles, 0 to 60 in.^{3}, R.T. to 950°F	10 hr at 60 in.^{3}, 950°F High relaxation-test discontinued
012		Acceptance level test	1.0 psi at R.T. 0.85 psi at 800°F		5.20 psi at 800°F	*	*	*	2238 hr at 60 in.^{3}, 725°F FSM-1 system test. Unit met system requirements
013		Acceptance level test	0.75 psi at R.T. 0.65 psi at 800°F		5.05 psi at 800°F	*	*	*	2238 hr at 60 in.^{3}, 725°F FSM-1 system test. Unit met system requirements.
014		Qualification level, 5 psig alcohol fill to 10 in.^{3}	0.68 psi at R.T. 0.55 psi at 800°F		5.00 psi at 800°F	*	*	*	*
015			*		*	*	*	*	*
016			0.85 psi at R.T.		5 psi at 800°F		*	4 cycles, 0 to 60 in.^{3}, R.T. to 800°F	*
017			0.85 psi at R.T.		5.8 psi at 800°F 9.7 psi with GTA at 750°F	*	*	12 cycles, 0 to 60 in.^{3}, R.T. to 750°F, 2-1/2 cycles, R.T. to 800°F	936 hr at 60 in.^{3}, 750°F Final pressure = 9.15 psi After 2960 hr, 800°F Final pressure = 8.6 psi Test discontinued
018			0.99 psi at R.T. 0.90 psi at 800°F		5.13 psi at 800°F		*	70 cycles, 0 to 60 in.^{3}, R.T. to 750°F	310 hr at 60 in.^{3}, 750°F Final pressure = 4.52 psi Test discontinued
019	AM 350, 0.010 in. thick 14 convolutions	Qualification level, 5 psig alcohol fill to 10 in.^{3}	0.90 psi at R.T.	No damage	5.30 psi at 800°F		*	14 cycles, 0 to 60 in.^{3}, R.T. to 750°F	5995 hr at 60 in.^{3}, 750°F Final pressure = 4.25 psi Test discontinued

*No test performed.
Note R.T. – room temperature
All pressures shown are gauge pressures.

Table 4. Single Bellows Assembly Test Summary (Sheet 2 of 3)

Serial Number	Bellows Assembly Material and Configuration	Environmental Tests Vibration, Shock, and Acceleration	Expansion Compensator Pressures Preload (psi)	Expansion Compensator Pressures 33 psi – Launch Restrained	Expansion Compensator Pressures 60 in.^{3} Displacement	Burst Pressure	Fatigue Cycles Pressure/Deflection (Room Temperature)	Thermomechanical Cycles	Operating Endurance (NaK-Vacuum Environment)
101	AM 350, 0.010 in. thick 14 convolutions	Acceptance level, 5 psig alcohol fill to 10 in.^{3}	1.37 psi at R. T.	*	*	*	*	*	
102		Acceptance and qualification level, 5 psig alcohol fill to 10 in.^{3}	1.42 psi at R. T.	No damage	5.45 psi at 750°F	*	*	10 cycles, 0 to 60 in.^{3}, R. T. to 750°F	2203 hr at 60 in.^{3}, 750°F Final pressure = 5.0 psi Ruptured after 20 hr at 120 in.^{3}, 11 psi
103		Acceptance level, 5 psig alcohol fill to 10 in.^{3}	1.40 psi at R. T.	*	5.27 psi at 750°F	*		1 cycle, 0 to 72 in.^{3}, R. T. to 750°F	*
104		Acceptance level, dry, unpressurized	1.34 psi at R. T.	*	*	*	*	*	*
105			1.45 psi at R. T.	*	5.02 psi at 750°F	*	*	1 cycle, 0 to 72 in.^{3}, R. T. to 750°F	After 1.6 hr at 938°F reactor outlet temperature, FS-1 unit failed
106			1.42 psi at R. T.	*	5.27 psi at 750°F	*	*	1 cycle, 0 to 72 in.^{3}, R. T. to 750°F	After 1.6 hr at 938°F reactor outlet temperature, FS-1 unit failed
108		Acceptance level, dry, unpressurized	1.50 psi at R. T.	No damage	5.38 psi at 750°F	*	*	1 cycle, 0 to 72 in.^{3}, R. T. to 750°F	*
109		*	*	*	*	*	*	*	*
110		Acceptance level, dry, unpressurized	1.50 psi at R. T.	No damage	5.33 psi at 750°F	*	*	1 cycle, 0 to 72 in.^{3}, R. T. to 750°F	*
111		*	*	*	*	*	*	*	*
112	AM 350, 0.010 in. thick 14 convolutions	*	*	*	*	*	*	*	*
114	AM 350, 0.010 in. thick 14 convolutions No spring	*	1.05 psi at R. T.	*	6.05 psi at R. T.	Rupture at 51 psi, 120 in.^{3} displacement, along circum. 3 OD welds	*	*	*
115	AM 350, 0.010 in. thick 14 convolutions	Acceptance level, dry, unpressurized	1.20 psi at R. T.	No damage	5.55 psi at 750°F	*	*	1 cycle, 0 to 72 in.^{3} R. T. to 750°F	*
116		*	*	*	*	*	*	*	*
117		*	*	*	*	*	*	*	*
118		Acceptance level, dry, unpressurized	1.10 psi at R. T.	No damage	5.13 psi at 750°F	*	*	1 cycle, 0 to 72 in.^{3} R. T. to 750°F	*
119	AM 350, 0.010 in. thick 14 convolutions	*	*	*	*	*	*	*	*

*No test performed.
Note R. T. — room temperature
All pressures shown are gauge pressures.

Table 4. Single Bellows Assembly Test Summary (Sheet 3 of 3)

Serial Number	Bellows Assembly Material and Configuration	Environmental Tests	Expansion Compensator Pressures			Burst Pressure	Fatigue Cycles Pressure/Deflection (Room Temperature)	Thermomechanical Cycles	Operating Endurance (NaK-Vacuum Environment)
		Vibration, Shock, and Acceleration	Preload (psi)	31 psi — Launch Restrained	60 in.^{3} Displacement				
001	AM 350, 0.009 in. thick 13 convolutions	*	*	*	*	Rupture, 156.5 psi, 124 in.^{3} displacement	*	*	*
002	AM 350, 0.009 in. thick 13 convolutions No spring	*	0.43†	No damage detected†	3.37 psi†	*	37,980 cycles, 0 to 60 in.^{3}, R.T. Rupture in one ID convolution weld	*	*
003		*	0.76†		3.57 psi†	*	*	*	*
004		*	0.62†		3.23 psi	*	*	*	*
005		*	0.68†		3.12 psi	Rupture, 146 psi, 123 in.^{3} displacement	*	*	*
006	AM 350, 0.009 in. thick 13 convolutions No spring	*	0.65†		3.15 psi	*	*	*	*
007	AM 350, 0.009 in. thick 13 convolutions	Qualification level No damage detected	0.67† 1.05 w/sp. 1.05 at 750°F		3.15 psi	*	*	12 cycles, 0 to 60 in.^{3}, R.T. to 750°F	1158 hr at 60 in.^{3}, 750°F Final pressure = 4.28 psi 24 hr at 120 in.^{3} Final pressure = 9.52 psi No damage — test discontinued
008	AM 350, 0.009 in. thick 13 convolutions	Qualification level No damage detected	0.54† 0.98 w/sp. 0.88 at 750°F		3.35 psi 4.88 psi at 750°F	*	*	5-1/2 cycles, 0 to 60 in.^{3}, R.T. to 750°F	4250 hr at 60 in.^{3}, 750°F Final pressure = 4.35 psi Test continuing
009	AM 350, 0.009 in. thick 13 convolutions No spring	*	0.62†		3.10 psi	*	30,000 cycles, 0 to 60 in.^{3}, R.T. (no change in preload) no damage	*	*
010	AM 350, 0.009 in. thick 13 convolutions	Acceptance level No damage detected§	0.60† 0.95 w/sp.	No damage detected†	3.27 psi 5.43 psi	*	100,000 cycles, 0 to 60 in.^{3}, 750°F, no failure	*	*

*No test performed
†Supplier Proof Test Data
§An additional 30,270 cycles with a dwell at resonant frequency, 5 g load input. No damage was detected.
Note: ECU numbers were not assigned for Development Tests although ECU's were assembled except for instrumentation.
w/sp. —with spring
All pressures shown are gauge pressures.

Table 5. Single Bellows Assembly Test Summary (Alternate Bellows Supplier)

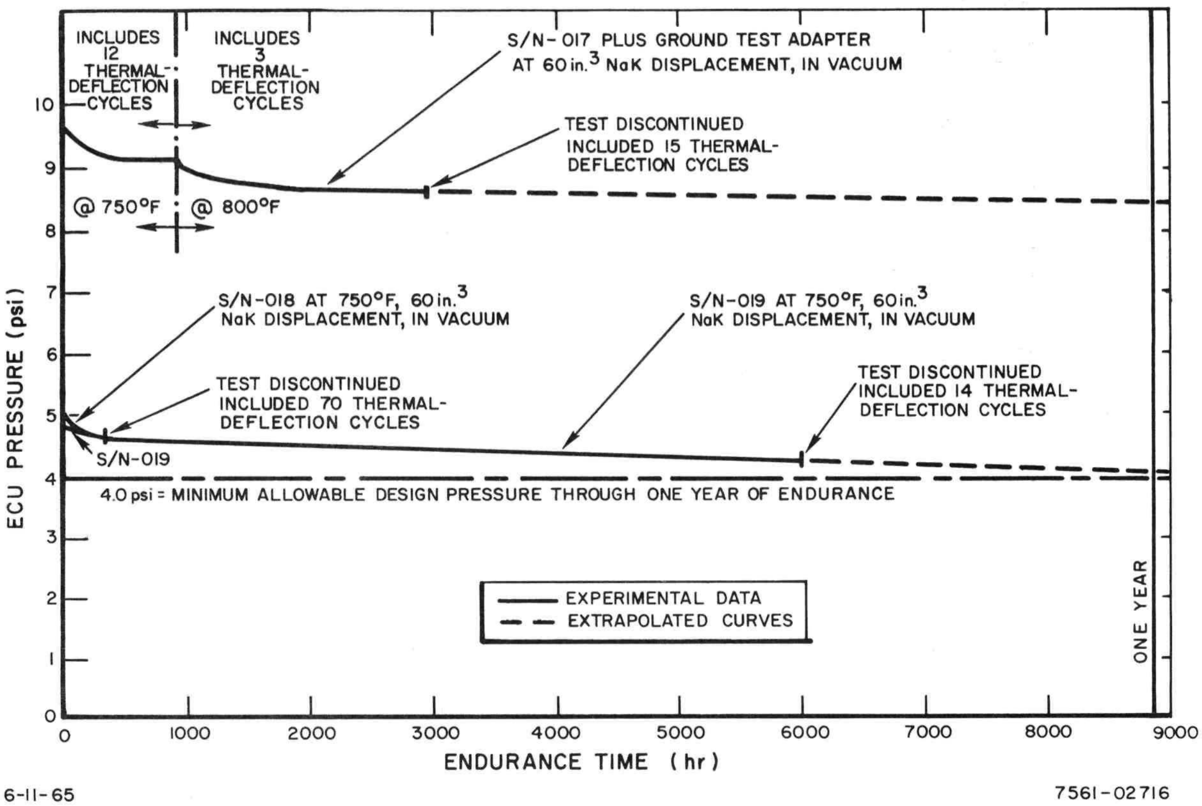


Figure 19. Relaxation Curves of Single Bellows Assembly

b) A weld bead specification applicable to thin foil TIG* burndown welds was applied to bellows fabrication. This specification required a minimum penetration depth of 1.0 t and where porosity or inclusions were present a minimum projected distance, as measured normal to the plane of the bellows disc, of 1.5 t between the root of the weld and the nearest edge of the defect was required.

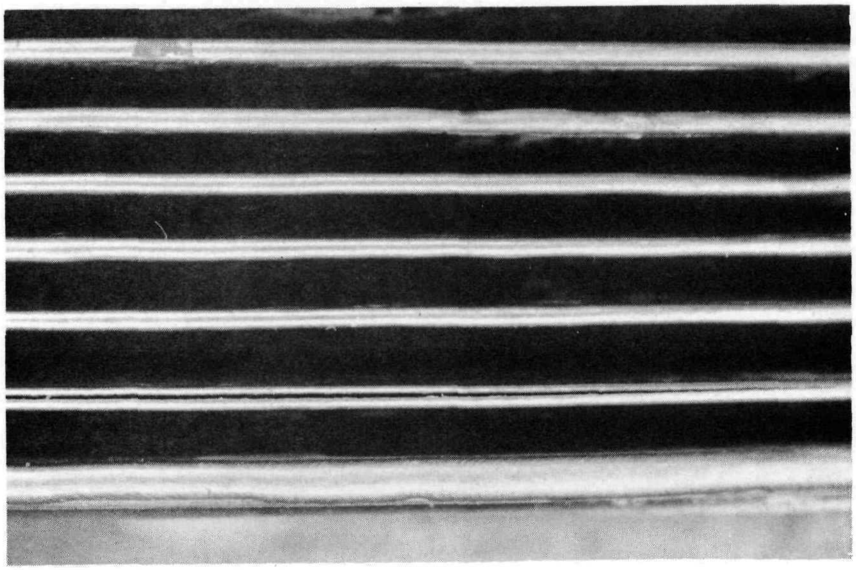
c) Radiographic inspection of all convolution welds were made to implement (b) above. Radiographic inspection techniques for detection of pores and inclusions in OD and ID weld beads were developed and then verified by metallurgical examination.

a. Metallurgical Examination

The failure of the S/N-105 bellows occurred in a region where the weld bead penetration was 1.1 t which did satisfy the weld specification; it was the smallest size bead of those examined. Additional bellows assemblies were metallurgically examined and a statistical study of weld bead geometry was carried out. Sections were cut from the various bellows assemblies, mounted and examined metallographically. Measurements were made of weld bead width, depth and degree of asymmetry (variation is projected overhang normal to the flat edge of the disc). Each section contained 15 OD weld beads and 14 ID weld beads, except for sections of Supplier II bellows, which contained one less convolution. Upwards of 1000 weld beads were examined. The metallographic findings for specific bellows assemblies were as follows:

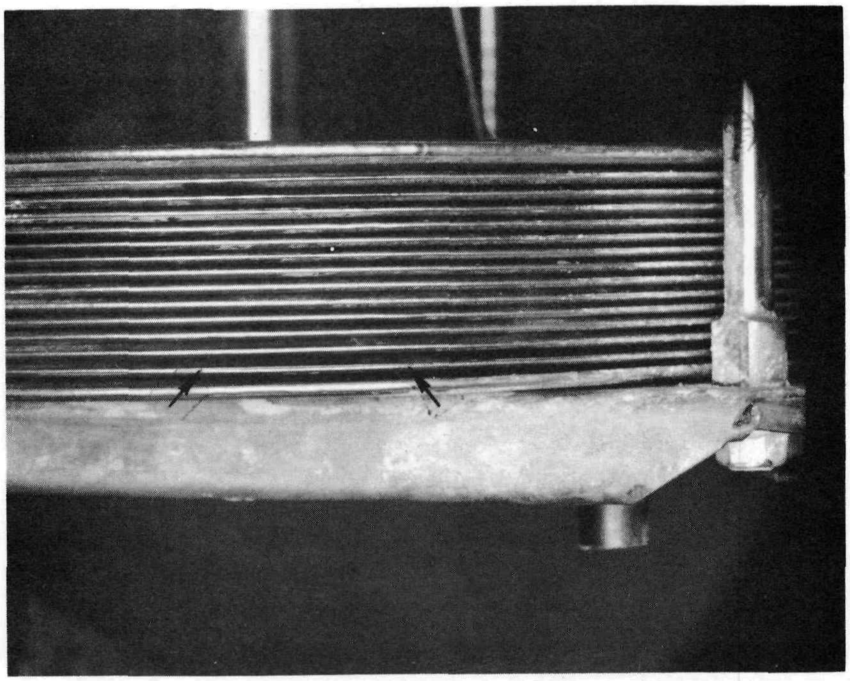
1) Bellows S/N-013 (ECU-001) survived the 90-day FSM-1 operation without incident.

*Tungsten inert gas (welding)



5X

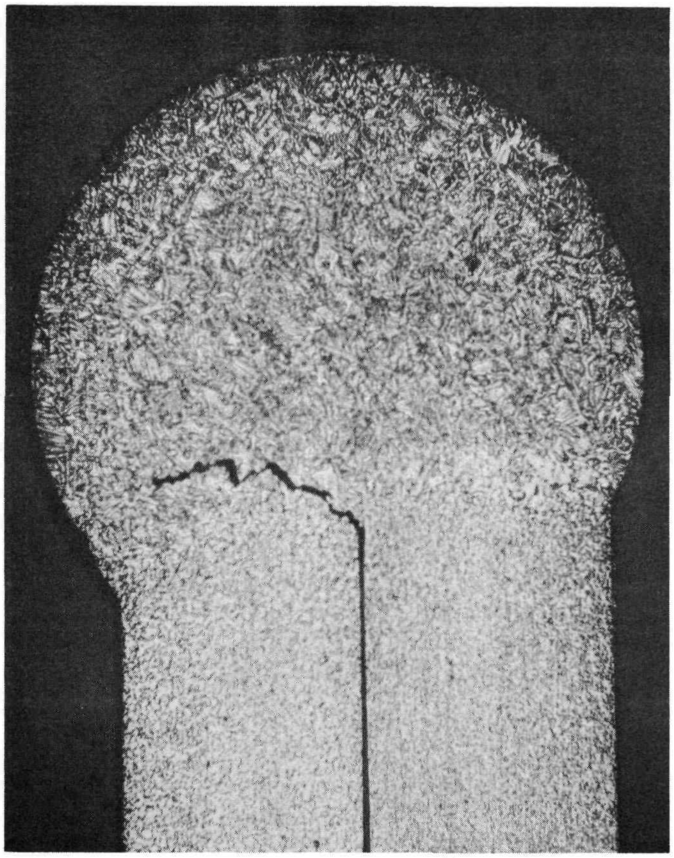
a. Enlarged View of Weld Bead Crack



0.93X

b. Partial View of Bellows Assembly
(arrows indicate ends of crack)

Figure 20. ECU Bellows Assembly S/N 105 After Failure



125X

Figure 21.
Crack Found in S/N 013 Bellows Assembly
After 90 Days S10A-FSM1
System Operation

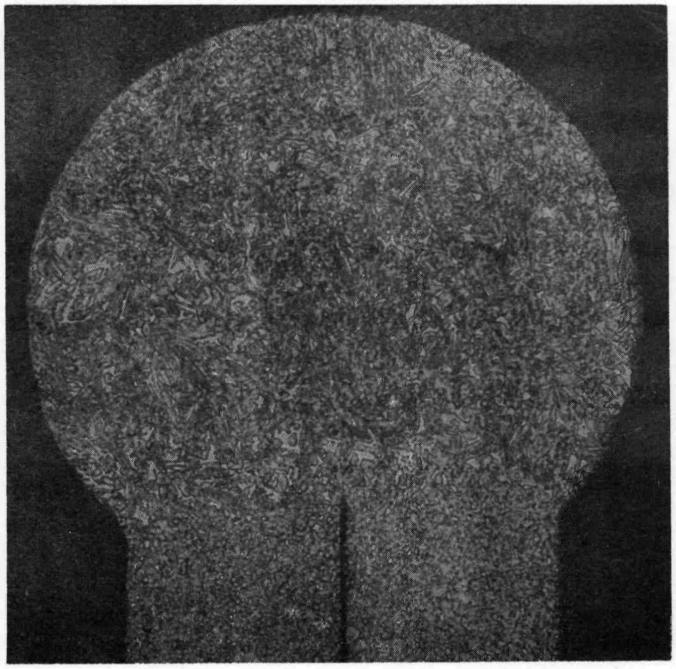
The ECU 001 bellows was from an earlier procurement generation than was the FS-1 bellows, and it had more and larger gas bubble pores than did the more recently procured bellows. Statistical evaluation of bead width and thickness shows a smaller variance than in the other bellows (1.2 to 2.5 t). One of the weld beads contained a crack near the heat affected zone propagating in short steps through the weld bead to within 0.002 in. of the outside of the bead.

2) Bellows S/N-104 (ECU-022) was overstressed but did not fail. The bellows was expanded to 120 in.^{3}. A good correlation was obtained between the weld width and the weld penetration. No cracks were observed.

3) Bellows S/N-114 (ECU-020) was burst tested and failed in four OD welds. It was cross sectioned in four places and the weld beads measured. These measurements confirmed the data obtained on ECU-022. All failure initiations were associated with thinner-than-average weld beads (1.05 to 1.5 t); some of the failures propagated through the weld beads and some through the heat affected zone (HAZ).

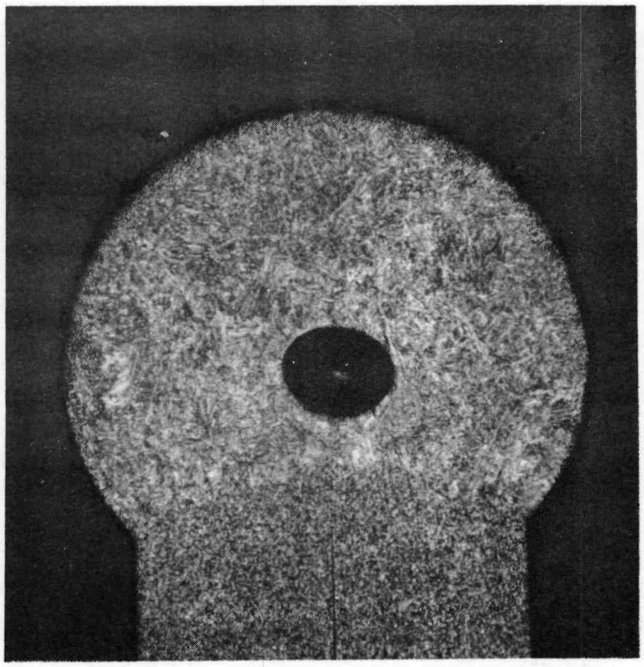
4) Alternate Supplier Unit S/N-001 was burst tested and failed completely around three OD convolution welds. All failures were in the HAZ and none through the welds. The ID welds were smaller, on average, than the OD welds. The penetration thickness of weld beads in the failure region ranged from 1.9 to 2.8 t.

5) Alternate Supplier Unit S/N-002 failed in one ID weld as a result of a cyclic fatigue test. Several other ID welds contained fatigue



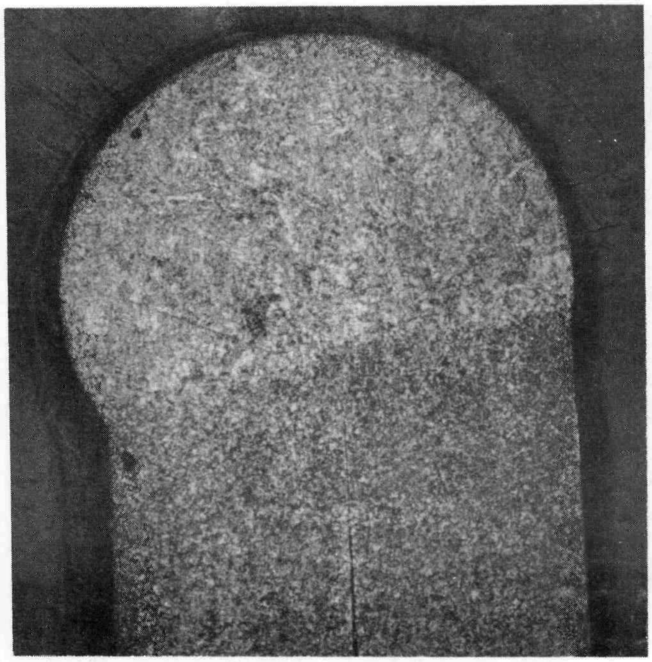
100X

a. Acceptable Weld Bead



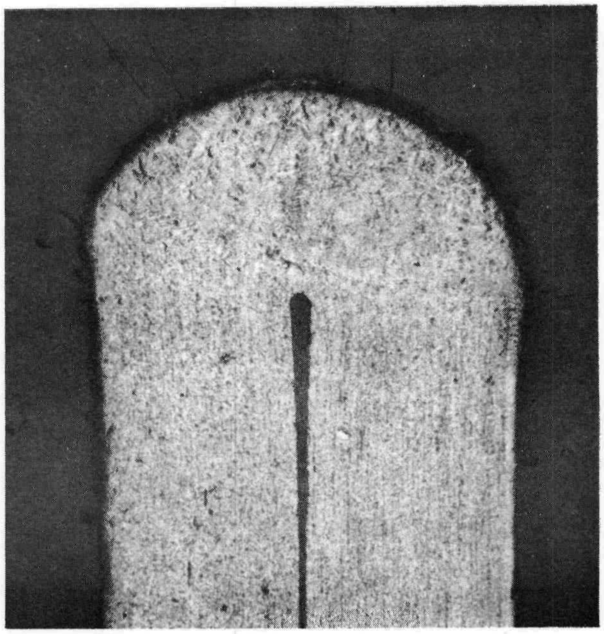
100X

b. Weld Bead With Large Pore
(unacceptable)



125X

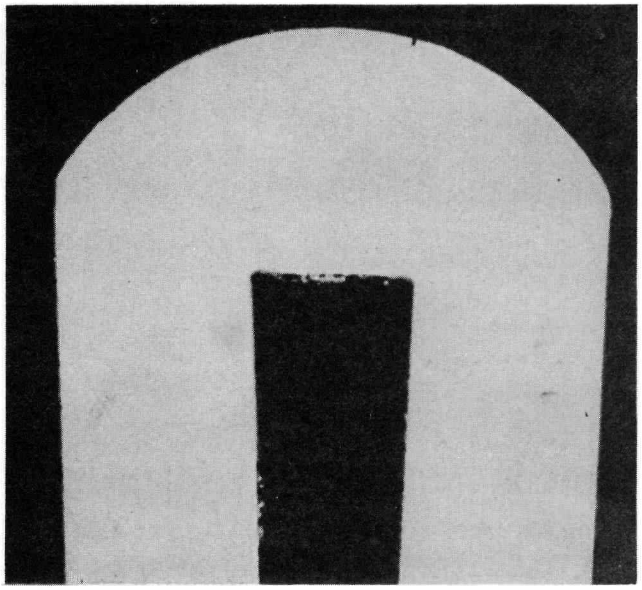
c. Unsymmetrical Weld Bead
(unacceptable)



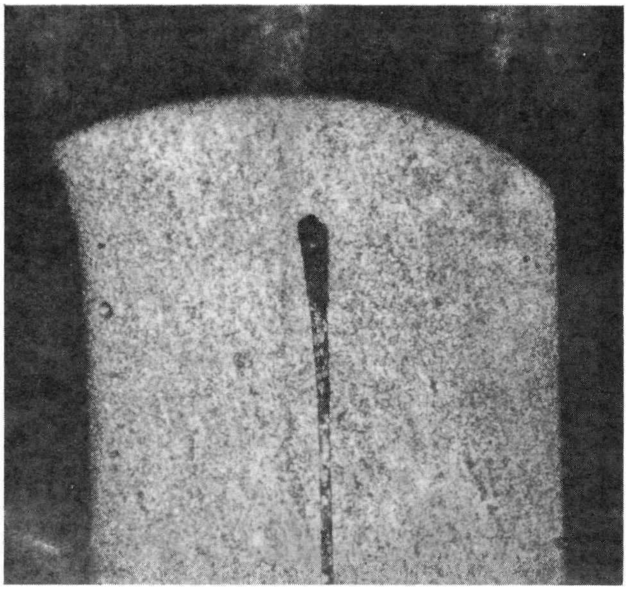
100X

d. Undersize Weld Bead
(unacceptable)

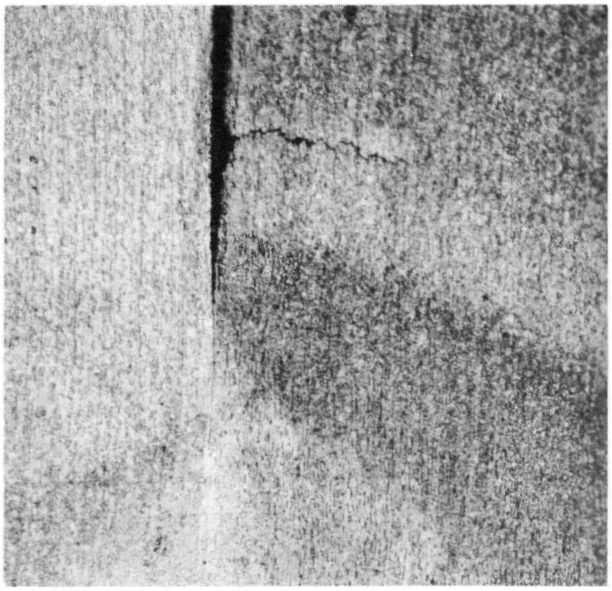
Figure 22. Bellows Weld Bead Cross-Sections — Material AM-350



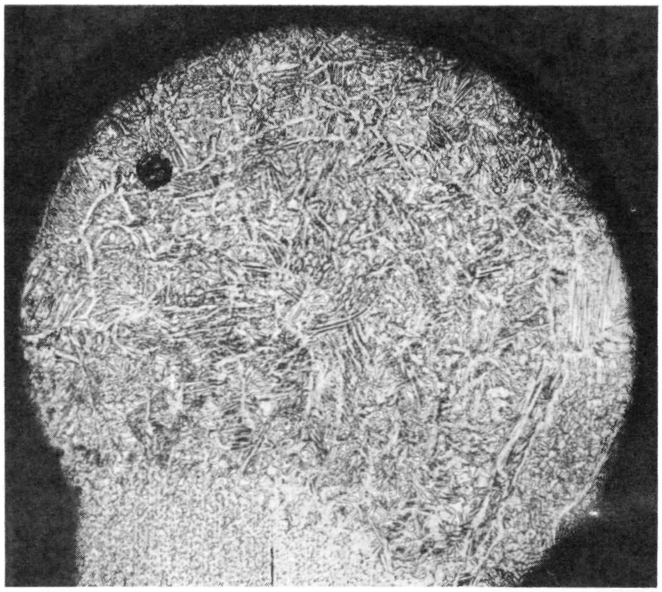
a. Extreme Undersize Weld Bead (unacceptable)



b. Extreme Undersize Weld Bead With Excessive Root Gap (unacceptable)



c. Crack in Heat-affected Zone of Weld Bead (unacceptable, not detectable by nondestructive testing)



d. Inclusion in Weld Bead (acceptability dependent on size and location of inclusion)

Figure 23. Bellows Weld Bead Cross Sections — Material AM-350

cracks which had not progressed to failure. The OD welds were smaller, on average, than the ID welds.

The conclusions resulting from the metallurgical studies were as follows:

1) Convolution weld joint failure occurred preferentially in thinner than average weld beads which proved to be weak links in the assembly; the cracks that developed were confined to the local regions of the thin weld sections.

2) Weld beads having less than 1.2 t penetration depth tended to fail through the weld bead rather than in the heat affected zone. Since a properly formed weld joint should be stronger than the heat affected zone (transition region between the weld joint and the base metal) a satisfactory weld bead should have a penetration depth greater than 1.2 t.

3) The applicable weld bead specification requiring a minimum of 1.0 t depth was inadequate to ensure requisite reliability of the welded bellows assemblies. A minimum of 1.3 t appeared to be adequate to prevent cracking through the weld bead.

b. Statistical Studies

Regression studies were performed on data obtained during the metallurgical examination of seven bellows. The data analyzed consists of weld bead size measurements; thickness or penetration, width and overhang. See Figure 24 for the dimension locations. The results of the regression studies are shown in Table 6.

The regression studies indicate a correlation between the bead width and root thickness (weld penetration) which means that the thickness can be estimated with a high degree of accuracy by nondestructively measuring the width. As seen in the table above, there is 97.5% confidence that welds exhibiting approximately 2.4 to 2.5 t width

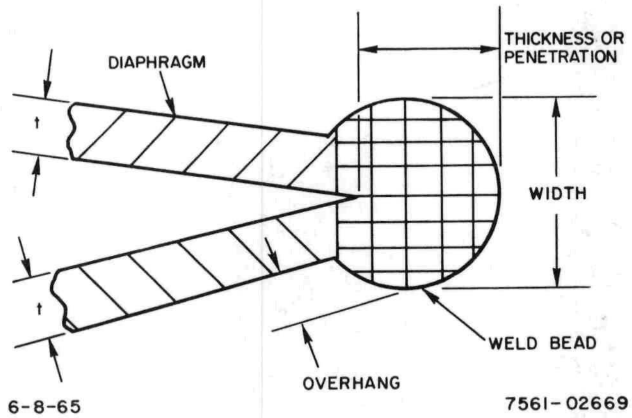


Figure 24. Weld Bead Dimensions

would also have at least a 1.5 t penetration depth.

Statistical tests were also performed to determine if the weld beads were asymmetrical. A tabulation of the pertinent data from these studies is shown in Table 7.

The above tabulation indicates an asymmetrical condition for the weld beads of bellows assemblies S/N-102, -106, -013, and -114 and -001. Sufficient information is not available to determine whether it is more prevalent in exterior welds than in interior welds, or in either vendor's product.

An analysis of variance, performed on the root thickness data from Bellows S/N-104, indicated the following:

1) Root thickness of exterior welds is significantly less than that of interior welds.

2) Root thickness varies significantly among readings taken approximately 90° apart around the entire bellows, but does not vary significantly among readings taken within 1/2 to 1 in. of each other.

3) Root thickness varies significantly among the 13 exterior or interior stacked welds with the bellows.

TABLE 6

REGRESSION STUDIES BETWEEN BEAD WIDTH AND ROOT THICKNESS (WELD PENETRATION)

Fabricator	Bellows S/N	External or Internal Weld	Average Width	Standard Deviation Sigma of Width	Average Thickness or Penetration	Sigma of Thickness	Correlation Coefficient	Correlation Significant*	Regression Line† Y = Thickness X = Width	Required Width to Assure 97 5% of Root Thickness above 1 5 t
Supplier I	102	ext	2 48 t	0 20	1 90 t	0 26	0 86	Yes	Y = -0 88 + 1 12 X	2 37 t
		int	2 95 t	0 23	2 50 t	0 24	0 86	Yes	Y - -0 22 + 0 92 X	2 14 t
	105	ext	2 45 t	0 22	1 90 t	0 34	0 68	Yes	Y = -0 73 + 1 08 X	2 55 t
		int	2 86 t	0 22	2 55 t	0 44	0 31	Yes	Y - +0 81 + 0 61 X	2 55 t
	104	ext	2 44 t	0 23	1 89 t	0 33	0 85	Yes	Y - -1 09 + 1 22 X	2 41 t
		int	2 86 t	0 26	2 39 t	0 22	0 68	Yes	Y - +0 79 + 0 59 X	2 20 t
	106	ext	2 66 t	0 29	2 08 t	0 36	0 73	Yes	Y -0 38 + 0 93 X	2 57 t
		int	3 03 t	0 32	2 46 t	0 36	0 80	Yes	Y - -0 20 + 0 88 X	2 42 t
	114	ext	2 44 t	0 23	1 76 t	0 44	0 86	Yes	Y = -2 21 + 1 62 X	2 57 t
		int	2 52 t	0 17	1 84 t	0 16	0 80	Yes	Y = -0 09 + 0 77 X	2 34 t
	013	ext	2 50 t	0 16	1 96 t	0 24	0 72	Yes	Y = -0 69 + 1 06 X	2 38 t
		int	2 59 t	0 17	2 05 t	0 26	0 66	Yes	Y = -0 60 + 1 02 X	2 45 t
	017	ext	2 65 t	0 19	2 11 t	0 29	0 91	Yes	Y = -1 63 + 1 41 X	2 40 t
		int	2 67 t	0 11	2 19 t	0 16	0 77	Yes	Y = -0 86 + 1 14 X	2 27 t
Supplier II	001	ext	2 69 t	0 11	2 43 t	0 24	0 52	Yes	Y - -0 51 + 0 09 X	2 20 t
		int	2 57 t	0 17	2 12 t	0 19	0 80	Yes	Y - -0 18 + 0 89 X	2 10 t
	002	ext	2 48 t	0 24	1 85 t	0 32	0 77	Yes	Y -0 69 + 1 02 X	2 52 t
		int	2 69 t	0 27	2 04 t	0 23	0 73	Yes	Y +0 35 + 0 63 X	2 33 t

Supplier I t - 0 010 in., Supplier II t = 0 009 in.

The meaning of a correlation coefficient being significant is an indication that the weld bead thickness is highly dependent upon the weld bead width A correlation coefficient of >0 20 is significant for this analysis based on the sample size of over 100 samples per bellows

†*The regression line equations show the relationship between the bead thickness and bead width since a correlation exists*

From knowledge of above comment (1) and the fact that exterior welds are fabricated in a vertical plane, whereas interior welds are fabricated in a horizontal plane, the measurements taken on all exterior welds were analyzed separately from the interior weld measurements The data were not separated between welds or sections, however, as the effects noted in above comments (2) and (3) are contributors to the capability of the welding process With this separation in the data, the capability of the welding process, based on data from S/N-104, is as follows

Exterior Welds — Bead width = average bead width ± 0 693 t

Bead thickness - average bead thickness ± 0 996 t

Interior Welds — Bead width = average bead width ± 0 774 t

Bead thickness = average bead thickness ± 0 669 t

This means the weld process is capable of producing exterior welds having 99% of the bead widths within a 0 693 t of the average bead width

TABLE 7

WELD BEAD ASYMMETRY ANALYSIS

Fabricator	Bellows S/N	Exterior or Interior Width	Average Overhang Above Weld	Average Overhang Below Weld	Average Overhang Below Significantly Greater Than Average Overhang Above Weld	Average Overhang Above Significantly Greater Than Average Overhang Below Weld
Supplier I	102	ext	2 80 t	2 22 t	—	Yes
		int	5 42 t	4 09 t	—	Yes
	104	ext	No asymmetry data obtained			
		int				
	105	ext	0 22 t	0 22 t	No	—
		int	0 42 t	0 44 t	No	—
	106	ext	0 37 t	0 28 t	—	Yes
		int	0 58 t	0 45 t	—	Yes
	114	ext	0 27 t	0 21 t	—	No
		int	0 25 t	0 32 t	Yes	—
	013	ext	0 26 t	0 25 t	—	No
		int	0 27 t	0 32 t	Yes	—
	017	ext	2 20 t	4 27 t	—	No
		int	3 20 t	3 49 t	—	No
Supplier II	001	ext	0 37 t	0 32 t	—	Yes
		int	0 29 t	0 28 t	—	No
	002	ext	0 25 t	0 23 t	—	No
		int	0 35 t	0 36 t	No	—

and 99% of the bead thickness within 0 996 t of the average bead thickness, and interior welds having 99% of the widths within 0 774 t of the average width and 99% of the bead thickness within 0 669 t of the average thickness

These tolerance results indicate that the welding process is not capable of remaining within the specified weld tolerances, 2 4 t minimum, and 3 5 t maximum width, which have an average of 2 95 t The bead widths that could be maintained 99% of the time based on an average of 2 95 t, are 2 26 t minimum and 3 64 t maximum for exterior welds The specified minimum bead thickness is 1 3 t which from the statistical tolerances, indicates that the average thickness should be as large as 2 3 t for exterior welds and 2 0 t for interior welds

In summary, it can be concluded from the statistical data that the root thickness is a dependent variable of the weld bead width and if the root thicknesses are less than 1 3 t a potential failure point is indicated

As a result of this analysis, weld bead size requirements were established and used as part of the purchase specification for the secondary containment ECU assemblies The specification sizes are

Weld bead width — 2 4 to 3 5 t

Weld bead root thickness — 1 3 t minimum

Overhang — 0 0005 in

The dependency between bead width and penetration permits implementation of this specification by 100% visual inspection of bead width

c. Material Studies

The material used for fabrication of the bellows assemblies is AM-350 precipitation hardenable stainless steel Typical analysis of AM-350 is presented in Table 8 The material is formed and welded in the mill-supplied condition The mill heat treatment consists of solution treating at 1900 to 1975°F, followed by water quenching * In this condition the nominal room temperature properties are

Y S (0 2% offset)	60,000 psi
U T S	145,000 psi
Elongation (in 2 in)	40 0 %
Hardness	20 0 Rockwell C

TABLE 8

TYPICAL ANALYSIS OF AM-350 ALLOY

Element	%
Carbon	0 08
Manganese	0 80
Silicon	0 25
Chromium	16 50
Nickel	4 30
Molybdenum	2 75
Nitrogen	0 10

The SCT-850 heat treatment consists of reannealing at 1710°F ± 25° — carbide precipitation temperature range — then hardening by cooling for 3 hr at -100°F (austenite transforms to martensite) followed by tempering for 3 hr at 850°F This heat treatment develops the highest strength combined with adequate ductility

Successful heat treatment of AM-350 alloy — development of requisite mechanical property values — is affected by slight variation in chemical composition this variation may still conform to the AMS material specification The ability of the heat treated alloy to resist corrosion is also dependent upon the material chemistry A slight excess of nitrogen tends to stabilize the austenite phase during sub-zero cooling resulting in decreased martensite transformation The alloy thus affected has reduced tensile strength and lowered resistance to corrosion This latter condition is created by a reduced concentration of delta ferrite. The delta ferrite concentration for good corrosion resistance is however unknown Excess of carbon similarly reduces the corrosion resistance of AM-350.

A correlation has been developed which shows the effect of chemical composition upon corrosion susceptibility of AM-350 alloy † Salt spray tests were performed with material from 49 heats of AM-350 The tests consisted of exposures of strips of AM-350, which were stressed by bending to 70% of ultimate, to a 20% salt spray solution for 168 hr Development of a crack in the material constituted failure The correlation is shown graphically in Figure 25 The test results indicated that stress corrosion resistance of AM-350 was improved by limiting the carbon plus nitrogen content to a maximum of 0 185% and the chromium plus 1 8 times the molybdenum percentage concentration to a minimum of 21 5% These requirements were made a part of the material procurement specification for the S10A compensator bellows assemblies Salt spray stress corrosion tests are in progress to verify that the bellows material behaves similarly to the materials tested by G Wald

Metallographic investigation is continuing to gain a better understanding of conditions which

*Allegheny Ludlum Steel Corporation brochure SS47-Ed. 3-1M-363J, "AM-350/AM-355 Precipitation Hardening Stainless Steels."

†G. Wald, Lockheed Corp., paper presented to the Western Regional Conference of the National Association of Corrosion Engineers.

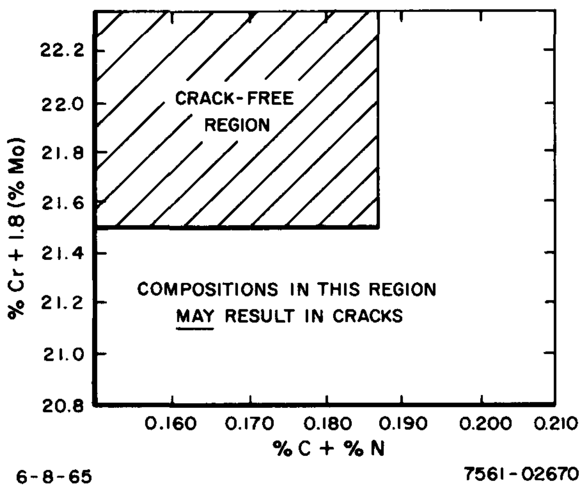


Figure 25. Effect of AM-350 Chemical Composition Upon Stress Corrosion Susceptibility

can improve the corrosion resistance of AM-350 alloy. These conditions include chemical composition, quenching rates after annealing, and aging temperature after sub-zero cooling.

d. Quality Control

All structural materials for the S10A secondary containment expansion compensator units which were procured for development testing, qualification and flight system utilization were procured in accordance with applicable AMS and ASTM specifications, which were upgraded where required as previously noted. Certified chemical and physical analyses were required from all suppliers and verifying analyses were performed by the bellows supplier and at AI. Prior to forming of bellows diaphragms, samples of each AM-350 coil were mechanically tested in the as-received and heat treated condition to verify conformance of yield strength, tensile, hardness, and percentage elongation values with the specification. Salt spray stress corrosion tests were also performed.

Strict process controls were imposed upon fabrication of the compensator assemblies. Specifications were prepared for cleaning, welding, heat treatment, radiographic inspection, mass spectrometer leak detection, and packaging.

To assume full implementation of the process control and inspection specifications the vendor's equipment and personnel were subjected to approval by AI Quality Assurance prior to start of fabrication and the fabrication was fully monitored by AI manufacturing inspection personnel.

3. Secondary Containment ECU

The secondary containment ECU development test program was designed to generate performance capability and to delineate component problem areas in a rapid manner in order to conform to the SNAP 10A program schedule requirement. The first seven secondary containment compensators (011 through 017) were assigned to development test use. Two additional units (021, 022) were subsequently assigned for development tests. The development test sequence for each of the units is shown in Table 9. The acceptance test and qualification test conditions are presented in later sections of this report.

As of the date of preparation of this progress report, February 18, 1965, the following paragraphs explain the significant development test results.

ECU 011 satisfied acceptance test requirements except for leakage in the secondary system. The unit was not affected by the qualification level shock, vibration, and acceleration tests. The primary and secondary bellows each sustained 200 psig internal pressure at maximum bellows deflection of 3.64 in. without failure. The bellows assemblies did undergo yield. This pressure capability compared very favorably with the results of single bellows ECU pressure tests. The unit was then subjected to complete metallurgical analysis. The leakage in the secondary system was ascertained to be due to stringers in the outer can weld preparations.

TABLE 9
SECONDARY CONTAINMENT ECU DEVELOPMENT PROGRAM

ECU Number	Acceptance Test	Qualification Level Vibration, Shock and Acceleration	Fatigue Cycling	Endurance in NaK	Burst Pressure
011	X	X			X
012	X			ΔV = 60 in.^{3} T = 750°F	
013	X	X		ΔV = 74 in^3 T = 750°F	
014			Dwell at resonant vibration frequency		X
015	X	X		ΔV = 60 in^3 T = 775°F	
016	X		0⟷60 in.^{3} 30,000		
017	X	X	0⟷60 in.^{3} 10,000	ΔV = 60 in^3 T = 750°F	
021	X			ΔV = 60 in^3 T = 800°F	
022	X	X		NaK in secondary T = 750°F	

In order to eliminate this problem, the method of manufacturing the outer can was changed from machining it from heavy wall seamless 347 Cres tubing, to forming it from 347 sheet The sheet was rolled into a cylindrical shape, longitudinally welded, and then formed at the ends to provide the weld preparations. This method of fabrication precluded the presence of stringers lying in a direction normal to the thin wall of the outer can, these cans were installed in all ECU units fabricated subsequently to 014 and solved the secondary leakage problem.

ECU-012 was placed on endurance test at ECU design condition after completing the acceptance test This unit has operated satisfactorily in excess of 3400 hr and operation is continuing. The bellows relaxation characteristic is shown in Figure 26 Extrapolation of this curve to one year operation indicates that the pressure degradation is well within the specification of a minimum of 4 psi.

ECU-013 is being endurance tested at the off-design test condition of 74 in^3 displacement at 750°F. This unit successfully passed the acceptance test and the qualification level shock, vibration, and acceleration tests The 74 in^3 displacement represents the operating volume of the S10A-FSM4 system This unit has logged 2180 hr, the pressure has changed from an initial value of 10 41 psi to 9.21 psi. Extrapolation of the relaxation data shown graphically in Figure 26 indicates that the pressure degradation at this over-stressed operating condition will still be less than allowed per the design specification

ECU-014 was utilized to investigate a possible problem resulting from the addition of the secondary bellows to the compensator design the problem being marginal integrity of the secondary bellows during the launch phase of system operation The secondary bellows is more susceptible to vibration damage than the primary

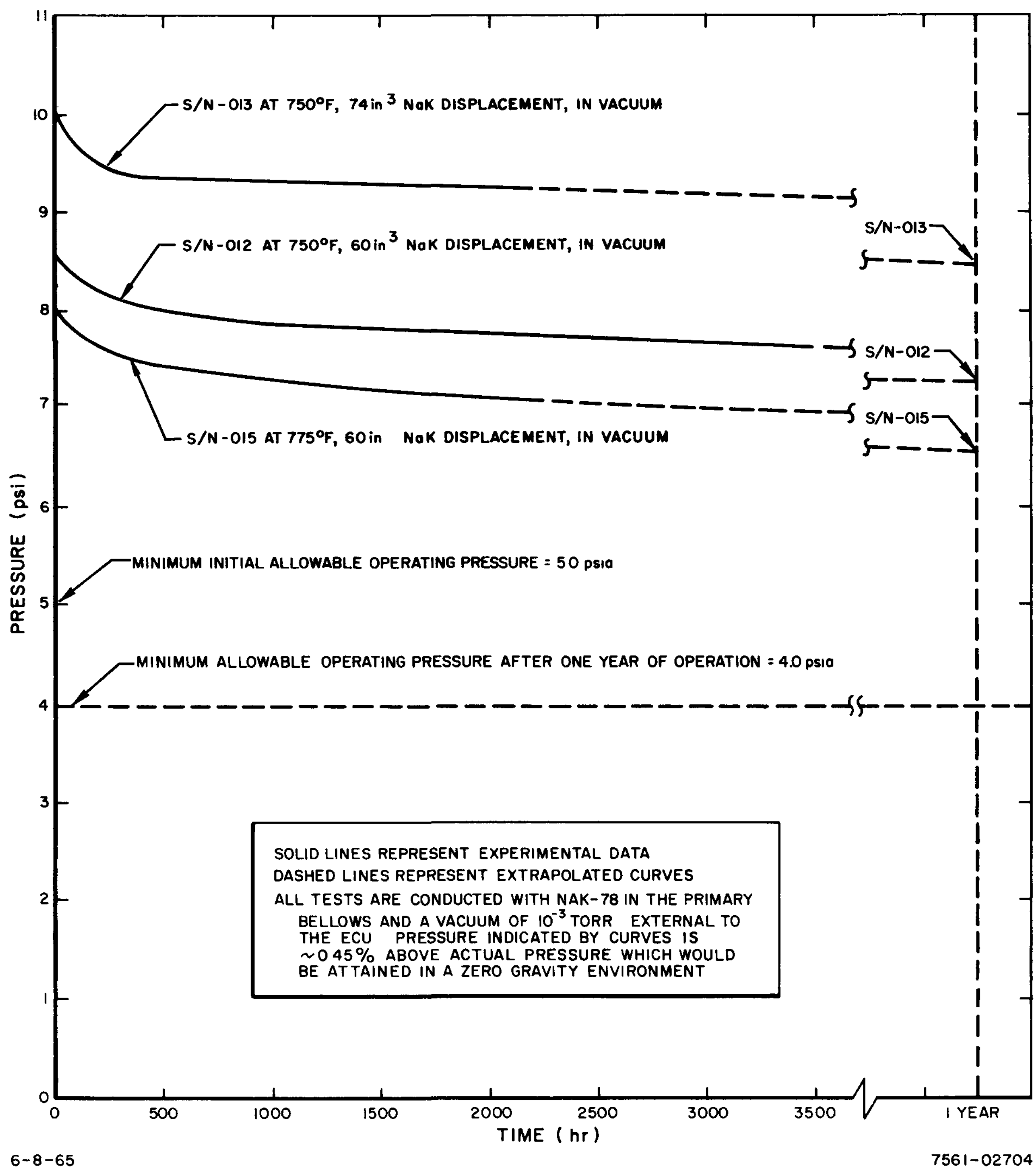


Figure 26. SNAP 10A Developmental Program – Secondary Containment Expansion Compensator Units Relaxation Curves

bellows since the former is in an extended, relatively unrestrained condition at launch. The primary bellows is in a compressed condition, restrained by the auxiliary spring from large amplitude oscillation.

The resonant frequency of the secondary bellows in its installed condition was measured and found to be 92.0 cps. Based upon assumed vibration loading of the ECU during launch, the predicted required cycle life of the bellows is 1275 cycles. To determine the margin of safety the ECU-014 was vibrated at the resonant frequency until failure. The failure point was determined by continuous vacuum pressure change leak check during vibration. A pin-hole rupture occurred after 15,200 ± 1,200 cycles. This result indicated a safety factor in excess of 10 and verified results obtained in vibration tests of secondary bellows assemblies only. It was concluded that no vibration dampers were required to be added to the secondary containment ECU design.

ECU-014 was subsequently subjected to a pressure test of the primary bellows. The bellows was subjected to 150 psig without rupture, which verified the ECU-011 pressure test results. The high rupture strength of the new bellows assemblies was attributed to improvement in manufacturing quality, especially as related to the convolution weld beads.

ECU-015 was acceptance tested, subjected to qualification level shock and vibration and then endurance tested at the off-design condition of 60 $in.^3$ displacement at 775°F. After 2250 hr the pressure has decreased from 8.22 to 7.06 psi. This unit, as shown in Figure 26 will also conform to the minimum pressure requirement after one year operation. Temperature measurements of the expansion compensators taken during operation of S10A-FSM1 and FSM4 nonnuclear qualification test systems show that the actual component operating temperature is ~725°F. The successful 775°F operation indicates that the ECU has an adequate operating temperature margin.

ECU-016 was successfully acceptance tested and then subjected to 30,000 deflection cycles of zero to 60 $in.^3$ displacement at room temperature. The primary bellows sustained the cycling with no damage. The secondary bellows failed, however, between 500 and 5000 cycles. The gross uncertainty in this number is due to the fact that the cycle counter was connected to the primary bellows, which did not fail, and that the secondary bellows failure occurred during a period of unattended operation. The cycling rate was ~5 cpm. The early failure of the secondary bellows was due to "oil-canning" of the convolutions at large deflections. To remedy this problem the number of convolutions of the secondary bellows was increased from 13 to 18 to decrease the deflection per convolution that occurred during ECU operation. This change was instituted on all compensator units starting with ECU-017.

ECU-017 was successfully acceptance tested, subjected to 10,000 cycles of zero to 60 $in.^3$ displacement at room temperature, and then endurance tested at design conditions. This unit has been reassigned to a qualification unit status and test results are reported in the qualification section of this report.

ECU-021 was subjected to high temperature endurance testing in a gas test rig instead of NaK. The purpose was to provide accelerated bellows relaxation data. After acceptance testing the unit was subjected to 5 thermal cycles at temperatures ranging from room temperature to a high end range of 785 to 813°F. These tests resulted in an excessive degradation in breakaway pressure: 0.87 to 0.31 psi. The design required is 0.90 psi minimum. All secondary containment ECU's have satisfied this requirement as determined by acceptance test except for ECU-020. Its breakaway pressure (P_B) was 0.71 psi. The results of testing of ECU-021 showed the large P_B loss that can result from heating the ECU in excess of 775°F. A slotted spacer was designed and tested to act as a shim on the auxiliary spring and increase the P_B by 0.2 psi in the event that excessive temperatures occurred during thermal reference testing of flight systems.

The ECU-021 has logged 500 hr at 800°F and 60 $in.^3$ displacement subsequent to the 5 thermal cycles. The pressure at 60 $in.^3$ changed from 6.28 to 6.07 psi. Endurance testing of this unit is continuing at 825°F.

The development tests of the secondary containment ECU are continuing. Most tests are in the endurance phase. Test of the reliability of the secondary system to contain NaK in the event of a primary bellows leak is in preparation. The development program completed to date shows that the secondary containment ECU design conforms to the component specification and exceeds the performance and reliability of the single bellows ECU design.

VI. QUALIFICATION TEST PROGRAM

A QUALIFICATION TEST REQUIREMENTS

The objective of the qualification test program is to verify that the selected ECU design will fulfill all performance requirements of a flight system component.

B. QUALIFICATION TEST PROCEDURE

In order to fulfill the test objective, four ECU's are subjected to a sequence of tests designed to effectively simulate the design conditions to which a flight system is chronologically subjected from the time of component fabrication through the operational lifetime in orbit.

Three of the four ECU's are to undergo the endurance phase of the test sequence at normal design operating conditions, i.e , 60 in^3 NaK displacement at 750°F in a vacuum environment, through 90 days to meet the S10A SNAPSHOT design objective and for one year to meet the S10A system objective

The fourth ECU is to undergo its endurance phase of the test sequence in the malfunction design operating condition, i.e., 120 in^3 NaK displacement at 750°F in a vacuum environment, through at least 24 hr. Such operation could be required of a flight system ECU if, during the earth orbital prestartup phase, the bellows deflection locking pin on its companion ECU failed to release on command

The sequence of qualification tests is outlined in Table 10. The tests are referenced to the flight system test phases being simulated. The major tests of this sequence are explained in more detail in the following paragraphs The detailed tests are referenced to Table 10 by test numbers

Test 1 — The ECU must satisfactorily complete the acceptance test as delineated in the Acceptance Test Procedure section of this report. As each ECU installed in a SNAP 10A system must first satisfactorily complete this acceptance test, full simulation is achieved

Test 7 — Vibration and shock tests are conducted in order to simulate the dynamic mechanical environment imposed upon a flight system ECU during launch and earth orbital insertion The test input load levels are of sufficiently high multiplication factor, with respect to anticipated system loads, that this set of tests simulates both the effects of system prelaunch, acceptance vibration tests and those of launch and orbital insertion

During testing the ECU is mounted on a 9° offset fixture. This provides for displacement inputs along the NPU major axes with respect to the ECU rather than the major axes of the ECU itself. The ECU undergoes testing with the primary bellows filled with ethanol under 5-psig static pressure at the pin-locked position. A sinusoidal vibration test is conducted along each of the three major NPU axes of the fixtured ECU, proceeding from 5- to 2000-cps input frequency in 25 min at a constant octave sweep rate Input loads are imposed per the following schedule

Frequency	Load
5 to 20 cps	1/4 in double amplitude
20 to 400 cps	5 0 g's
400 to 2000 cps	7 5 g's

Accelerometers mounted on the ECU provide a record of the ECU dynamic response to the programmed input.

Two shock cycles are imposed in each direction along each major NPU axis of the fixtured ECU before or after the appropriate vibration sweep The shocks are of approximate half-sine wave form and of 6 msec duration each and are of the following magnitudes

TABLE 10

EXPANSION COMPENSATOR UNIT QUALIFICATION TEST SEQUENCE AND RELATIONSHIP TO SNAP 10A SYSTEM TEST PHASE SIMULATION

	Qualification Test Sequence	System Test Phase
1	Acceptance tests	
2	Determine secondary containment volume	
3	Seal secondary containment inlet line	
4	Determine weight — dry	
5	Examination	
6	Determine weight — ethanol filled, pin-locked at 5 psig	
7	Vibration and shock tests	vehicle launch
8	Determine primary containment volume when pin-locked at 5 psig	
9	Determine weight — ethanol filled, pin-locked at 34 psig	
10	Acceleration tests	vehicle launch
11	Determine primary containment volume when pin-locked at 34 psig	↑ ↑ ↑ ↑
12	Remove pin-puller actuator and determine primary bellows volume vs deflection over design range	Determine ECU acceptability for system use and NaK containment integrity through launch phase
13	Redetermine dry weight	
14	Helium leak test	
15	Install in endurance test rig and load primary bellows with NaK-78	
16	Conduct 5 deflection cycles at room temperature with the ground test adapter installed	Prelaunch system ground tests
17	Conduct 5 thermal-deflection cycles with the ground test adapter installed	
18	Conduct squib-firing pin-lock release test	
19	Conduct one deflection cycle without the ground test adapter installed	Orbital startup and endurance testing of system in space
20	Conduct 5 thermal-deflection cycles without the ground test adapter installed	
21	Helium leak test of secondary containment	
22	Conduct endurance test with intermittant helium leak tests of secondary containment	
23	Remove ECU from test rig, remove NaK charge, and clean with butanol	
24	Helium leak test	Post-mortem examination of ECU
25	Conduct deflection cycle at room temperature	
26	Disassemble ECU and examine	

NPU Axis and Direction	Shock Magnitude
+X (forward)	20 g's
-X (aft)	20 g's
+Y, -Y, +Z, -Z (lateral and normal)	10 g's

The shock and vibration tests are conducted on a 7500-lb capacity Ling Model A246 electromagnetic induction shaker system and associated microslip table (see Figure 18 for a photograph of a test setup).

Test 10 — The acceleration tests, like the vibration and shock tests, are conducted in order to simulate the flight system launch and orbital insertion conditions. The ECU primary bellows is filled with ethanol and maintained under 34-psig static pressure in the pin-locked position during the test runs. The 34-psig pressure corresponds to the pressure imposed on a flight system ECU by the system NaK head at maximum launch acceleration. The tests are conducted in a 100-lb capacity Trio-Tech Model G-338-3 centrifuge per the following schedule

System Axis and Direction	Load	Duration
+X (forward	5 g	10 min
-X (aft)	10 g	10 min
+Y, -Y, +Z, -Z (lateral and normal)	6.3 g	10 min each

See Figure 17 for a photograph of a typical test setup

Tests 16 and 17 — The ECU is installed in the high-temperature, NaK-vacuum test rig (see Figures 14, 15, and 16) where it remains through endurance testing The Ground Test Adapter (GTA) is installed on the ECU The primary bellows is loaded with NaK-78 via an argon gas pressurized NaK reservoir

Prior to NaK loading the primary bellows interior, together with the interior of the NaK test system, is alternately evacuated and purged with argon gas in order to reduce oxygen content in the NaK charge. The exterior of the ECU/GTA is similarly subjected to evacuation and purging in the test vacuum chamber prior to thermal cycling. This is done to reduce outgassing pressure rises and oxidation of the ECU/GTA during testing.

Five deflection cycles are conducted at room temperature with the ECU/GTA external environment being ambient air at approximately standard temperature and pressure. The primary bellows is deflected between zero deflection (zero displacement volume) and 60 $in.^3$ NaK displacement by pressurizing the argon head on the NaK reservoir

Five thermal-deflection cycles are conducted next with the ECU/GTA external environment being 10^{-3} torr vacuum. The primary bellows is deflected, as before, between zero and 60 $in.^3$ displacement/volume while the ECU is simultaneously heated from room temperature to 750°F, holding at 750°F-60 $in.^3$ for 1/2 hr during each cycle.

These tests are conducted to simulate anticipated SNAP 10A prelaunch acceptance testing of the entire NPU, both thermal and nonthermal.

Tests 18 and 19 — The bellows locking pin extraction is tested by squib firing the actuator. This test simulates bellows unlocking during the flight system earth orbital prestartup phase. The firing is conducted in ambient air rather than vacuum as the effect of pin release on ECU operation, rather than squib performance, is being tested The lack of space-simulating vacuum is thus considered to be irrelevant to the results of this particular test A deflection cycle is subsequently conducted in room temperature ambient air to determine if the pin release test has adversely affected normal bellows deflection capability. These tests are conducted on the ECU only, the GTA is first removed.

Test 20 — Five thermal-deflection cycles are performed as in Test 17 with the exception that the test is conducted on the ECU only, the GTA has been removed. This testing provides a confidence factor for the system space startup phase.

Test 22 — The endurance test is conducted in order to simulate flight system design operation while in earth orbit. The ECU remains on continuous test at 750°F in a vacuum environment (10^{-3} to 10^{-4} torr) with the primary containment NaK filled and the secondary containment evacuated to 10^{-1} torr helium pressure. The primary bellows deflection is maintained by varying the argon pressure head on the NaK reservoir to provide either a constant 60- or 120-in.^{3} NaK displacement volume, as previously stated, through a minimum test life representing the primary qualification goal (90 days at 60 in^3 or 24 hr at 120 in^3) These tests are to be carried through to one year of endurance, if possible, before concluding the test and subjecting the units to post-mortem examinations.

In addition to the major test phases discussed above, the ECU is also subjected to helium leak tests at several junctures of the test sequence utilizing a standard, laboratory type, mass spectrometer, leak detector Such testing indicates any loss in containment integrity incurred during testing

Early in the sequence, the ECU is also subjected to tests, as indicated in Table 10, which determine its basic physical characteristics such as weight, primary bellows zero deflection volume, pin-locked displacement volume, and volume versus deflection, and secondary containment volume versus bellows deflection. Ethanol is used as the volume measurement medium in all cases

Test 26 — At the conclusion of endurance testing each ECU bellows assembly is to be subjected to destructive metallurgical examination of the bellows welds and other critical areas.

C QUALIFICATION TEST STATUS AND RESULTS

At the present time there are three ECU's (S/N-017, -023, and -026) undergoing the 90-day endurance test phase of the qualification test sequence. All three have successfully completed the preceding test phases outlined in Table 10. The three units are functioning properly and have fulfilled or surpassed design requirements to date.

The fourth ECU, which is to undergo endurance at 120 in^3 primary bellows NaK displacement, will be tested in the near future A summary report, to be written after completion of all testing, will delineate the results of the testing on all four units. The interim results of present tests are discussed in the following paragraphs. The significant test results on ECU's S/N-017, -023, and -026 as opposed to design requirements can be found in Table 11.

Figure 27 is a plot of the volumetric displacement versus bellows deflection characteristics of ECU S/N-023, as found at room temperature using ethanol. The figure graphically illustrates the volumetric variance of the primary and secondary containment chambers as measured, and also as corrected for design operating temperature. The measured volumetric displacement of the pin-locked deflection under a 5-psig head was found to be 16.9 in^3 The displacement volume at the pin-locked position under a 33- to 34-psig head, which corresponds to the maximum anticipated acceleration head occurring during system launch into space, was measured at 22 2 in^3 Both values are in excess of the 10 in^3 required minimum

Figure 28 is a plot of ECU S/N-023 pressure versus deflection of the primary bellows The figure graphically illustrates test pressures

TABLE 11

PRIMARY OPERATING CHARACTERISTICS OF QUALIFICATION ECU's
S/N-017, -023, -026

Characteristic	S/N-017	S/N-023	S/N-026	Design Requirements
Bellows deflection equivalent to 60 in.^{3} primary bellows displacement volume				Designed for 1.46 in.
measured at room temperature	1.43 in.	1.43 in.	1.43 in.	
750°F calculated equivalent	1.41 in.	1.41 in.	1.41 in.	
Primary bellows displacement volume at the pin-locked position				10 in.^{3} minimum
measured at 5 psig pressure	15.5 in.^{3}	16.9 in.^{3}	13.3 in.^{3}	
measured at ~34 psig pressure	22.1 in.^{3}	22.2 in.^{3}	20.3 in.^{3}	
Secondary containment volume				
measured at room temperature from 0 to 1.5 in. bellows deflection	50.5 in.^{3} to 49.5 in.^{3}	50.5 in.^{3} to 49.5 in.^{3}	50.5 in.^{3} to 49.5 in.^{3}	Designed for a constant 50 in.^{3} with minimal values desired
750°F calculated equivalent	51.3 in.^{3} to 50.3 in.^{3}	51.3 in.^{3} to 50.3 in.^{3}	51.3 in.^{3} to 50.3 in.^{3}	
ECU pressure at 0.1 in. bellows deflection at room temperature				0.9 psi minimum
at start of acceptance test	1.8 psi	1.7 psi	1.7 psi	
at start of qualification endurance	1.6 psi	1.3 psi	1.5 psi	
ECU pressure at 60 in.^{3} primary bellows displacement at 750°F				Minimums 5.0 psi at start of endurance 4.5 psi after 90 days 4.0 psi after one year Maximum 11.0 psi
during acceptance test	7.1 psi	7.0 psi	6.9 psi	
at start of qualification endurance	6.9 psi	6.8 psi	6.8 psi	
Ground test adapter pressure contribution to the ECU				3.6 psi minimum
at room temperature during acceptance test	3.7 psi at 0 in. deflection to 5.3 psi at 60 in.^{3} displacement	3.8 psi at 0 in. deflection to 5.4 psi at 60 in.^{3} displacement	3.6 psi at 0 in. deflection to 5.3 psi at 60 in.^{3} displacement	
at 750°F at start of qualification endurance	3.8 psi at 0 in. deflection to 5.3 psi at 60 in.^{3} displacement	3.8 psi at 0 in. deflection to 5.4 psi at 60 in.^{3} displacement	3.8 psi at 0 in. deflection to 5.4 psi at 60 in.^{3} displacement	
Position transducer output tolerance band	O.K. see Figure 33	O.K. see Figure 33	O.K. see Figure 33	Linear from 0 ± 3.5 mv at 0 in. bellows deflection to 50 ± 3.5 mv at 2.0 in. deflection

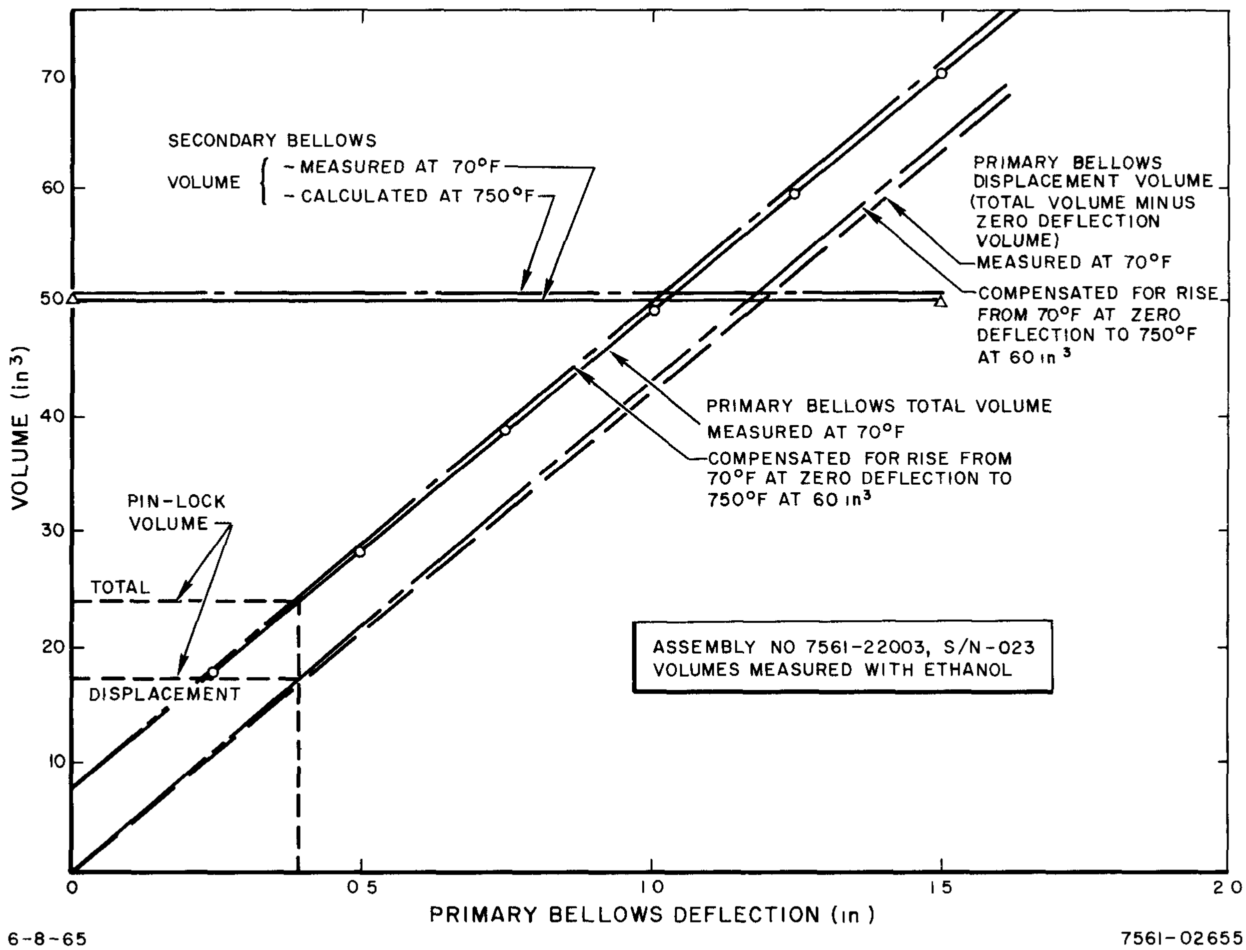


Figure 27. SNAP 10A Expansion Compensator Unit (ECU) S/N-023 Volume vs Deflection Characteristics

versus bellows deflections as measured during the thermal cycles, just prior to endurance testing. Curves are shown for the ECU and for the ECU/GTA combination. The breakaway pressure is 0.87 psi and the operating pressure at design conditions (1.46-in. deflection, 750°F) is 7.00 psi. Both values are in excess of requirements. The alternate temperature scale along the bellows deflection scale x-axis indicates the temperatures and deflections at which data were taken. The simultaneous increase in deflection and temperature simulates flight system operation wherein the bellows expands as the system NaK volume increases with increasing temperature during earth orbital startup.

Figures 29, 30, and 31 depict operational characteristics of ECU S/N-023 during its acceptance test sequence. By correlating these figures with those mentioned in the preceding paragraph, the rate of degradation of the pressure supplied by the ECU from inception to completion of pre-endurance qualification testing can be resolved. This is essentially the degree of degradation that would be expected in a SNAP 10A flight system ECU from the time of its acceptance test to the time of the earth orbital startup of its system. This being the case, the ECU is expected to perform satisfactorily in this regard in the SNAP 10A NPU, as ECU S/N-023, as well as S/N-017 and, S/N-026 performed efficiently

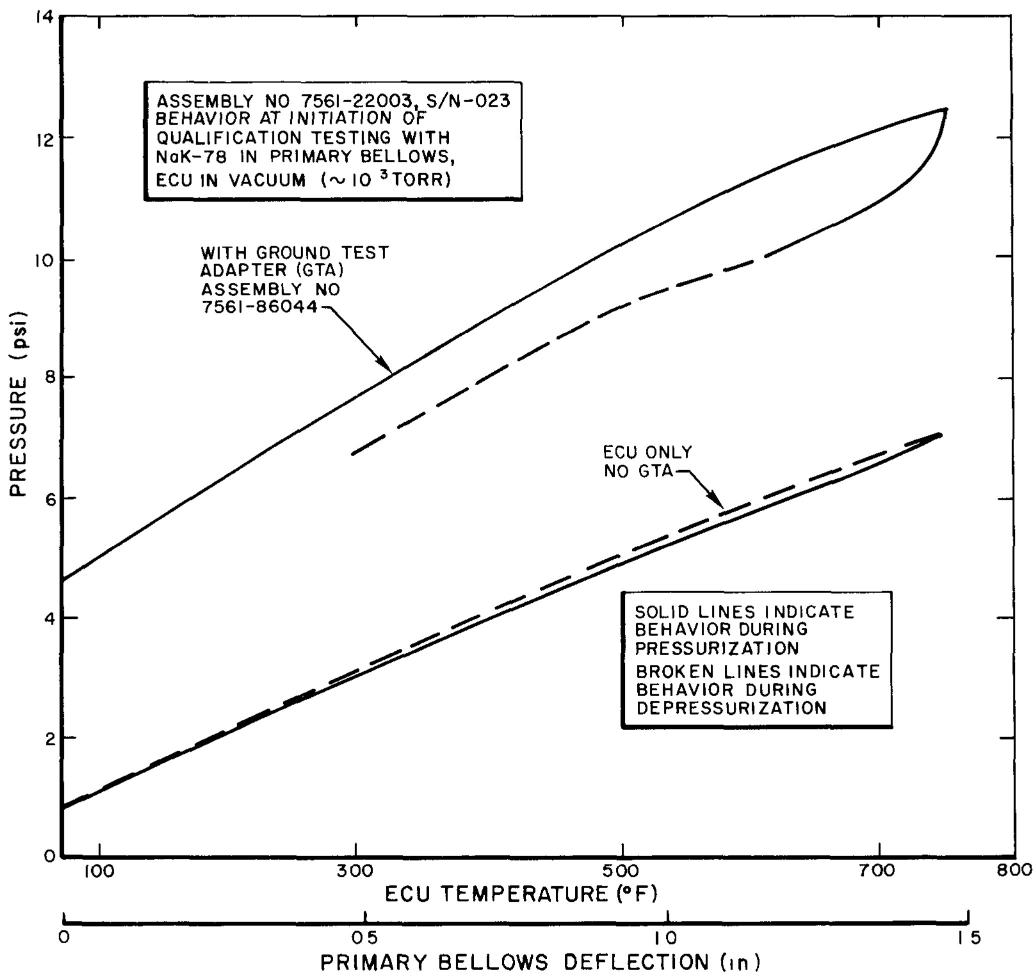


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Figure 28. SNAP 10A Expansion Compensator Unit (ECU) S/N-023 Volume vs Deflection Characteristics During Qualification Testing

within the specified limits of allowable deliverable pressure through initiation of endurance testing.

Thus far the rates of pressure degradation during endurance testing on ECU's S/N-017,-023 and -026 appear to be acceptable as evidenced by Figure 32, which is a plot of ECU pressure output endurance test history for ECU's S/N-017, -023, and -026. Although the tests are not complete, the data can be extrapolated to state conservatively that the ECU's will maintain system operating pressures in excess of the design minimum of 4 0 psi, and most probably in excess of 5.0 psi throughout one year of NPU earth orbital design operation.

The output of the bellows deflection indicating transducer/demodulator is also being monitored throughout the endurance life of each of the qualification units. Initial data indicate that the monitored signals, which on a flight system are telemetered to an earth tracking station during NPU earth orbital operation, will degrade at a rate which will not exceed 1.0 mv in the first 90 days at the design output level The signals generated through the first few hundred hours of operation, at the design bellows deflection level

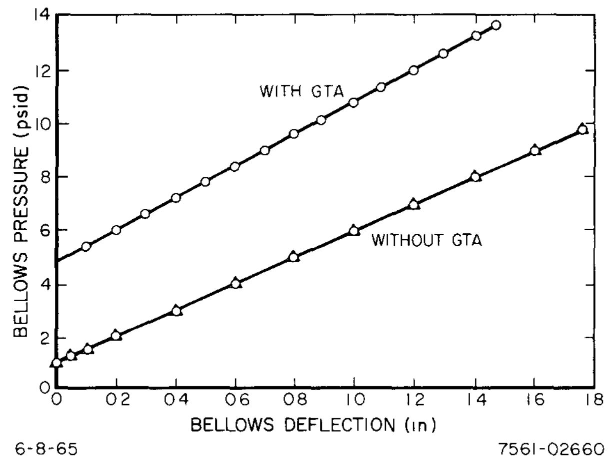

Figure 29. Ambient Temperature Pressure-Deflection Characteristics of ECU S/N-023 During Acceptance Testing

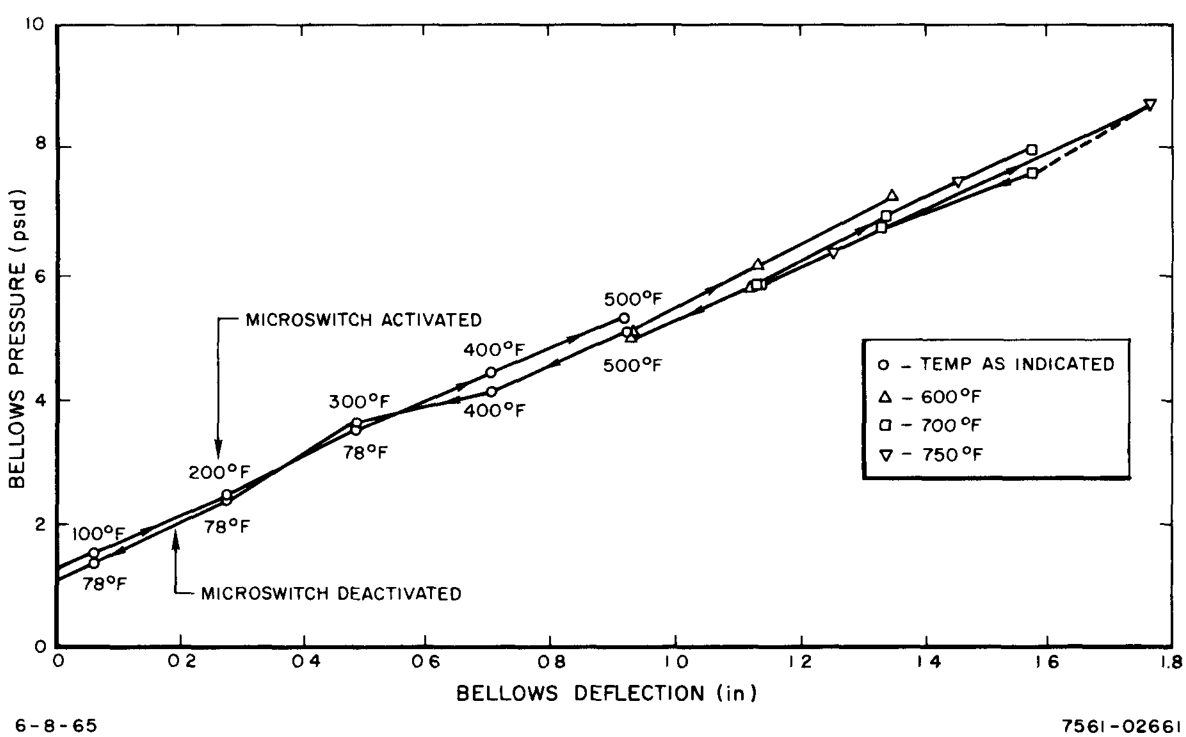

Figure 30. Thermal Cycle Pressure-Deflection Characteristics of ECU S/N-023 During Acceptance Testing

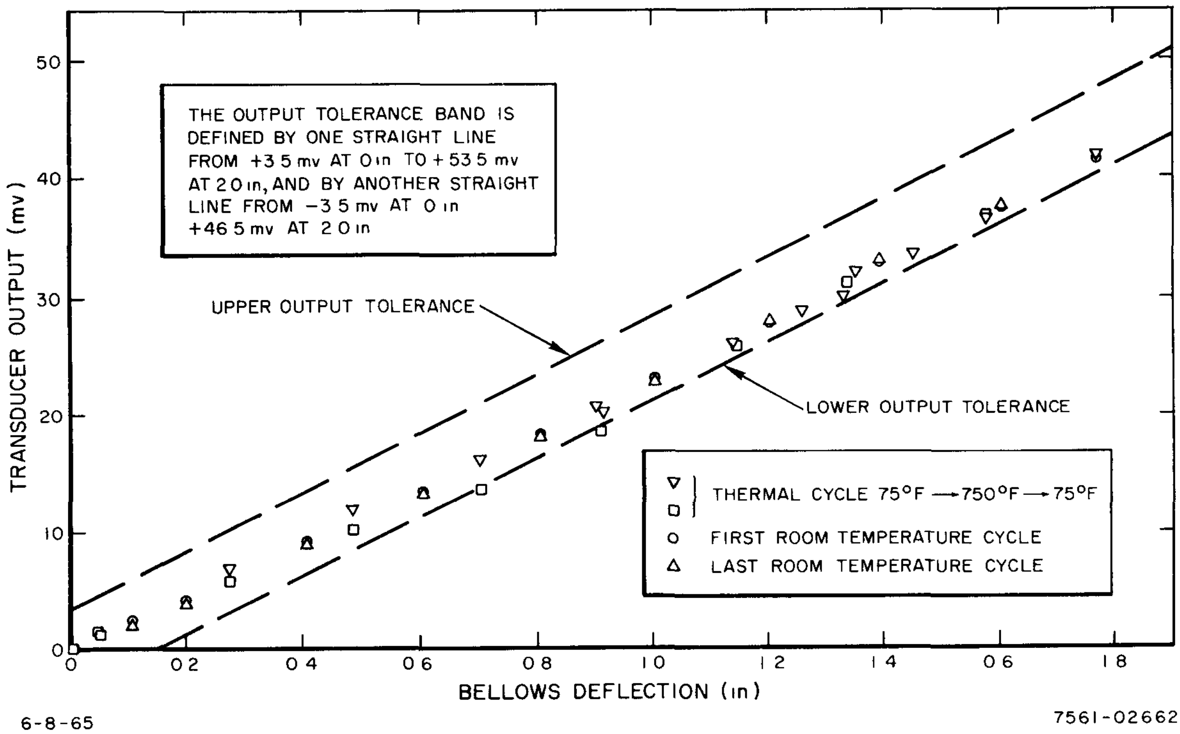

Figure 31. Position Transducer Output vs Bellows Deflection on ECU S/N-023 During Acceptance Testing

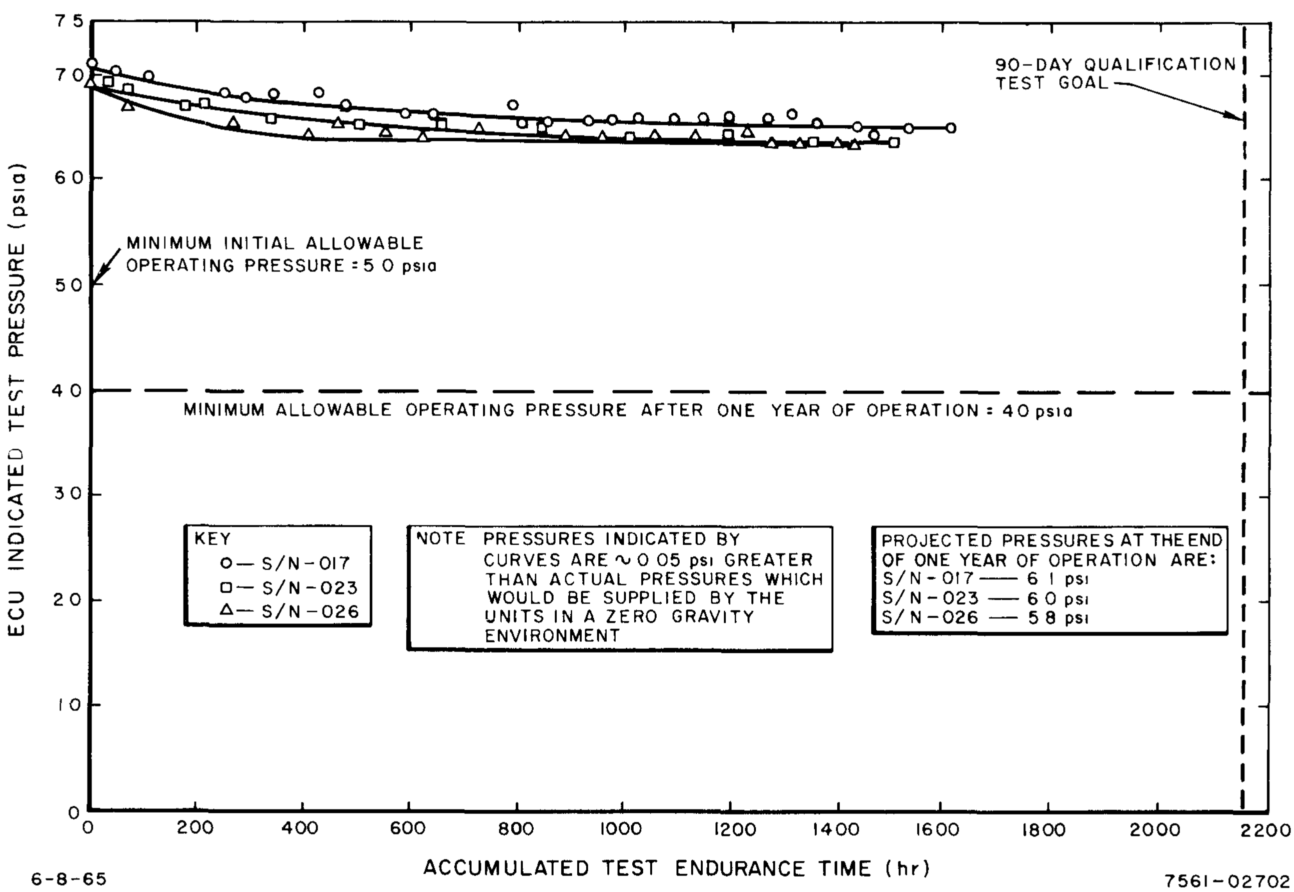

Figure 32. SNAP 10A Expansion Compensator Qualification Test Unit, Pressure vs Time Characteristics to Date – February 9, 1965

(1 46 in or ~60 in^3 displacement), are steady and within specified limits. Figure 33 is a plot of the accumulated data

The pin release, squib-firing tests conducted on ECU's S/N-017, -023, and -026 were completed successfully with no apparent resultant adverse effect upon subsequent ECU function.

The ground test adapters were found to operate satisfactorily although there was a great deal of hysteresis and/or friction prevalent, resulting in "jerky" deflection versus pressurization characteristics and lower pressures at given deflections when depressurizing, as indicated by Figure 30.

Where characteristic operational curves for ECU's S/N-017 and -026 are not presented in this report, it is because their operation is closely approximated by that indicated by the curves presented for S/N-023. ECU S/N-017 has a slightly different pressure response (see Figure 32) due primarily to the 10,000 room temperature cycle test imposed upon it alone, as discussed in the following paragraphs on test deviations from established criteria

Deviations from established procedures were imposed upon these qualification test ECU's as follows

1) ECU S/N-017 was the first unit received from the vendor including the design change from 13 to 18 convolutions on the secondary bellows. As such it was subjected to 10,000 deflection cycles at room ambient

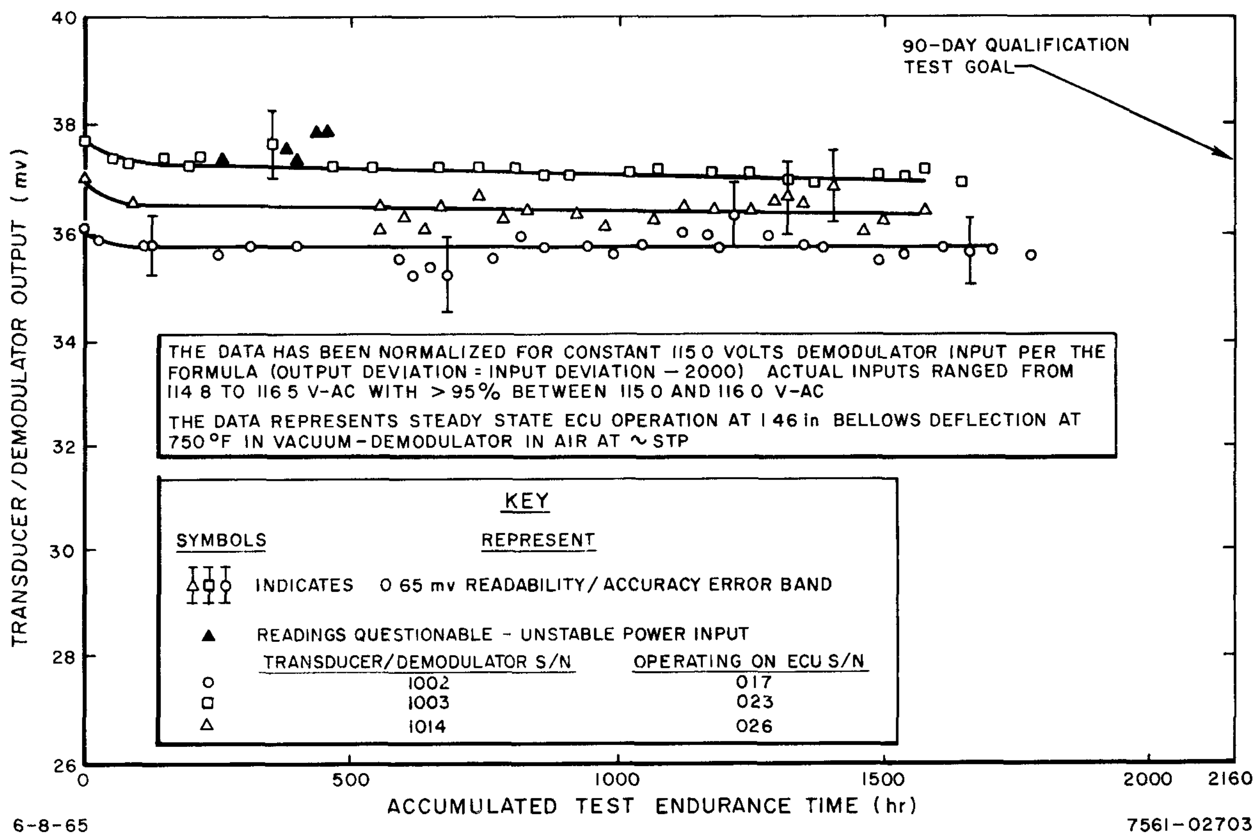

Figure 33 SNAP 10A Expansion Compensator Qualification Test Unit Displacement Indicating Transducer Output vs Time Characteristics to Date — February 16 1965

temperature (~75°F), between zero deflection and 1 46 in deflection, utilizing argon gas pressurization at the rate of ~4 cpm The test was conducted subsequent to acceptance testing and prior to the established qualification sequence The test was conducted to determine if the secondary bellows would maintain its containment integrity now that the excessive "oil-canning" buckling phenomenon observed on the 13 secondary convolution design had been eliminated through the use of 5 additional convolutions. The ECU survived this test with no detectable damage.

2) The switch lever on unit S/N-017 was subject to a malfunction due to inadequacy of the existing design to survive the additional proof test recently imposed during ECU acceptance, i.e., the 200 deflection cycles at 750°F. The lever was replaced and the problem area corrected by design and test procedural changes (the switch is now installed after the 200-cycle test).

The switch in this unit (S/N-017) is set to actuate at ~0 95-in. primary bellows deflection, rather than at the ~0 20-in. deflection established for the flight design As such it correlates with the setting on the nonnuclear ground test system, FSM-4. ECU's S/N-023 and -026 have their switches set to actuate at the flight design point (~0.20 in)

3) Subsequent to vibration, shock, and acceleration test phases of the qualification test sequence, it was noticed that the ECU S/N-023 had a weld fracture in the secondary containment at the base of the secondary inlet tube. The fracture resulted from an inadequate weld which had inadvertently passed inspection. The weld was re-fused after which the vibration and shock test phases were repeated to ensure the integrity of the new weld, (the vibration test imposes the most severe test upon weld integrity, the effects of acceleration are negligible). The test was completed with no indicated damage and the test sequence was resumed

4) Units S/N-017 and -023 underwent the vibration, shock, and acceleration test phases of the qualification test sequence with their secondary inlet tubes open to the ambient air. ECU S/N-023 had its line pinched and sealed subsequent to the helium leak check following these tests S/N-017 remains open to a helium atmosphere at a low vacuum pressure (~100 torr) during long term endurance testing This was done in order to provide highly positive helium leak checks of the ECU secondary containment which are not possible subsequent to pinch-off and welding of the secondary inlet

These deviations and other minor nonconformances encountered have all been deemed to be of no essential import with regard to the overall qualification of the individual ECU's.

Qualification of this design is not entirely predicated on the successful operation of these component qualification tests The operational test experience gained from single bellows (single containment) units of essentially the same bellows design as the present secondary containment design, and the test experience accumulated to date on all developmental test secondary containment ECU's lends confidence in the utility of the latest design. More than 2-1/2 yr of operating time have been accumulated by 14 developmental and prequalification test units while at design or over-design conditions with vacuum external environment and NaK-78 internal environment (reference Tables 4 and 5)

In addition, two SNAP 10A ground test systems are in operation at simulated flight system endurance conditions. These are the FSM-4 nonnuclear and the FS-3 nuclear powered systems Each system has two ECU's of the present design, the performance of which will influence the design qualification. ECU operation in each system has been satisfactory thus far.

VII. ACCEPTANCE TEST PROGRAM

A. ACCEPTANCE TEST OBJECTIVES

The objectives of the acceptance test program are to (1) verify that each ECU will fulfill the system operating requirements, and (2) eliminate any ECU that may have material or operational defects.

B. ACCEPTANCE TEST PROCEDURE

Outlined in this section is the acceptance test sequence which is conducted on each ECU in order to implement the objectives stated above. All these tests are conducted with either inert gas or ambient air in the primary and secondary containments.

Test 1. Examination of Product — The ECU assembly is inspected to verify conformance to applicable fabrication specifications with regard to dimensions, workmanship, materials, and finishes, fasteners, and visible defects.

Test 2. Verification of Documentation — All fabrication and test records of all assemblies and subassemblies are examined for conformance to requirements.

Test 3. Helium Leak Detection — A leak test is conducted with the aid of a standard laboratory type mass spectrometer helium leak detector to verify that the bellows assembly primary and secondary containments are free from leaks.

Test 4. Position Transducer Calibration — The position transducer is installed and calibrated over an inert gas pressurized bellows deflection range of 0 to 1.77 in. (72-in.^{3} displacement).

Test 5. Thermal Cycle Proof Test — Two hundred pressure-deflection fatigue cycles from 0 to 1.46 in. (60-in.^{3} displacement) bellows deflection at constant 750°F are conducted in vacuum.

Test 6. Helium Leak Detection — The leak test is repeated.

Test 7. Pressure Proof Test — The primary bellows and then the primary and secondary containment are inert gas pressurized to 33 psig in the pin-locked position for 5 min each, at room temperature.

Test 8. Position Switch Calibration — The position switch is installed to actuate at a given bellows deflection level (0.2 in. for flight systems). Actuation is checked on a room temperature calibration cycle over an inert gas pressurized bellows deflection range of 0 to 1.77 in.

Test 9. Vibration Test — A sinusoidal vibration test is conducted along each of the three major NPU axes of the fixtured ECU at a constant octave sweep, proceeding from 5 to 2000 cps in 5 min per the following input load schedule:

Frequency	Input Load
5 to 20 cps	0.17 in. double amplitude
20 to 400 cps	3.5 g's
400 to 2000 cps	5.0 g's

Test 10. Helium Leak Detection — The leak test is repeated.

Test 11. Performance Check — A room temperature inert gas bellows pressurization cycle is conducted over a bellows deflection range of 0 to 1.77 in.

Test 12. Thermal Performance Cycle — The ECU primary bellows is pressurized and concurrently heated in vacuum over a deflection range of 0 in. at room temperature to 1.77 in. at 750°F.

Test 13. Performance Check — Test 11 is repeated.

Test 14. Ground Test Adapter Calibration — The GTA is installed on the ECU and set to provide a specified additional pressure to the ECU (3.8 psi over the ECU pressure at 0.1 in deflection). The ECU/GTA combination is then calibrated at constant room temperature over an inert gas pressurized primary bellows deflection range of 0 to 1.46 in.

Test 15. Performance Check — Test 11 is repeated without the GTA.

Test 16. Helium Leak Detection — The leak test is repeated.

Test 17 Weight Check — The ECU is weighed.

Test 18. Secondary Containment Sealing — The secondary containment inlet line is "pinched-off" and weld sealed with an internal environment of helium under vacuum (10^{-3} torr for flight systems).

Test 19. Examination of Product — Test 1 is repeated.

C. ACCEPTANCE TEST STATUS AND RESULTS

All of the secondary containment ECU's have been subjected to a full or partial acceptance test. A summary of the acceptance test results is shown in Table 12.

The development ECU's, S/N-011 and -016, were partially acceptance tested prior to undergoing other tests. It was during acceptance helium leak detection testing that the leaks in the secondary containment can weld preparations were detected.

The qualification ECU's S/N-017, -020, -023, and -026 were fully acceptance tested with modified secondary sealing procedures previously stated in Test 18. The data obtained during the test· ECU and ECU/GTA pressure output versus bellows deflection at constant room ambient temperature, ECU output pressure versus bellows deflection with concurrent thermal cycle (room temperature to 750°F to room temperature), and transducer millivolt output versus bellows deflection have been plotted and are shown in Figures 29, 30, and 31, respectively. These data are representative of the entire ECU acceptance test data for units S/N-017 through S/N-035 with the exception of minor variations in the pressure and transducer millivolt outputs.

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ECU Serial Number	ACCEPTANCE TEST RESULTS																									SUBSEQUENT TEST RESULTS
	Examination of ECU and Documentation	Helium Leak Detection	Position Transducer Room Temperature Calibration	ECU Pressures at 0 and 60 in.^{3} Primary Displacement (psi)	200 Cycles at 750°F, 0 to 60 in.^{3}	Helium Leak Detection	33 psi Proof Pressure Tests at Room Temperature	Position Switch Room Temperature Calibration	ECU Pressures at 0 and 60 in.^{3} (psi)	Vibration Tests	Helium Leak Detection	Performance Check – 0 to 72 in.^{3} Room Temperature Cycle	ECU Pressures at 0 and 60 in.^{3} (psi)	Thermal Performance Cycle (0 – 72 in.^{3} (Room Temperature – 750°F))	ECU Pressures at 0 and 60 in.^{3} 750°F (psi)	Performance Check – 0 to 72 in.^{3} Room Temperature Cycle	ECU Pressures at 0 and 60 in.^{3} (psi)	GTA Calibration Cycle	ECU/GTA Pressures at 0 and 60 in.^{3} (Room Temperature) (psi)	Performance Check – 0 to 72 in.^{3} Room Temperature Cycle	ECU Pressures at 0 and 60 in.^{3}	Helium Leak Detection	Secondary Containment Pinch and Weld Sealing	ECU Weight (lb)	ECU Examination	
011	●	SL	N	N	●*	SL	●	N	1.80 10.4	●	SL	●	1.75 10.2	●	– 8.75	●	1.40 9.70	N	N	N	N	SL	N	N	●	Completed (1) qualification test level shock and vibration testing, (2) a 200-psig primary bellows pressure proof test at 3-in. deflection, followed by a proof test at 3-in. deflection with 200 psig gas pressure in primary and secondary containments with no apparent detrimental effects. Unit subsequently destructively, metallurgically examined.
012	●	SL	N	N	●*	SL	●	N	1.85 10.2	●	SL	●	1.47 9.65	●	1.80 8.65	●	1.40 –	N	N	N	N	N	N	N	●	Completed 10 argon gas, primary bellows pressurization cycles between 0 in. deflection at room temperature and 1.46 in. deflection at 750°F holding at 1.46 in., 750°F for 1/2 hr on each cycle. Subsequently experienced 3200 hr of endurance to date at 750°F in vacuum with NaK in primary at 1.46 in. deflection. Remains on test.
013	●	SL	●	N	●	N	●	●	1.50 10.3	●	●	●	1.50 10.3	●	1.27 7.78	●	1.10 9.50	N	N	N	N	N	N	N	●	Completed 2000 hr endurance at 750°F and 1.83 in. deflection in vacuum with NaK in primary bellows, including 1-1/2 cycles between 0 in. at room temperature and 1.83 in. at 750°F. Remains on test.
014	●	SL	●	1.42 6.95	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	●	Completed 15,200 cycles during a resonant dwell (92 cps for bellows convolutions) sinusoidal vibration test before a rupture developed in the secondary bellows. Less than 1/10 as many cycles is the performance requirement. Subsequently proof pressure tested with primary bellows under a 150 psig load at >3 in. deflection with minor primary bellows leak.
015	●	●	●	N	●	●	●	●	1.49 9.55	●	●	●	1.49 9.56	●	1.50 8.14	●	1.25 9.26	N	N	N	N	●	N	N	●	Completed 2000 hr endurance at 775°F and 1.46 in. deflection in vacuum with NaK in primary, including 2-1/2 cycles between 0 in. at room temperature and 1.46 in. at 750°F. Remains on test.
016	●	●	●	1.44 9.50	●	●	●	●	1.44 9.50	●	●	●	1.44 9.50	●	1.40 7.88	●	1.22 8.95	N	N	N	N	●	N	N	●	Completed 30,000 fatigue cycles at room temperature between 0 in. and 1.46 in. deflection with no resultant rupture in primary. Secondary bellows ruptured in many welds after <7000 cycles.
017	●	●	●	1.43 8.34	●	●	●	●	1.43 8.34	●	●	●	1.43 8.38	●	1.35 7.40	●	1.36 8.34	●	5.10 13.7	●	1.37 8.32	●	N	14.3	●	Completed 10,000 fatigue cycles at room temperature between 0 in. and 1.46 in. deflection. Subsequently completed qualification testing through 1600 hr at 750°F with 60 in.^{3} primary bellow NaK displacement.
018	●	●	●	1.23 8.06	●	●	●	●	1.16 8.03	●	●	●	1.15 8.05	●	1 10 7.07	●	1.08 7.92	●	4.80 13.5	●	1.09 7.95	●	●	N	●	Installed on SNAP 10A, non-nuclear, ground test system FSM-4
019	●	●	●	1.19 8.04	●	●	●	●	1.15 8.05	●	●	●	1.13 8.03	●	1.03 6.76	●	1.03 7.90	●	4.70 13.3	●	1.03 7.96	●	●	N	●	Installed on SNAP 10A, non-nuclear, ground test system FSM-4.
020	●	●	●	0.86 7.83	●	●	●	●	0.85 7.81	●	●	●	0.86 7.83	●	0.78 6.82	●	0.78 7.75	●	4.45 13.2	●	0.78 7.75	●	●	14.3	●	Scheduled for qualification testing including NaK endurance testing at 750°F and 120 in.^{3} primary bellows displacement.
021	●	●	●	1.01 8.00	●	●	●	●	0.97 8.05	●	●	●	0.98 8.07	●	0.95 7.12	●	0.92 7.97	●	4.60 13.6	●	0.92 7.99	●	●	14.2	●	Scheduled for developmental testing at over-design temperatures.
022	●	●	●	1.19 8.29	●	●	●	●	1.16 8.21	●	●	●	1.16 8.23	●	1.13 7.27	●	1.13 8.17	●	4.75 13.5	●	1.12 8.18	●	●	14.6	●	Scheduled for developmental testing including endurance testing at 750°F and 35 in.^{3} primary bellows displacement with NaK in secondary.
023	●	●	●	1.20 8.20	●	●	●	●	1.27 8.24	●	●	●	1.26 8.23	●	1.24 7.35	●	1.24 8.21	●	5.00 13.6	●	1.24 8.21	●	●†	14.6	●	Has completed qualification testing through 1500 hr at 750°F with 60 in.^{3} primary bellows NaK displacement.
024	●	L	●	1.21 8.19	●	L	●	●	1.21 8.27	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	●	Destructively metallurgically analyzed.
025	●	●	●	1.30 8.27	●	●	●	●	1.28 8.32	●	●	●	1.29 8.26	●	1.29 7.26	●	1.20 8.20	●	4.85 13.5	●	1.20 8.30	●	●	14.7	●	Installed on SNAP 10A, nuclear, ground test system FS-3.
026	●	●	●	1.26 8.15	●	●	●	●	1.23 8.13	●	●	●	1.23 8.13	●	1.16 7.26	●	1.16 8.04	●	4.85 13.5	●	1.17 8.04	●	●	14.2	●	Has completed qualification testing through 1400 hr at 750°F with 60 in.^{3} primary bellows NaK displacement.
027	●	●	●	1.23 8.01	●	●	●	●	1.22 8.04	●	●	●	1.22 8.05	●	1.17 7.02	●	1.15 7.95	●	4.75 13.2	●	1.15 7.98	●	●	14.4	●	Destructively metallurgically analyzed.
028	●	●	●	1.17 8.25	●	●	●	●	1.15 8.19	●	●	●	1.17 8.21	●	1.10 7.12	●	1.10 8.12	●	4.85 13.6	●	1.10 8.13	●	●	14.3	●	Installed on SNAP 10A, nuclear, ground test system FS-3.
029	●	●	●	1.23 8.10	●	●	●	●	1.21 8.08	●	●	●	1.25 8.08	●	1.22 7.16	●	1.16 8.00	●	4.75 13.3	●	1.17 8.01	●	●	14.6	●	Installed on SNAP 10A flight system FS-4.
030	●	●	●	1.39 8.40	●	●	●	●	1.40 8.39	●	●	●	1.40 8.38	●	1.40 7.42	●	1.33 8.30	●	4.90 13.5	●	1.33 8.30	●	●	14.8	●	Installed on SNAP 10A flight system FS-4.
031	●	●	●	1.11 8.08	●	●	●	●	1.09 8.09	●	●	●	1.09 8.04	●	1.03 7.01	●	1.03 7.96	●	4.80 13.6	●	1.05 7.97	●	●	14.5	●	Installed on SNAP 10A flight system FS-5.
032	●	●	●	1.07 8.02	●	●	●	●	1.05 8.19	●	●	●	1.07 8.12	●	0.97 7.14	●	0.97 7.99	●	4.70 13.3	●	0.98 8.03	●	●	14.9	●	Installed on SNAP 10A flight system FS-5.
033	●	●	●	1.19 8.15	●	●	●	●	1 16 8.18	●	●	●	1.17 8.20	●	1.10 7.14	●	1.10 8.09	N	N	N	N	●	●	14.4	●	Held in storage as spare system component.
034	●	●	●	1.43 8.24	●	●	●	●	1.39 8.21	●	●	●	1.39 8.20	●	1.30 7.19	●	1.30 8.12	N	N	N	N	●	●	14.7	●	Held in storage as spare system component.
035	●	●	●	1.22 8.10	●	●	●	●	1.02 7.87	●	●	●	1.02 7.87	●	1.00 6.91	●	0.98 7.83	N	N	N	N	●	N	N	●	Held in storage as spare system component.

NOTES AND SYMBOLS

● Test completed with satisfactory results

N Test not performed

L Leak indicated between primary containment and external environment of ECU

SL Leak indicated between secondary containment and external environment of ECU

† The secondary containment inlet line on S/N-023 was pinch and-weld-sealed after qualification test vibration, shock, and acceleration testing, not at termination of acceptance testing

* 200 cycles performed at room temperature, not 750°F, on S/N-011 and 012

ECU's S/N 011 and 012 were subjected to the 200 cycles at room temperature between the 33 psig proof pressure test and the vibration tests, not immediately after the position transducer room temperature calibration ECU's S/N-013 -015, -016, and 017 were subjected to the 200 cycles at 750°F just prior to the Thermal Performance Cycle The position switch actuation levers on ECU's S/N-013, -015 and -017 bent and malfunctioned due to the high temperature cycling The malfunctioned levers were replaced On subsequent units (S/N-018 on) the position switch was installed and calibrated after the 200 cycles at 750°F had been performed This corrected the problem

All units have AM 350 bellows discs

Developmental units S/N-011 through -016 have 13 primary bellows convolutions and 13 secondary bellows convolutions They all exhibited undesirable oil canning All subsequent units (S/N-017 on) are of the flight design and have 13 primary bellows convolutions and 18 secondary bellows convolutions and do not exhibit the undesirable oil canning of the previous design

Units S/N 011 through 014 have a type 347 stainless steel machined outer can on the secondary containment They exhibited leakage through stringers in the outer can material across machined surfaces Units S/N-015 through -035 have a type 347 stainless steel formed outer can and exhibited no leakage

Units S/N-031 through 035 have primary bellows top plates (cup assemblies) fabricated from vacuum-melted stainless steel, previous units were of nonvacuum melted material

TABLE 12
SECONDARY CONTAINMENT ECU TEST STATUS

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VIII. SUMMARY AND CONCLUSIONS

The secondary containment expansion compensator designed to accommodate the thermal expansion of NaK and to provide void-free pressurization of the S10A Nuclear Power System has been essentially qualified for flight system utilization. Three compensator units of similar manufacture to units produced for S10A flight systems have met all qualification test objectives. Three additional units of identical manufacture to the flight system design are currently undergoing qualification testing and are within 10 to 20 days of completing the 90-day endurance test phase in NaK. All component design objectives are being satisfied.

Production quality of AM-350 welded bellows has been greatly improved through imposition of strict process control and inspection procedures. The requisite reliability of bellows assemblies for space nuclear power systems, where long life is of great importance, however, has yet to be adequately demonstrated. Secondary containment design which prevents loss of NaK from the S10A system in the event of primary bellows failure and simultaneously provides sufficient system pressurization to permit continued S10A operation affords high component reliability required of space system components.

Elastic fixed beam theory affords a conservative approach to bellows analysis, assuming that the fabrication quality is adequate. Optimization of bellows assembly designs requires more accurate methods of bellows stress analysis, especially for the actual bellows disc nested ripple profile.

Radiographic and visual inspection of convolution weld beads are useful nondestructive tests to determine the quality of welded bellows assemblies. Statistical analysis of weld bead dimensions has shown that weld bead penetration can be ascertained with confidence upon the basis of measurement of the weld bead width. The strength of the convolution weld joint has been shown to be dependent upon penetration and a minimum penetration depth to ensure full joint strength has been established.

CONTINUING WORK

Development and qualification tests of S10A expansion compensator assemblies is continuing. The qualification endurance tests of secondary containment units will be continued for one year's duration. Evaluation of effects of chemistry and heat treatment of AM-350 alloy upon corrosion resistance and mechanical properties of this sheet is also continuing. An analytical method for determining stresses in bellows diaphragms which includes the plastic strain region is being developed at AI in a related SNAP program. This method will be applied to the S10A ECU design and the results will be checked against the test data to verify applicability of the analysis.

APPENDIX A
ANALYSIS OF STRESSES IN BELLOWS ASSEMBLY

Basis — Elastic beam theory

Assumption:

1) Deflection Loading — Diaphragm is simple beam acting as guided cantilever.

2) Pressure Loading — Diaphragm is simple beam fixed at both ends.

a. Deflection Stress

$$S = \frac{3Eyt}{L^2}$$

b. Pressure Stress

$$S = \frac{pL^2}{2t^2}$$

c. Total Stress for N Number of Diaphragms

$$S = \frac{3Eyt}{NL^2} + \frac{pL^2}{2t^2}$$

where

S = total stress, psi

E = modulus of elasticity, psi

y = total bellows deflection, in.

t = diaphragm thickness, in.

L = diaphragm width, in.

p = pressure, psi

APPENDIX B
ECU OPERATIONAL STRESS LEVELS – CALCULATED

	Bellows Deflection (in)	Bellows Volume (in ^{3})	Pressure (psi)	Temperature (°F)	Pressure† Stress (psi)	Deflection Stress (psi)	Total§ Stress (psi)
Room Temperature	0	0	6 39	80	20,400	34,200	54,600
	1 0	40.7	10 27	80	32,800	85,200	118,100
	1 5	41 05	12 22	80	39,100	110,700	149,800
	1 75	71 2	13 19	80	42,200	123,500	165,700
	1 90	77 3	13 77	80	44,100	131,200	175,200
	2 40	97.68	15 69	80	50,200	156 700	206,900††
	3 0	122 1	18 04	80	57,700	187,300	245 000
Elevated Temperature	0	0	5 59	750	17,900	28,700	46 600
	1 0	40 7	8 98	750	28,700	71,600	100,300
	1 5	61 05	10 69	750	34,200	93,000	127,200
	1 75	71 2	11 54	750	36,900	103,800	140,700
	2 3	93 6	13 38	750	42,800	127,300	170,200
	2 8	114 0	15 12	750	48,400	148,700	197,000††
	3 0	122 1	15 79	750	50,500	157,300	207,900

Beyond prestress condition of 0 67 in initial deflection
†Ground Test Adapter installed
§Stress values are necessarily approximate because of simplifying assumptions of analysis and non-applicability of analysis beyond yield point of material
Exceeds yield strength of material
††Exceeds ultimate strength of material

APPENDIX C
MECHANICAL PROPERTY DATA FOR AM-350

Alloy Metallurgical Condition	AM-350			
	Annealed		H. T. SCT-850	
	Wrought	Welded	Wrought	Welded
Y.S. 0.2% Ksi at 80°F	52 Minimum 55 Typical 72 Maximum	83 Average	160 Minimum 173 Typical 190 Maximum	165-172
Y.S. 0.2% Ksi at 700°F			102 Minimum 128 Typical 141 Maximum	AM-355 Filler 120 Average
Y.S. 0.2% Ksi at 800°F			99 Minimum 125 Typical 135 Maximum	AM-355 Filler 113 Average
Ultimate Ksi at 80°F	140 Minimum 145 Typical 171 Maximum	145 Average	185 Minimum 206 Typical 218 Maximum	191-203
Ultimate Ksi at 700°F			162 Minimum 190 Typical* 174 Maximum	AM-355 Filler 181 Average
Ultimate Ksi at 800°F			159 Minimum 186 Typical* 170 Maximum	AM-355 Filler 172 Average
Elongation at 80°F	30% Minimum 40% Typical 55% Maximum	6.5% Average	4.0% Minimum 13.5% Typical 20% Maximum	4-6%
Elongation at 700°F			8.0% Typical	AM-355 Filler 4.5% Average
Elongation at 800°F			9.5% Typical	AM-355 Filler 5.0% Average
Mod. of E at 80°F			29 30 x 10^6	
Mod. of E at 700°F			22 24 x 10^6	
Mod. of E at 800°F			22 24 x 10^6	

NOTE: The data were obtained from 25 to 125-mil sheet stock unless otherwise noted.

*Maximum and minimum values from DMIC Report 156, 1961 — Typical value from Allegheny Steel Corp., AM-350: AM-355 Typical Mechanical Data Report, 1960.