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SPACE NUCLEAR SYSTEM
VOLUME ACCUMULATOR DEVELOPMENT
SUMMARY REPORT

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SUMMARY REPORT

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FOREWORD

The work described here was done at the Atomics International Division of Rockwell International Corporation, under the direction of the Space Nuclear Systems Division, a joint AEC-NASA office. Project management was provided by NASA-Lewis Research Center and the AEC-SNAP Project Office.

DISTRIBUTION

This report has been distributed according to the category "Systems for Nuclear Auxiliary Power (SNAP) Reactor – SNAP Program," as given in the Standard Distribution for Classified Scientific and Technical Reports, M-3679, and according to the NASA Supplementary Report Distribution List at the end of this report.

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ABSTRACT

The engineering, design, and fabrication status of the volume accumulator units (VAU's) to be employed in the NaK primary and secondary coolant loops of the 5-kwe Reactor Thermoelectric System are described. Three identical VAU's are required — two for the primary coolant loop, and one for the secondary coolant loop. The VAU's utilize nested-formed bellows as the flexing member, are hermetically sealed, provide double containment and utilize a combination of gas-pressure force and bellows-spring force to obtain the desired pressure regulation of the coolant loops. All parts of the VAU, except the NaK inlet tube, are to be fabricated from Inconel 718.

I. INTRODUCTION

A series of compact nuclear reactors and electrical power systems were designed, developed, and tested for the Systems for Nuclear Auxiliary Power (SNAP) program. The zirconium hydride (ZrH) reactors for these systems were fueled by hydrided zirconium-uranium elements. Windows in the external beryllium neutron reflector were adjusted by rotating drums or sliding segments to regulate the neutron leakage from the core, and thus the power output of the reactor. A direct radiating thermoelectric module powered Power Conversion System (PCS) produced over 500 w of electrical power on the flight-tested SNAP 10A System. Mercury Rankine cycle turbogenerator PCS's of 3- and 30-kwe power range were demonstrated for the SNAP 2 and SNAP 8 Systems respectively. The latest 5-kwe Reactor Thermoelectric (TE) System, shown in Figure 1, was based on the use of compact tubular thermoelectric PCS. The NaK, used to transfer the heat from the reactor to the PCS and from the PCS to the space radiator, was circulated by dc conduction electromagnetic pumps on the thermoelectric systems, and by mechanical centrifugal pumps on the Mercury-Rankine systems.

This report summarizes the engineering, design, and fabrication status of the Volume Accumulator Units (VAU's) for the NaK primary and secondary coolant systems of the 5-kwe Reactor Thermoelectric System, hereafter referred to as the 5-kwe System.

A. FUNCTION OF VOLUME ACCUMULATOR UNITS

Three identical volume accumulator units (VAU's) are used in the 5-kwe System; two in the primary coolant system, and one in the secondary coolant system. The VAU locations in the 5-kwe System are shown in Figure 1. The VAU's are branched off, and communicate with the respective coolant loops through 1/2-in. outside diameter stainless steel tubing.

The VAU's are utilized to:

1) Accommodate NaK coolant thermal volumetric expansion and contraction during the 5-kwe System startup, operation, shutdown, and storage

2) Provide void-free NaK coolant systems

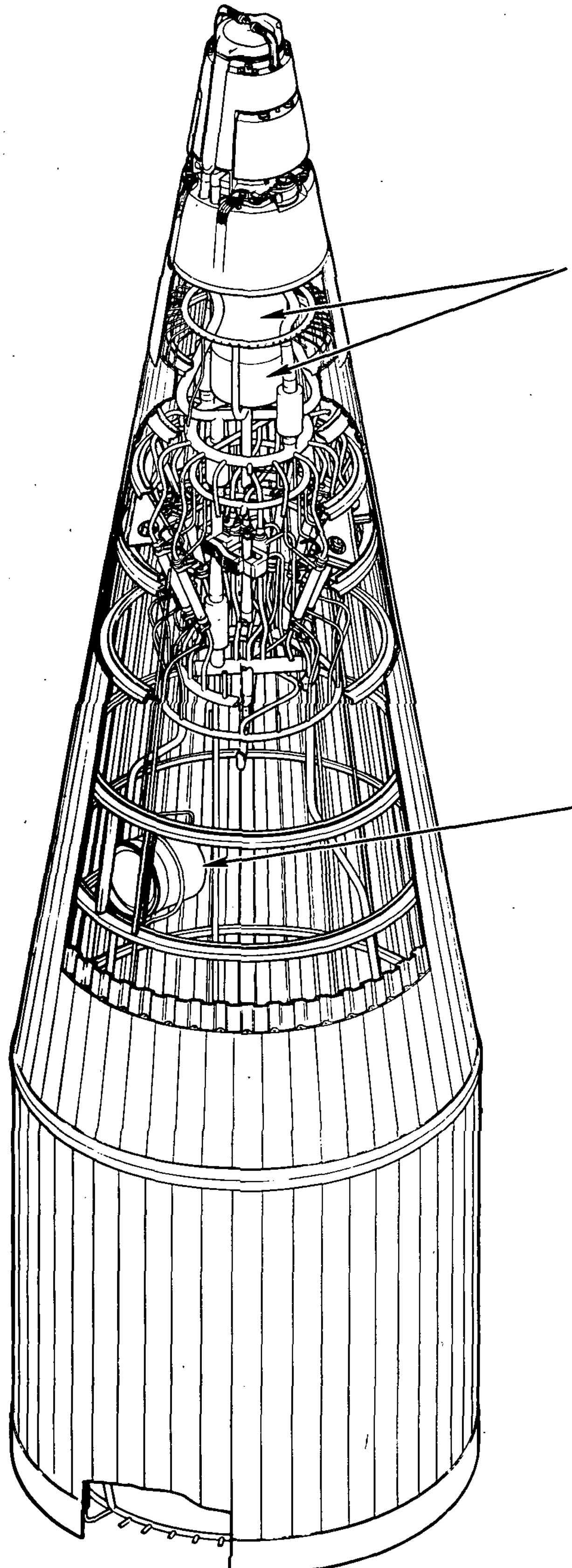

Figure 1. 5-kwe Reactor Thermo-electric System

3) Provide pressure regulation of the NaK coolant systems for prevention of cavitation and excessive pressure.

B. VOLUME ACCUMULATOR UNIT GENERAL REQUIREMENTS

The general design requirements for the VAU's were:

1) The combined weight of the VAU's was minimized, within the objectives of meeting bellows stress limitations, volumetric capacity, pressure regulations requirements, and reliability goals.

2) To maximize VAU reliability, the design utilized double containment of NaK and pressurizing gas within the VAU.

3) The material for the VAU detail parts had to be compatible with NaK, and be weldable to the Tube 316 stainless steel piping of the 5-kwe System.

4) The VAU was designed to operate with no maintenance for 5 years at the operating conditions of the 5-kwe System, after being subjected to acceptance test and system launch conditions.

5) A common design was used for all VAU's in the 5-kwe System, where possible.

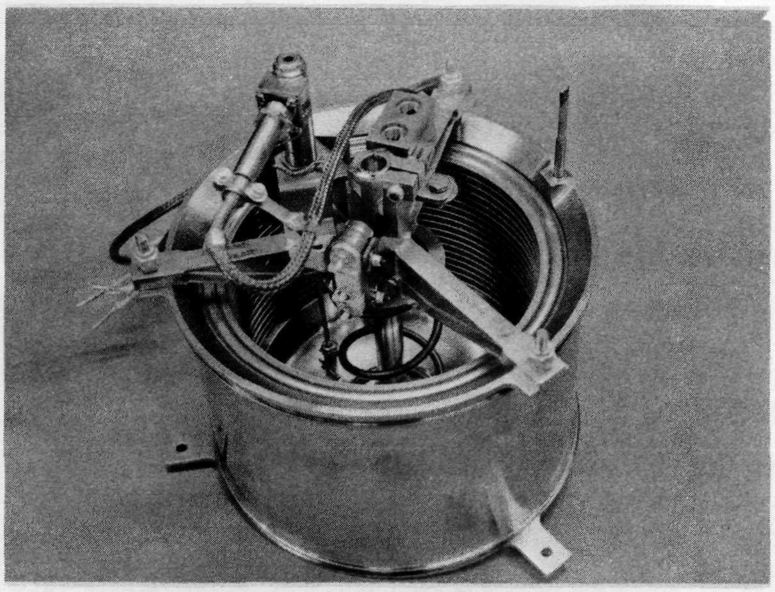

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Figure 2. Fully Instrumented SNAP 10A Volume Accumulator Unit

TABLE 1

MAJOR PARTS OF SNAP 10A VOLUME ACCUMULATOR UNIT

Primary Bellows Assembly
Secondary Bellows Assembly
Containment Housing
Top Support
Helical Compression Spring
Position Transducer and Demodulator
Position Switch
Actuator Assembly

II. PRIOR SNAP VOLUME ACCUMULATOR EXPERIENCE

A. DESIGN DESCRIPTION

The SNAP 10A Space Nuclear Power Unit, which was successfully flight tested, utilized two identical volume accumulator units (called "expansion compensator units" in the SNAP 10A Program) to accommodate the NaK coolant thermal expansion and to pressurize the coolant system with a void-free device.[1]

Figure 2 shows a fully instrumented SNAP 10A VAU, and the major parts are listed in Table 1. Figure 3 shows a schematic of the SNAP 10A VAU bellows assembly. As seen in Figure 3, two welded bellows subassemblies, enclosed in a cylindrical containment housing, are utilized. The primary bellows contains the NaK during normal operation, and the secondary bellows – containment housing combination prevents loss of the NaK external to the system, in the event that the primary bellows fails. Both the primary and secondary bellows are made up of nesting, ripple diaphragms, welded at the inner and outer perimeters. The diaphragm material is AM-350 precipitation-hardened stainless steel. The desired pressure regulation of the coolant system is obtained by the combined spring characteristics of the bellows assembly and a helical compression spring (see Figure 2) working in parallel with the bellows. The helical compression spring is restrained at the upper end by the top support.

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. This is accomplished by a pin-puller actuator assembly, mounted on the top support. In the event of lock release failure of one unit, the bellows assembly of the second unit can absorb the full net expansion of the NaK without exceeding the maximum allowable pressure.

The instrumentation provided consists of: (1) a position transducer and demodulator, which provides a continuous indication of the bellows position, and therefore the system pressure, and (2) a position switch, the purpose of which is to sense contraction of the primary bellows from the normal operating deflection of 1.42 in. to a nominal 0.20 in. deflection, which would be indicative of a leak in the NaK system, and would activate an in-flight recorder to monitor specific diagnostic instruments.

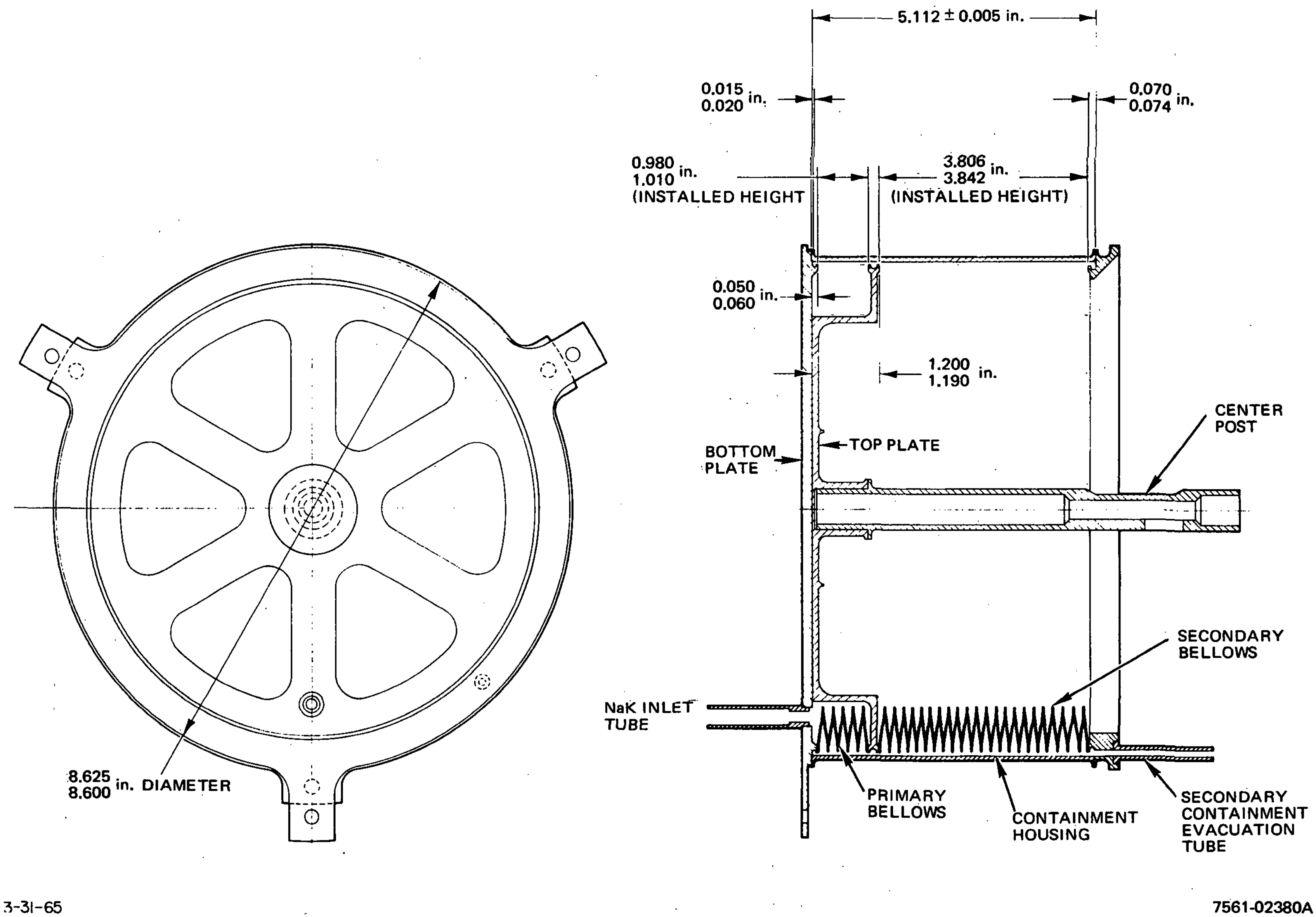


Figure 3. SNAP 10A Volume Accumulator Unit Bellows Assembly Schematic

The major performance requirements of the SNAP 10A VAU are shown in Table 2.

TABLE 2

SNAP 10A VOLUME ACCUMULATOR UNIT PERFORMANCE REQUIREMENTS

Volume Change per VAU (in.^{3})	
Normal operation	60
Abnormal operation (max.)	120
Design Temperatures (°F)	
Launch	50 to 150
Operating	700 to 750
Design Pressures (psia)	
Launch and startup	
Minimum	0.90
Maximum	35
Operating	
Initial (min.)	5
60 in.^{3} condition (max.)	11
120 in.^{3} condition (max.)	25
After 90 days (min.)	4.5
After 1 year (min.)	4
Operating Life	
At operation design point (year)	1
Thermal cycles	10

B. TESTS

Component development and qualification tests were successfully completed on the SNAP 10A VAU's.[(1)] The following types of development tests were performed upon bellows assemblies and/or complete VAU's:

TABLE 3

VOLUME ACCUMULATOR 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 VAU 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 five deflection cycles at room temperature with the ground test adapter installed	Prelaunch system ground tests
17 Conduct five 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	
20 Conduct five thermal-deflection cycles without the ground test adapter installed	Orbital startup and endurance testing of system in space
21 Helium leak test of secondary containment	
22 Conduct endurance test with intermittent helium leak tests of secondary containment	
23 Remove VAU from test rig, remove NaK charge, and clean with butanol	
24 Helium leak test	Post-mortem examination of VAU
25 Conduct deflection cycle at room temperature	
26 Disassemble VAU and examine	

1) Burst pressure
2) Cyclic fatigue
3) Thermal endurance
4) Vibration, shock, and acceleration
5) Partial or full acceptance
6) System operational sequence.

Descriptions of the test rigs used are given in References 1 and 2.

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

The development tests showed that: (1) the design of the SNAP 10A VAU, after the number of convolutions in the secondary bellows was increased from 13 to 18 to decrease the deflection per convolution, met all performance requirements with the adequate margins of safety, and (2) the quality of the materials used and/or the method of fabrication had to be such that stringers lying in a direction normal to a thin wall, which were sources of leakage problems, were precluded.

Four VAU's were subjected to the qualification tests, the sequence of which is shown in Table 3. All four VAU's successfully completed the qualification test program.

C. VOLUME ACCUMULATOR UNIT PERFORMANCE IN SNAP 10A NUCLEAR POWER UNIT (NPU) SYSTEMS. (1)

Two SNAP 10A NPU Systems were operated, using nuclear reactors as the system heat source. One was the S10FS-3 ground test system, and the other was the S10FS-4 earth orbiting flight system. There were two VAU's in each of these systems. In the S10FS-3 ground test system, the performance of the VAU's during the system startup phase, and the first 82 days of operation, was satisfactory. After 82 days of normal operation, the deflections of the bellows systems began to decrease. The total change in the VAU bellows systems deflection stabilized at an active equivalent volume decrease of $\sim$ 50 $in.^3$, the volume of one VAU secondary containment vessel. There was no leakage of NaK from the system into the test chamber. It was concluded that a leak had developed in one of the VAU primary bellows assemblies, and that the NaK had filled the secondary containment volume. The operation of the system was not seriously affected by the VAU leak, and operation was continued for a total of 417 days. In the S10FS-4 earth orbiting flight system, the performance of the VAU's was totally satisfactory, during the entire 43 days that the system operated.

III. 5-kwe SYSTEM VOLUME ACCUMULATOR UNIT STUDIES

A. VOLUME ACCUMULATOR UNIT DESIGN REQUIREMENTS

In the 5-kwe System VAU trade studies, the VAU design requirements were taken to be as follows:

1) Accumulator volumes:

   a) At 100°F temperature (system NaK fill and "pinch-off") — movable head ~ 0.125 in. from closed position, in both primary and secondary loops

   b) At NaK maximum bulk temperature (1250°F) (volume change from 100°F volume condition):

      (1) Primary loop — 350 in^3.

      (2) Secondary loop — 193 in^3.

2) Loop pressures (minimum):

   a) At 100°F temperature (system NaK fill and "pinch-off"):

      (1) Primary loop (the bellows movable head ~ 0.125 in. from the closed position, at zero volume change, to facilitate loop pressure determination during NaK loading)(with no primary containment bellows failed):

         (a) Flight system — 1.5 psia

         (b) Ground system — 1.5 psia

      (2) Secondary loop:

         (a) Flight system — 2.0 psia

         (b) Ground system — 4.0 psia

   b) At NaK maximum bulk temperature (1250°F):

      (1) Primary loop (with all primary containment bellows failed):

         (a) Flight system — 8.0 psia

         (b) Ground system — 7.0 psia

(2) Secondary loop (for both flight system and ground system) — to be determined; expected to be less than that required at 100° F. which allows meeting pressure requirements at maximum bulk temperature and ambient temperature

(3) Other design requirements

a) State-of-the-art design and fabrication

b) Bellows capable of proof pressure test to 1.2 x design pressure, without bellows yielding or instability buckling

(1) At zero volume accumulation and room temperature

(2) At maximum volume accumulation and 660° F surrounding sink temperature

c) Bellows capable of overpressure test to 2.0 x design pressure without rupturing, at 660° F temperature.

d) Launch shock and vibration to be determined; however, bellows natural frequencies equal to or less than 20 Hz are assumed unacceptable, natural frequencies between 20 and 30 Hz are undesirable

e) Fatigue cycle life

(1) Simulated launch vibration (at room temperature)

(a) 32-sec dwell at bellows natural frequency

(b) 1.1 x full stroke deflection (1.1 factor for estimate of effects of "standing wave" on deflection)

(2) Thermal-volume-pressure cycles (room temperature to 660° F, 0 to full volume, corresponding initial to operating pressures)

(a) Acceptance tests — 200

(b) Normal operation — 50

f) Radiation level — 4×10^{13} nvt/5 years, fast neutrons (E > 0.1 Mev)

g) Optimum ratios — reliability/cost/size/weight

h) Secondary containment backup of NaK primary containment bellows

i) Thermal environment governed by radiator, neutron shield, and hot NaK lines temperature — assumed to be 660°F (max.)

j) System reliability goal — 0.997 for 5-year operation.

B. VOLUME ACCUMULATOR UNIT TRADE STUDIES

1. Description

a. Materials Evaluations and Selection

The materials evaluated were Inconel 718, AM 350 (SCT 850)* (for welded bellows only), and Type 347 stainless steel. Inconel X-750 and A-286 were considered, but dropped. For bellows material, the evaluation indicated Inconel 718 to be the best choice, with AM 350 (SCT 850)* as the alternate material for welded bellows. For a design stress level of two-thirds of yield strength, the VAU weight difference between using Inconel 718 and AM 350 is ~ 4 lb less for Inconel 718. Use of Type 347 stainless steel results in an excessive VAU weight penalty, due to the low yield strength (~ 33,000 psi) of this material.

b. VAU Concepts

Design calculations were made for 20 VAU concepts, involving the following options:

1) Bellows types

a) Welded bellows (nested ripple, disc type) (see Figure 4)

b) Formed bellows (hydroformed, or convoluted type with straight wall) (see Figure 5)

c) Nested-formed bellows (similar to the bellows of Figure 5, but with a bellows convolution forming radius of ~ 2 times the material thickness, and having a curved span)

*SCT 850 - Heat treatment of AM 350

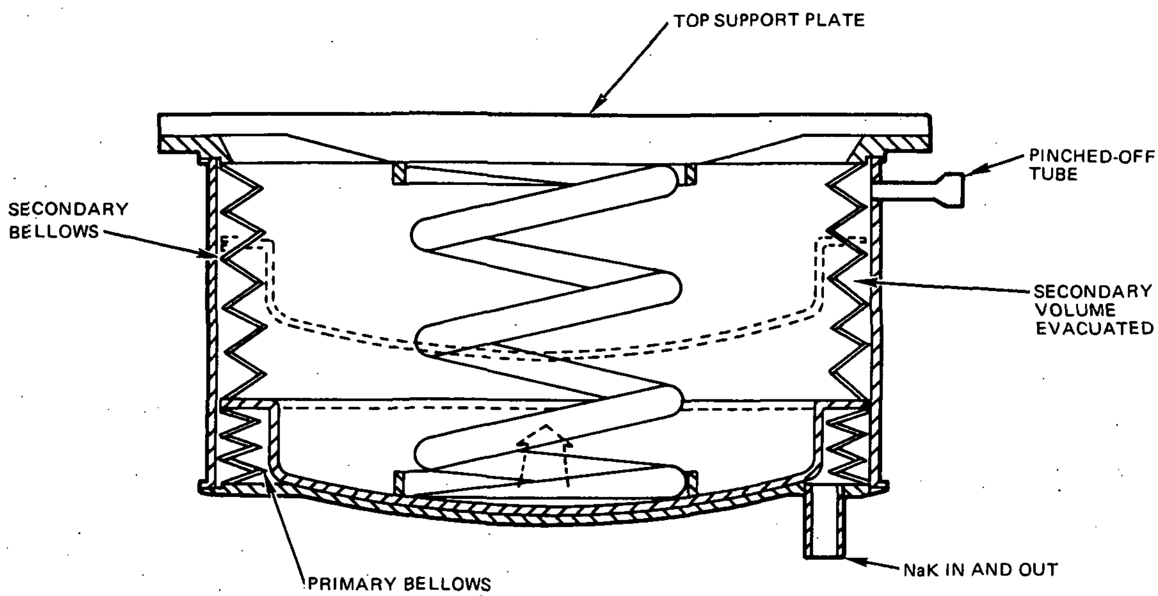


Figure 4. Redundant Bellows Arrangement, Welded Bellows, Spring Backed

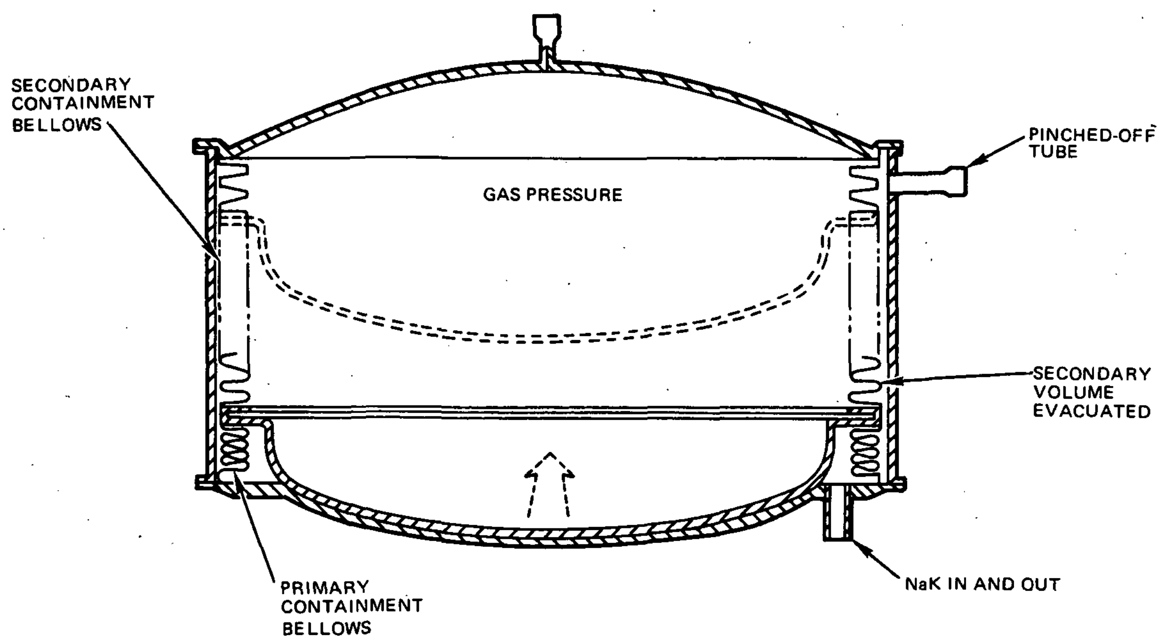


Figure 5. Redundant Bellows Arrangement, Standard Formed Bellows, Gas Backed

2) Auxiliary Pressurization methods

a) Gas pressure (charged and sealed)(see Figures 5 and 6)

b) Helical coil spring (see Figures 4 and 7)

3) Number of VAU's in system

a) Two units — one per loop

b) Three identical units — two in primary loop, one in secondary loop

c) Six identical units — four in primary loop, two in secondary loop

d) One VAU per system was considered, but dropped, because:

(1) Common NaK volume — not feasible, because of NaK flowing through VAU from one loop to the other, and the possibility of bypassing thermoelectrics, radiator, etc.

(2) Common gas volume — not feasible, because of NaK pressures of one loop influenced by the pressures of the other loop, resulting in unknown VAU bellows positions during NaK loading

4) Bellows arrangements

a) Redundant bellows approach (see Figure 4). This arrangement employs two bellows per VAU — primary NaK containment bellows, and a secondary NaK containment bellows. The volume external to the bellows (secondary volume in Figure 4) is evacuated. This arrangement is similar to the bellows arrangement of the SNAP 10A VAU.

b) Double opposed, redundant bellows approach (see Figure 6). This bellows arrangement employes four bellows per VAU — two primary NaK containment bellows, and two secondary NaK containment bellows. This approach is comparable to two,

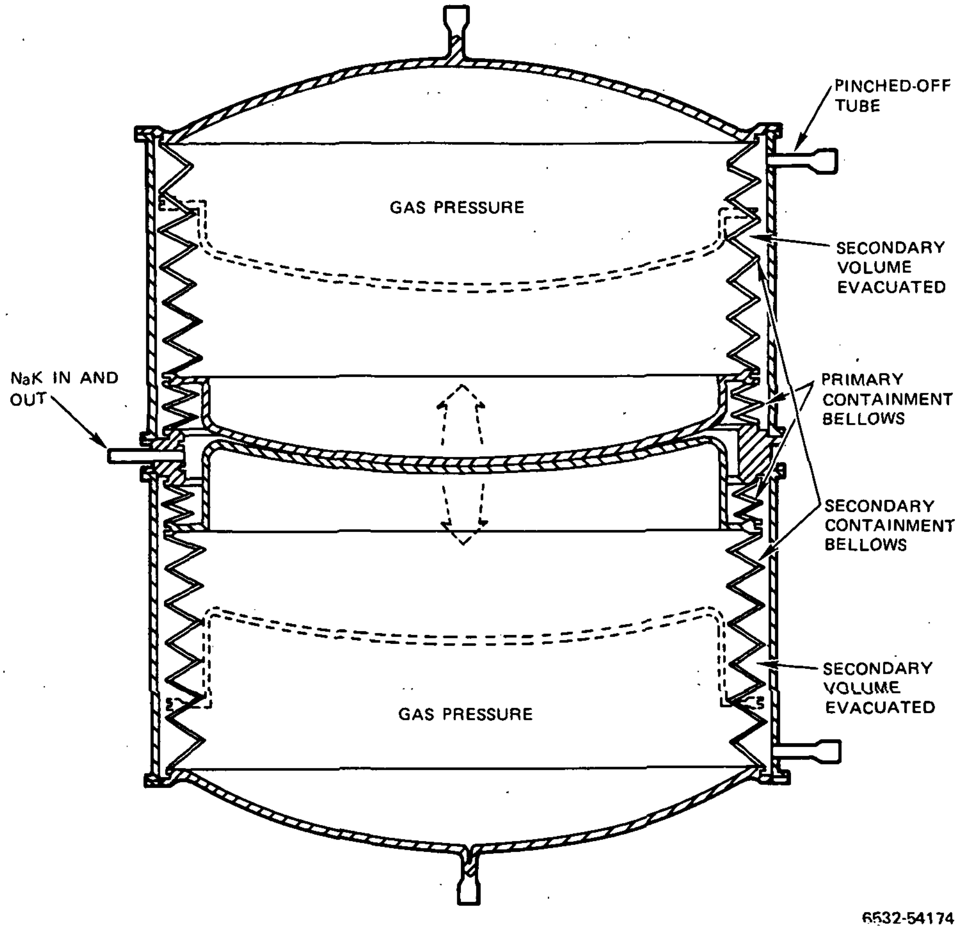


Figure 6. Double Opposed, Redundant Bellows Arrangement, Welded Bellows, Gas Backed

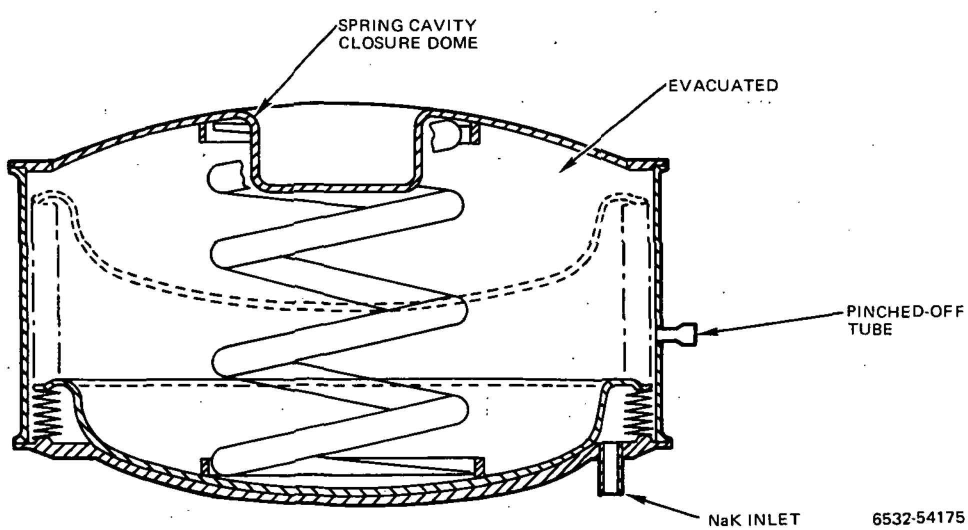


Figure 7. Single Bellows Arrangement, Welded Bellows, Spring Backed

one-half size redundant bellows units with bottom plates removed, and welded back-to-back.

c) Single bellows, spring backed, approach (see Figure 7). This approach employs six small VAU's — four in the primary loop, and two in the secondary loop — and is comparable in volume displacement per bellows to the double opposed, redundant approach. Only one bellows per VAU is needed, because the structural can, enclosing both bellows and auxiliary spring, provides for secondary containment of the primary NaK containment bellows. The spring cavity is evacuated. The gas-backed pressurization method for this approach was considered, but dropped. Use of gas requires a secondary containment bellows, higher operating design pressures, and consequently, uncompetitive VAU weights.

5) Secondary volume evacuated vs NaK filled (see Figures 5 and 8) — All of the preceding concepts were evaluated, based on the secondary volume (see Figure 5) being evacuated and sealed. If the secondary volume is filled with NaK (see Figure 8), the differential pressure across the bellows is reduced. For evaluation of the evacuated vs NaK-filled secondary volume comparisons, the design approach of gas pressure, welded bellows, redundant bellows arrangement was studied.

The 20 VAU concepts for which design calculations were made, and the results of the design calculations, are shown in Table 4. In the design calculations for all of these concepts, the bellows material thickness was taken to be 0.010 in., and the bellows pressure/deflection stress ratio of 0.8 was used (the minimum weight design point for the VAU occurred near a bellows pressure/deflection stress ratio of 0.8 for the configurations studied with the equations

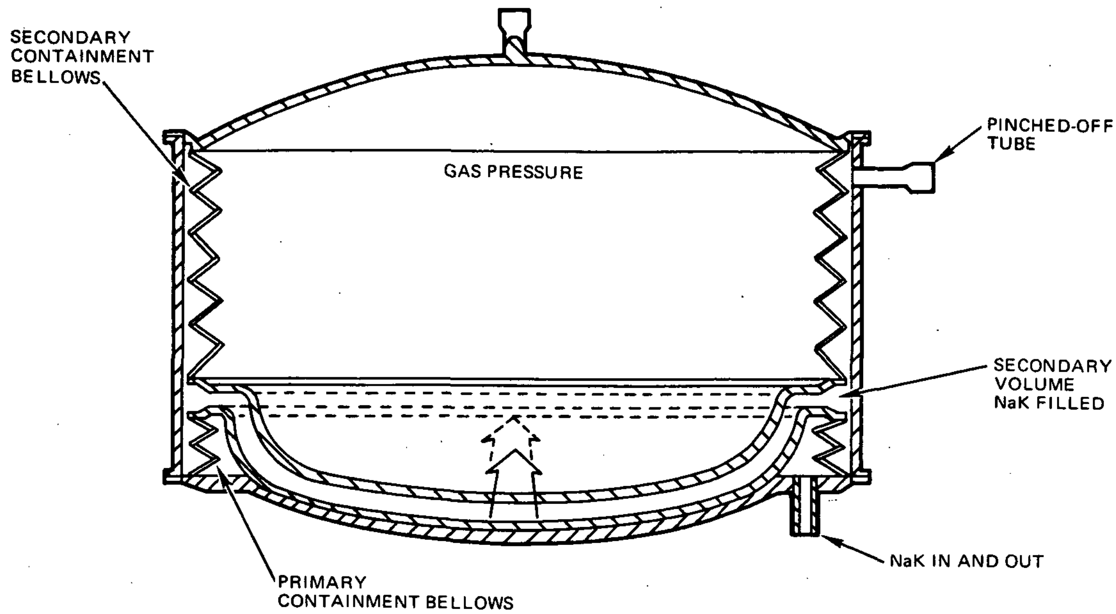


Figure 8. Redundant Bellows Arrangement, Welded Bellows, Gas Backed, Secondary Volume NaK Filled

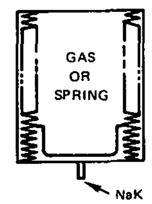
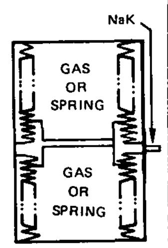
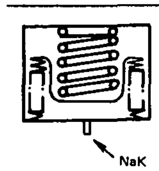
used). Also shown in this table are the results of a reliability study for these concepts. It is seen that the VAU system reliability of all of these concepts either essentially meets or exceeds the goal of 0.997 for 5-year operation (Section III-A-2).

c. VAU Concept Evaluations

Two types of VAU concept evaluations were made; a performance comparisons evaluation, and a numerical evaluation. The results of the performance comparisons evaluation were as follows:

1) The best bellows arrangement is the redundant arrangement. The double opposed, redundant arrangement is more costly to fabricate and assemble, and offers no significant advantage. The single bellows concepts show a high weight penalty, without appreciable gain in system reliability.

2) The three-VAU system concept is chosen over the two-VAU system concept, since the performance of these two concepts is not significantly different, and the cost of development, testing and qualification

Configuration		Bellows Arrangement	Loop	Units Required	Capacity (in.^{3})	Bellows Type	Pressure From	OD (in.)	Height (in.)	Weld Length (ft)	System Weight (lb)	Probability of Failure: Nuclear Power Unit	Pressure (psia): Normal Operating Pressure	Pressure (psia): Primary Bellows Failure	Instability Buckling Pressure (psi)	Natural Frequency at Room Temperature (Hz)	Remarks
	1	Redundant Bellows	Primary	1	350	Welded	Gas	11.0	10.6	240	32.1	0.0034	26.2	20.5	62.3	34	Identical Bellows
			Secondary	1	193	Welded	Gas	11.0	7.5	133			26.2	21.2	204	62	ID and OD
	2		Primary	1	350	Formed	Gas	11.35	22.0	10.1	51.3	1.2×10^{-5}	15.2	11.1	23.3	28.4	
			Secondary	1	193	Formed	Gas	11.35	14.5	8.3			15.2	11.2	76.7	51.4	
	3		Primary	1	350	Welded	Spring	9.0	9.0	125	42.4	0.00092	10.5	8.09	13.0	20.4	
			Secondary	1	193	Welded	Spring	9.0	5.0	69.7			10.5	8.09	42.4	37.1	
	4		Primary	1	350	Formed	Spring	11.29	18.9	10.1	68.7	8×10^{-6}	17.5	8.5	25.1	29.8	Identical Bellows
			Secondary	1	193	Formed	Spring	11.29	10.6	8.0			17.5	8.9	95.7	59.4	ID and OD
	5 a		Primary	2	175	Welded	Gas	11.0	7.5	133	38.4	0.0024	24.0	19.6	204	62	Identical VAU's
			Secondary	1	193	Welded	Gas	11.0	7.5	133			26.2	21.2	204	62	
	6 a		Primary	2	175	Formed	Gas	11.35	14.5	8.3	61.0	1.2×10^{-5}	14.6	10.7	76.7	51.4	
			Secondary	1	193	Formed	Gas	11.35	14.5	8.3			15.2	11.2	76.7	51.4	
	7		Primary	2	175	Welded	Spring	9.0	5.1	78.3	49.2	0.00083	10.7	8.0	45.5	37.3	
			Secondary	1	193	Welded	Spring	9.0	5.1	78.3			11.4	8.8	45.5	37.3	
	8		Primary	2	175	Formed	Spring	11.29	10.5	8.0	78.3	1.3×10^{-5}	17.5	8.01	96.1	59.6	
			Secondary	1	193	Formed	Spring	11.29	10.5	8.0			18.9	9.5	96.1	59.6	
	9	Double Opposed Redundant Bellows	Primary	1	350	Welded	Gas	11.0	11.1	116.4	33.9	0.0017	25.1	19.4	245	67.8	Identical Bellows
			Secondary	1	193	Welded	Gas	11.0	8.0	65.4			25.1	20.6	800.9	122.9	ID and OD
	10		Primary	1	350	Formed	Gas	11.35	23.5	8.1	58.8	1.6×10^{-5}	15.2	10.9	93.4	56.7	
			Secondary	1	193	Formed	Gas	11.35	16.0	7.1			15.2	11.38	306.4	102.8	
	11		Primary	1	350	Welded	Spring	9.0	9.7	63.3	49.7	0.00056	10.5	8.09	40.9	40.9	
			Secondary	1	193	Welded	Spring	9.0	5.8	35.9			10.5	8.08	169.8	74.1	
	12		Primary	1	350	Formed	Spring	11.29	21.2	8.0	76.2	1.6×10^{-5}	17.5	8.3	100	59.6	Identical Bellows
			Secondary	1	193	Formed	Spring	11.29	12.9	7.0			17.5	8.7	333	118.8	ID and OD
	13		Primary	2	175	Welded	Gas	11.0	8.0	65.4	36.6	0.0012	21.03	17.18	800.9	122.9	Identical VAU's
			Secondary	1	193	Welded	Gas	11.0	8.0	65.4			25.1	20.6	800.9	122.9	
	14		Primary	2	175	Formed	Gas	11.35	16.0	7.1	72.1	2.2×10^{-5}	13.2	10.8	306.4	102.8	
			Secondary	1	193	Formed	Gas	11.35	16.0	7.1			15.2	11.38	306.4	102.8	
	15		Primary	2	175	Welded	Spring	9.0	5.9	41.9	60.3	0.00045	10.65	8.01	180	73.1	
			Secondary	1	193	Welded	Spring	9.0	5.9	41.9			11.39	8.6	180	73.1	
	16		Primary	2	175	Formed	Spring	11.23	13.0	7.0	89.1	2.0×10^{-5}	18.7	8.4	387	116	
			Secondary	1	193	Formed	Spring	11.23	13.0	7.0			20.3	10.0	387	116	
	17	Single Bellows	Primary	4	87.5	Welded	Spring	7.0	4.1	87.0	52.4	3.8×10^{-4}	17.7	8.0*	67.4	44.2	
			Secondary	2	96.5	Welded	Spring	7.0	4.1	87.0			19.2	1.9†	67.4	44.2	
	18		Primary	4	87.5	Formed	Spring	7.2	7.7	6.7	78.6	4.0×10^{-6}	19.7	8.1*	40.4	45.3	
			Secondary	2	96.5	Formed	Spring	7.2	7.7	6.7			21.4	1.8†	40.4	45.3	
	5 b	Redundant Bellows Sec Volume NaK Filled	Primary	2	175	Welded	Gas	11	7.4	24.7	31.2	0.0022	38§	38§	35	37	
			Secondary	1	193		Gas	11	7.4	24.7			48§	48§	35	37	
	6 b	Redundant Bellows	Primary	2	175	Nested Formed	Gas	11.14	10.1	10.9	45.3	--	18.0	15.7	195	67.6	
			Secondary	1	198		Gas	11.14	10.01	10.9			21.4	16.8	195	67.6	

* - 3 primary bellows failed
† - 1 primary bellows failed
§ - ΔP across bellows ~ 1.0 psi

Table 4. Accumulator Concepts Evaluation Matrix

FOLDOUT FRAME

FOLDOUT FRAME 2

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of two different VAU designs would be much greater than for one single VAU design.

3) The gas pressurization approach is preferred over the spring pressurization approach, primarily due to about an 11-lb weight penalty for the spring approach.

4) The bellow type chosen is the welded bellows, with the nested-formed bellows as the alternate. A severe weight penalty is associated with the straight-wall-formed bellows. The nested-formed bellows has a weight penalty of ~ 7 lb, and a height penalty of 2.6 in., over the welded bellows. However, the welded bellows has a lower reliability than the nested-formed bellows, due to its ~ 730 ft greater weld length.*

5) The evacuated secondary volume is chosen over the NaK-filled secondary volume, since the disadvantages of the latter concept (i.e., high loop operating pressure, increased fabrication and assembly complexity, and the possibility of leakage of the secondary volume NaK fill, which could jeopardize the system) more than offset its advantages (i.e., lower bellows fabrication cost, and lower differential pressure across the bellows).

The results of the numerical comparisons evaluation were in agreement with the results of the performance comparisons evaluation.

*At the time the trade study was made, this was the conclusion that was reached. However, tests made, subsequent to the time of the trade study, showed that the higher reliability of the nested-formed bellows, due to the lower length of welding, more than compensated for the added 2.6 in. in height and the associated ~ 7 lb weight disadvantage. As a result, the nested-formed bellows was chosen, and the welded bellows became the alternate.

2. Conclusions

The conclusions drawn from the trade study are:

1) Of the available candiate materials, Inconel 718 is the best choice.

2) The redundant bellows arrangement is a better choice than the double opposed, redundant bellows arrangement.

3) Three identical VAU's in the system (two in primary loop plus one in secondary loop) is a better choice than two optimum design VAU's in the system (one design for the primary, and another design for the secondary loop).

4) The gas charge pressurization method is a better choice than the spring pressurization method.

5) The relatively new nested-formed bellows appears to be a better choice of bellows type than the conventional straight-walled-formed bellows.

6) The welded bellows is a better choice than the nested-formed bellows. However, the nested-formed bellows provides many of the inherent welded bellows advantages, and has a weld length approximately the same as that characteristic of the straight-wall-formed bellows. *

7) The nested-formed bellows merits choice as the alternate bellows type. *

8) The evacuated secondary volume approach is less complex and less costly than the NaK-filled approach.

C. BELLOWS EVALUATION

1. Description

A series of inspections and examinations were made on four welded and one nested-formed bellows capsules, to acquire fabrication evaluation data which would permit:

1) Verification that both welded and nested-formed bellows can be satisfactorily fabricated, using Inconel 718

*ibid

2) Choice of bellows type

3) Choice of vendor

4) Upgrading of quality control requirements for bellows fabrication.

Additionally, the following tests were made on these bellows capsules, in conjunction with material specimen tensile tests, to determine the accuracy of the bellows analytical approach:

1) Bellows effective area

2) Bellows spring rate

3) Bellows yield stress.

The pre-test inspections were dimensional, helium leak check, and radiographic inspections. A metallographic examination was performed on all bellows capsules, subsequent to the preceding tests.

2. Results

a. Pre-Test Inspection

The dimensions of the four welded and one nested-formed bellows capsules were as shown in Table 5.

The nested-formed bellows was fabricated by the hydroform process, which eliminates mechanical rolling and crushing of the bellows material.

No leaks were detectable in any of the five bellows capsules. The sensitivity of the leak detector was between 1 and 1.8×10^{-10} cc/sec helium.

The radiographic inspection of the four welded bellows capsules indicated one inclusion in an OD convolution weld bead of each of the four capsules as follows:

Welded Bellows Capsule Number	Diameter of Inclusion (in.)
1	~ 0.010
2	~ 0.020
3	~ 0.010
4	~ 0.005

TABLE 5

BELLOWS DIMENSIONS

	Welded Bellows Capsule Number				Nested-Formed Bellows Capsule
	1	2	3	4	
	Supplier				
	A		B		C
Bellows OD (in.)	9.49	9.49	8.97	8.97	10.716 ±0.029*
Bellows ID (in.)	8.48	8.48	7.74	7.74	9.68 ±0.02*
Material (Inconel 718) Thickness (in.)	0.0099	0.0095	0.0080	0.0080	0.010
Number of Convolutions	3	3	3	3	10

*Diameters shown are the mean dimension. The plus and minus value is the maximum measured variation from the mean dimension.

The radiographic inspection of the nested-formed bellows capsule indicated inclusions or voids, ~ 0.005 in. in diameter, in a total of four places in the two bellows installation welds (bellows neck-to-end plate welds).

b. <u>Test Results</u>

1) The measured effective bellows area was within 5% of the calculated effective area for the welded bellows, and was within 1% for the nested-formed bellows.

2) The measured bellows spring rate was within 6% of the calculated spring rate for Welded Bellows Capsules No. 1 and 2, and the nested-formed bellows capsule. For Welded Bellows Capsules No. 3 and 4, the calculated spring rate was less than the measured spring rate, by 34.4 and 35.3% respectively. The reason for the latter differences has not been ascertained.

3) The calculated bellows yield stresses are compared with the results of the bellows material yield stress tests in Table 6. The calculated bellows yield stresses are in reasonable agreement with the material yield stresses for the welded bellows, but are conservative, by over 20%, for the nested-formed bellows.

TABLE 6

BELLOWS YIELD STRESS

	Welded Bellows Capsule Number				Nested-Formed Bellows Capsule	
	1	2	3	4	Run No. 1	Run No. 2
Calculated Stress at Bellows Yield Point (psi)*	156,000†	150,000†	155,000	186,000	219,000	207,000
Minimum and Maximum Material Yield Stress (psi)	145,600§ 155,000	147,200§ 158,900	161,900 164,000	161,900 164,000	160,700 164,000	160,700 164,000
Stress Equation Error (%)*	+6.7** +0.6	+1.9 -5.9	-4.5 -5.8	+13 +12	+27 +25	+22 +21

*Bellows stress equations used are from Reference 1 for welded bellows, and from Reference 3 for formed bellows. The equations are described in the appendix.

†Welded Bellows Capsules No. 1 and 2 demonstrated an abnormal change in bellows free length at very low stress levels. The yield point of Welded Bellows Capsules No. 1 and 2 was therefore taken as being at the point where the change in bellows free length became nonlinear.

§This is less than the minimum yield strength value of 150,000 psi required by material specification.[4]

**These two numbers correspond to minimum and maximum yield stresses.

c. Metallographic Examination

The bellows capsules were cut in half, and sections were mounted in epoxy for examination. Radiographic film was used in determining where to cut the sections, so that the indications of inclusions or voids would be included in the mounting. The metallographic examination showed:

1) Welded bellows capsules

   a) No inclusions or voids could be found in any of the bellows welds

   b) All four capsules had root cracks in the welds. The metallographic examination was discontinued upon finding these root cracks.

2) Nested-formed bellows capsule

   a) No cracks, voids, or inclusions could be found in either the bellows installation welds, bellows longitudinal seam weld, or the inlet tube installation weld, even though the radiographic examination had indicated their presence in the bellows installation welds.

   b) No "orange peel" effect was found at the root or crown of the bellows convolutions.

   c) Photomicrographs of grain structure of the bellows heat-affected zone, and of the bellows parent metal, showed the parent metal grain size to be a little smaller, with more than 15 grains across the 0.010 in. thickness. Photomicrographs also showed that grain growth, due to bellows forming (cold work), did not take place.

   d) Comparison of parent metal thickness and bellows ID bend thickness to the bellows OD bend thickness indicated that $\sim$ 4.5% thinning in the OD bend thickness occurred.

3. Conclusions

The conclusions drawn from the bellows fabrication evaluation tests and examinations are as follows:

1) Welded bellows

   a) Inasmuch as all four bellows were found to have root cracks in the welds, it was determined that, prior to procurement of welded bellows of Inconel 718 material from the same supplier, a detailed review of the supplier's fabrication quality control and quality assurance requirements would be required.

b) The effective bellows area can be calculated to within ~ 5%. This error is considered to be within fabrication and tolerance limitations.

c) The spring rate of welded bellows cannot be reliably calculated. Hence, when welded bellows are to be used, the measured spring rate on prototype units should be employed in the final design.

d) The difference between the calculated bellows stress at yield point and the measured material yield stress ranged from -6 to +13%. All or part of the -6% may be the result of root cracks in the welds of the bellows tested.

2) Nested-formed bellows

a) These bellows can be satisfactorily fabricated from Inconel 718.

b) The effective area and spring rate can be adequately calculated.

c) The bellows stress equation used is conservative, by ~ 20%.

D. BELLOWS CAPSULE TESTS (PLANNED)

1. Objectives and Expected Results

The objectives of the planned bellows capsule proof and fatigue tests were to determine the fatigue life, launch vibration response, and pressure capability of the nested-formed bellows that were to be used in the volume accumulator unit. The bellows to be used in these tests were to have identical inside and outside diameters, wall thicknesses, bend radii, and end joints as those used in the system VAU. Figure 9 shows a schematic of the test bellows capsule. Any changes in volume requirements were to be made by changing the number of convolutions. Sufficient margin in the system pressure requirements were incorporated, so that any changes in pressure would not require redesign of the bellows.

The expected results of the planned bellows capsule tests were:

1) Verification of the bellows material mechanical properties

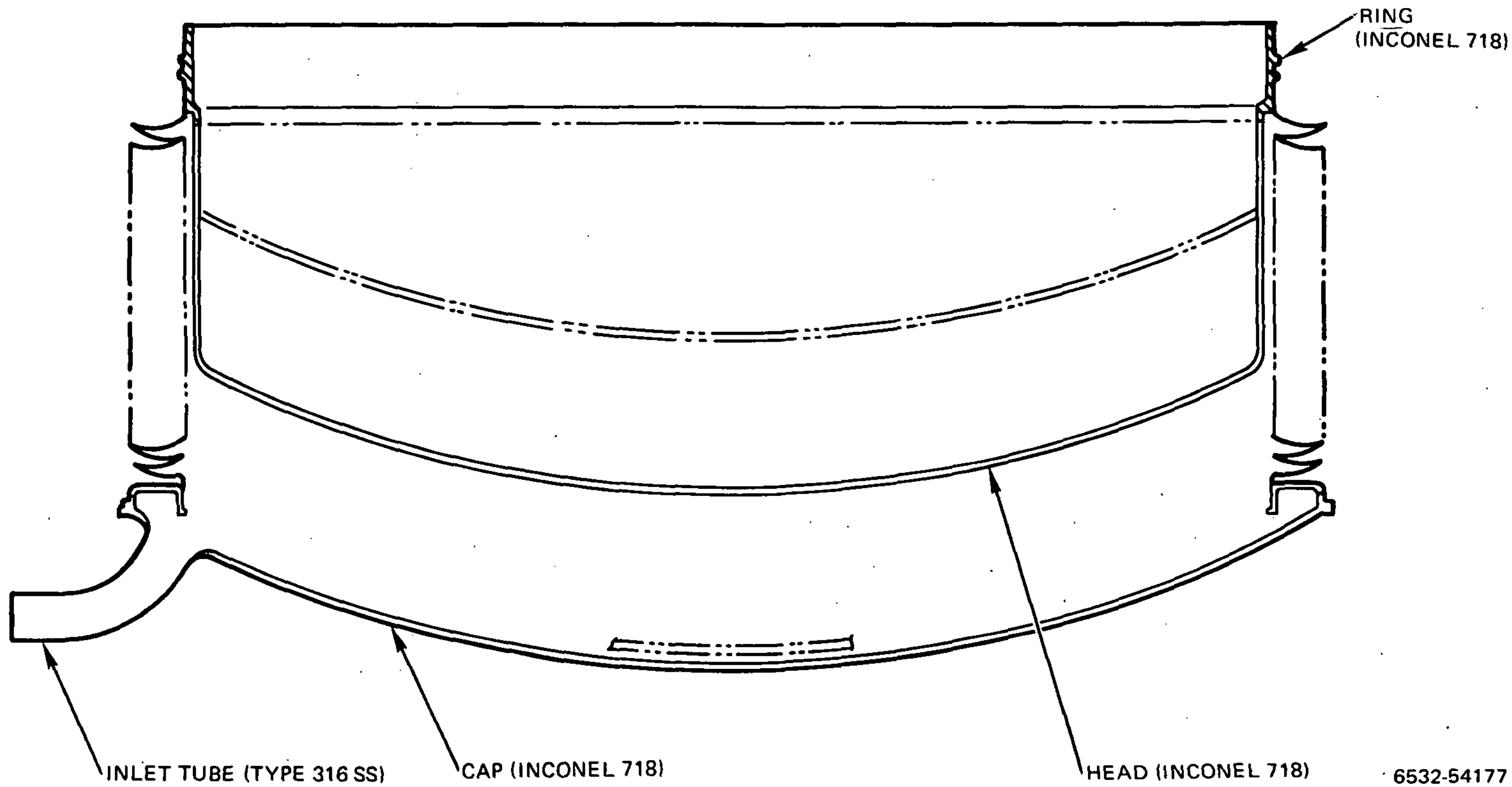

Figure 9. Schematic of Test Bellows Capsule

2) Verification of the calculated spring rate, effective area, and pressure-deflection-volume characteristics of the bellows.

3) Verification of the pressure capability of the bellows capsule.

4) Verification of the bellows fatigue cycle life during conditions simulating both the 5-kwe System launch and normal operation in space.

5) Determination of the quality of the longitudinal and end welds in the bellows.

2. Test Descriptions

A total of eight bellows capsules, plus material and weld tension test samples, were to have been tested.

A pre-test examination of all bellows capsules was to include helium leak check, radiographic and dye penetrant examination of the bellows end welds, and dimensional inspection of the bellows capsule, including the convolution crown radii. Nondestructive testing was to include spring rate, effective area, and pressure-deflection-volume determination on all eight bellows capsules.

Room-temperature proof-pressure test was to be conducted on all units at a pressure of 48.3 psig across the bellows, which is equivalent to 1.2 times the hot short-term design pressure of 36 psig at 750° F. No yielding of the bellows was to be allowed in the proof test.

One of the bellows was to be overpressure tested at a pressure of 80.5 psi, at room temperature, which is equivalent to 2.0 times the hot short-term design pressure of 36 psig at 750° F. During the overpressure test, the bellows would be allowed to yield.

One bellows capsule was to be subjected to a "standing wave" vibration test, performed at room temperature in air on an environmental shake table. The bellows would be pressurized internally, with and without water, and limited in its maximum stroke similar to the VAU. The unit would be vibrated in accordance with the system environmental specification. High-speed movie and/or strobe photography would be used to record the bellows response. The photographic results should indicate whether a standing wave was developed by the bellows when driven by the shake table. Development of such a wave could cause higher than average stresses to be encountered where bellows leaves are widely separated. The movement rate of the wave, and the maximum local strain, would be used in calculating the fatigue life of the bellows. The standing wave tests would be run to a minimum of three times the projected launch time.

Two capsules were to be used to determine the bellows fatigue cycle life. One of the fatigue tests was to be run at 750°F, and one at room temperature. The fatigue tests would be used to demonstrate that the bellows had a cycle life expectancy 1000 times that of the projected application. The equipment for this test would be designed to cycle the bellows sample through its maximum working stroke, by alternately pressurizing and evacuating the bellows interior. The pressurizing argon would be regulated to control the maximum differential pressure across the bellows. At the end of the pressure-stroke cycle, the pressure would be relieved by venting to the atmosphere. A dead weight would be sized to allow the bellows to close to its minimum height. The differential pressure across the bellows, and its stroke, would be measured and recorded during the cycling.

The remaining bellows were to be held in reserve, or placed in additional fatigue tests, depending upon the availability of funds and/or initial test results.

Following the completion of fatigue testing, metallographic examination of the bellows capsules was to be performed. Grain size, microhardness, orange peel effect, and end weld penetration were to be identified.

Tension testing of material heat treat samples and weld samples was to be performed at room temperature and at 750°F.

IV. PROTOTYPE VOLUME ACCUMULATOR UNIT

A. DESIGN DESCRIPTION

1. Design Approach

The prototype VAU was designed to be installed in any of the three VAU locations in the 5-kwe System. Two of these locations are in the primary coolant loop, and the other is in the secondary coolant loop.

On the basis of the results of VAU trade studies (Section III-B) and bellows evaluation (Section III-C), it was determined that the prototype VAU would utilize Inconel 718 nested-formed bellows in redundant arrangement, with the secondary containment volume evacuated, and the bellows force augmented by gas charge pressurization.

2. Performance Requirements

The performance requirements for the prototype VAU were as follows:

1) The VAU at 750° F must be capable of accommodating a NaK volume increase of 337 in.^{3} above the residual volume.*

2) The combined action of the gas charge and the bellows force imposes the following pressures on the NaK:

   a) The minimum initial pressure at 100° F VAU temperature on the residual volume of NaK* should be 4 psia.

   b) The maximum operating pressure should be 28.0 psia at 750° F VAU temperature.

   c) In the event of primary bellows failure, the VAU must maintain 6.0 psia minimum pressure on 236 in.^{3} plus the residual volume of NaK in the primary and secondary cavities at 600° F VAU temperature.

3) The VAU must have an operational life of 5 years, after being exposed to storage environment for up to 2 years, and to the preflight through launch environment, with no maintenance.

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*The NaK volume at 100° F which is required to fill the primary containment cavity with the movable head (see Figure 10) positioned 0.12 in. from the NaK dome.

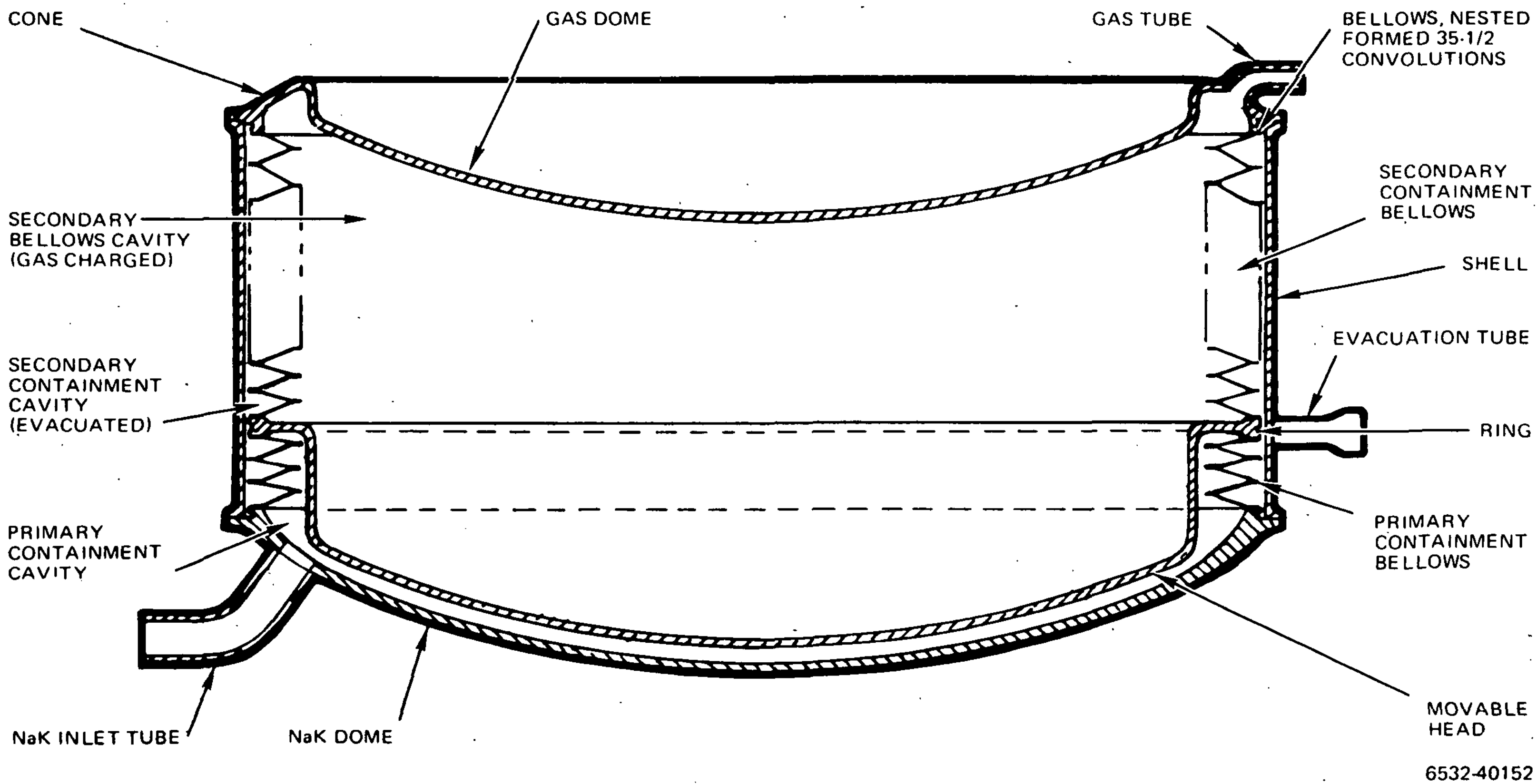

Figure 10. Prototype Volume Accumulator Unit Schematic

4) The reliability of the VAU should be 0.997 for operating 5 years without causing failure of the 5-kwe System.

3. Design Criteria

The following design criteria were applied in the design of the prototype VAU:

1) The design stress in the bellows at NaK pressure of 36 psia and 337 in.^{3} volume change must not exceed two-thirds of the minimum material yield strength at operating temperature.

2) Inlet and outlet piping loads were to be determined.

3) The VAU at 750° F must withstand NaK proof pressure of 10^{-3} torr to 43.2 psia without any permanent distortion or material yielding.

4) The VAU at 750° F must withstand NaK burst pressure of 72 psia without any rupture of the primary containment.

5) The axial natural frequency of the bellows, undamped except by atmospheric gas, must not be less than 35 Hz.

4. Description of Prototype Volume Accumulator Unit

Figure 10 shows a schematic of the prototype VAU. All VAU parts, except the NaK inlet tube, are fabricated from Inconel 718. The NaK inlet tube is Type 316 stainless steel. The major components of the VAU are:

1) Primary containment bellows

2) Secondary containment bellows

3) Gas dome

4) NaK dome

5) Movable head

6) Shell.

The primary containment bellows is the primary containment barrier for NaK in the VAU. It is a nested-formed type, and is fabricated from a single ply of 0.010-in. thick Inconel 718. It has 35-1/2 convolutions. One end of the primary containment bellows is welded to the NaK dome, and the other end is welded to the movable head, to form the primary containment cavity of the VAU.

The secondary containment bellows serves as a backup containment barrier for NaK in the VAU, in the event the primary containment bellows should leak or fail. The secondary containment bellows is physically identical to the primary containment bellows. One end of the secondary containment bellows is welded to the movable head, and the other end is welded to the gas dome, to form the secondary bellows cavity.

The gas dome and the NaK dome are welded to the respective ends of the cylindrical shell, to form the containment vessel which encompasses the bellows and the movable head. The space between the cylindrical shell and the bellows, which is the secondary containment cavity, is evacuated.

The secondary bellows cavity is charged with gas to a pressure of 7.05 psia at 100° F, to obtain the gas pressure force needed to augment the bellows spring force. The type of gas has not been selected, but it will probably be argon, due to its inertness, negligible activation at the radiation level to which it would be exposed, and relatively low diffusion rate.

B. STRESS ANALYSIS

A preliminary stress analysis of the prototype VAU has been made at the at the following conditions:

1) Design NaK pressure of 36 psia, with secondary containment cavity evacuated and the VAU located in a vacuum environment at 750° F
2) VAU subjected to proof pressure of 1.2 x 36 psia = 43.2 psia at 750° F
3) One VAU subjected to overpressure (2 x 36 psia = 72 psia) test at 750° F. During the overpressure test, yielding and distortion are acceptable, but pressure leakage is unacceptable.

For the bellows stress analysis, the bellows stroke was assumed to be that required to accommodate a volume change of 337 $in.^3$ in operating volume. For the stress analysis of the gas dome and cylindrical shell, it was assumed that both bellows have leaked, such that full pressure would be applied to these parts. The stress limits and stress categories used are from Figure NB3221-1, page 94, of Reference 5. The stress-intensity value used for the Inconel 718 structures is two-thirds of the minimum material yield strength. The stress-intensity value used for the Type 316 stainless steel tube at 750° F is 16,000 psi per page 396, Reference 5. A summary of the results of the stress analysis of the prototype VAU is presented in Table 7.

It is concluded, from the results of the stress analysis, that:

1) The VAU bellows and structure stress levels and margins of safety are acceptable, based on the design allowable criteria.

2) The gas dome may buckle during the overpressure test (of one VAU only). However, buckling is permissible, provided the dome does not leak pressure.

3) The thermal plus pressure stress of the NaK inlet tube is low, allowing an externally applied moment at the Type 316 stainless steel to Inconel 718 weld of 72 in.-lb maximum.

C. PERFORMANCE CHARACTERISTICS

The prototype VAU weighs 23.2 lb, and has a bellows natural frequency of 48 Hz. The reliability of the prototype VAU has been calculated to be 0.9999 to 0.9998 for a 5-year operation. Other calculated performance characteristics of the prototype VAU are shown in Table 8.

D. FABRICATION PLANS

Plans for the fabrication of prototype volume accumulator units were being formulated at the time of close-out of the 5-kwe Reactor Thermoelectric System Program. The fabrication of the VAU's was to be performed by outside sources, in accordance with appropriate specifications, drawings, and other controlling documents. In addition to the in-process quality assurance methods and steps specified in controlling documents, final acceptance inspections were planned.

TABLE 7

SUMMARY OF STRESS LEVELS, INSTABILITY, AND MARGINS OF SAFETY CALCULATIONS

	Bellows	NaK Dome	Movable Head	Gas Dome	NaK Dome Attachment Ring	Gas Dome Attachment Ring	Outer Can	NaK Inlet Tube
Design Pressure of 36 psig at 750° F								
Stress Allowable (psi)	138,000	92,000	92,000	92,000	92,000	92,000	92,000	24,000
Calculated Stress (psi)	111,186	15,900	14,700	27,800	3,150	42,400	46,250	3,210
Stress M. S.	+0.24	+4.8	+5.2	+2.3	+28.2	+1.17	+0.99	+6.5
Instability Allowable	113 psig	86,500 psi*	28,800 psi	12,700 psi	-	-	-	-
Calculated Stress or Pressure	36 psig	1000 psi*	3600 psi	9000 psi	-	-	-	-
Instability M. S.	+2.1	+85.5		+0.41	-	-	-	-
Proof Pressure Test of 43.2 psig at 750° F								
Stress Allowable (psi)	138,000	138,000	138,000	138,000	138,000	138,000	138,000	17,800
Calculated Stress (psi)	120,978	19,000	17,600	33,800	3,760	51,000	55,600	3,625
Stress M. S.	+0.14	+6.2	+6.8	+3.2	+35.6	+1.71	+1.48	+3.8
Instability Allowable	113 psig	86,500 psi*	28,800 psi	12,700 psi	-	-	-	-
Calculated Stress or Pressure	43.2 psig	1000 psi*	4320 psi	10,800 psi	-	-	-	-
Instability M. S.	+1.6	+85.5	+5.6	+0.18	-	-	-	-
Overpressure Test (One Unit) of 72 psig at 750° F								
Stress Allowable (psi)	165,000	165,000	165,000	165,000	165,000	165,000	165,000	72,000
Calculated Stress (psi)	160,458	31,800	29,500	55,500	6,300	84,300	91,970	5,282
Stress M. S.	+0.03	+4.2	+4.6	+2.0	+37.1	+0.96	+0.80	+12.6
Instability Allowable	113 psig	86,500 psi*	28,800 psi	12,700 psi	-	-	-	-
Calculated Stress or Pressure	72 psig	1000 psi*	7,200 psi	18,000 psi	-	-	-	-
Instability M. S.	+0.57	+85.5	+2.0	-0.30	-	-	-	-

*Maximum external pressure is 1 atm with internal VAU evacuation.

TABLE 8

SOME CALCULATED PERFORMANCE CHARACTERISTICS OF THE PROTOTYPE VOLUME ACCUMULATOR UNIT

VAU	Condition	Total NaK Volume* (in.^{3})	NaK Pressure† (psia) Normal	NaK Pressure† (psia) Failed Primary Bellows§	VAU Temperature (°F)	Average NaK Bulk Temperature (°F)
Primary Loop VAU	Over Design	344	26.9	21.4	740	-
		344	25.1	19.9	660	-
	Operation	337	26.5	21.1	750	1238
		319	25.5	20.3	750	1188
		319	23.8	18.8	660	
		300	24.5	19.5	750	1138
		300	22.8	18.0	660	
Secondary Loop VAU	Over Design	344	23.9	18.7	600	-
		344	22.4	17.6	525	-
	Operation	236	18.9	14.7	600	590
		236	17.6	13.7	525	
		190	17.1	13.2	600	540
		190	15.9	12.1	525	
		180	16.7	12.8	600	520
		180	15.5	11.8	525	

*Does not include residual volume.

†Based on gas charge fill pressure of 7.05 psia at 100°F, which provides an initial NaK pressure of 4.05 psia at $\Delta V = 0$.

§In the primary loop VAU's failed primary bellows is assumed in both VAU's.

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1. L. R. Stone and W. D. Whitaker, "SNAP 10A Expansion Compensator Final Report," NAA-SR-11952 (July 15, 1966)

2. S. Sudar, G. Paine, and L. Stone, "SNAP 10A Expansion Compensator," NAA-SR-9778 (October 1, 1965)

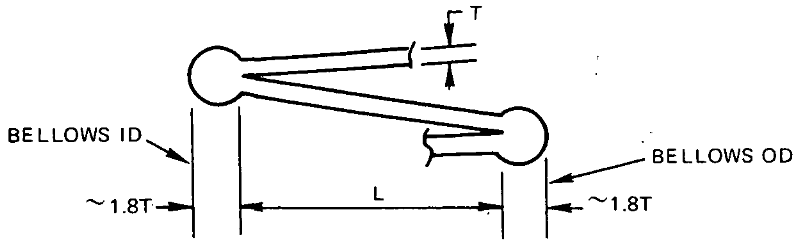
3. 1972 Addenda to Standards of the Expansion Joint Manufacturers Association, Inc.

4. AMS 5596, Alloy Sheet, Strip and Plate, Corrosion and Heat Resistant.

5. ASME Boiler and Pressure Vessel Code, Section III (1971)

APPENDIX
BELLOWS STRESS EQUATIONS

A. WELDED BELLOWS STRESS EQUATIONS[1]



$$L \approx \left(\frac{OD - ID}{2}\right) - 2(1.8T) = \left(\frac{OD - ID}{2} - 3.6T\right) \quad ...(1)$$

1. Pressure Stress, f_P

$$f_P = \left(\frac{PL^2}{2T^2}\right) \quad ... \quad (2)$$

where P is system pressure.

a. Welded Bellows Capsules No. 1 and 2

Capsule No. 1

$$L \approx \left(\frac{9.49-8.48}{2}\right) - 3.6\ (0.0099) = 0.469 \text{ in.}$$

$$f_P = \left[\frac{P(0.469)^2}{2(0.0099)^2}\right] = (1120)P$$

Capsule No. 2

$$L \approx \left(\frac{9.49-8.48}{2}\right) - 3.6\ (0.0095) = 0.461 \text{ in.}$$

$$f_P = \left[\frac{P(0.461)^2}{2(0.0095)^2}\right] = (1179)P$$

b. Welded Bellows Capsules No. 3 and 4

$$L = \left(\frac{8.97-7.74}{2}\right) - 3.6\ (0.008) = 0.586$$

$$f_P = \left[\frac{P(0.586)^2}{2(0.008)^2}\right] = (2685)P$$

2. Deflection Stress, f_δ

$$f_\delta = \left(\frac{3E\ \delta T}{NL^2}\right) \qquad \ldots \quad (3)$$

where E is modulus of elasticity and δ is deflection.

a. Welded Bellows Capsules No. 1 and 2

Capsule No. 1.

$$f_\delta = \left[\frac{3(20 \times 10^6)\delta\ (0.099)}{2(3)\ (0.469)^2}\right] = (65.2 \times 10^4)\ \delta$$

Capsule No. 2:

$$f_\delta = \left[\frac{3(29 \times 10^6)\delta\ (0.095)}{2(3)\ (0.461)^2}\right] = (65 \times 10^4)\ \delta$$

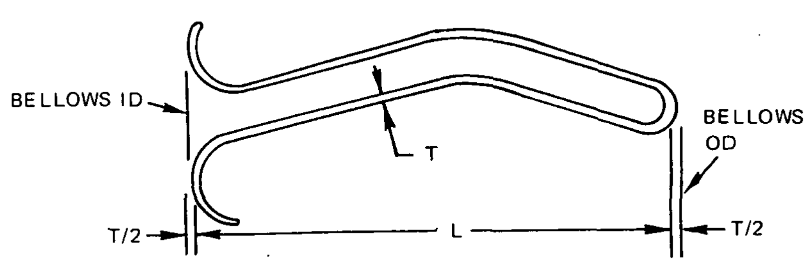
b. Welded Bellows Capsules No. 3 and 4

$$f_\delta = \left[\frac{3(29 \times 10^6)\delta\ (0.008)}{2(3)\ (0.586)^2}\right] = (33.8 \times 10^4)\delta$$

3. Total Stress, f_{TOT}

$$f_{TOT} = f_P + f_\delta \qquad \ldots \quad (4)$$

B. FORMED BELLOWS STRESS EQUATIONS[3]



$$L \approx \left(\frac{OD - ID}{2}\right) - 2\left(\frac{T}{2}\right) = \left(\frac{OD - ID}{2} - T\right) \qquad \ldots (5)$$

For the highest stress condition in the convolutions, use tolerances giving the maximum OD and minimum ID.

1. Meridional Membrane Stress Due to Pressure, S_3

$$S_3 = \left[\frac{PL}{2T_P}\right] \qquad \ldots \quad (6)$$

$$L = \left(\frac{10.687-9.7}{2}\right) - 0.01 = 0.4835$$

$$T_P = T\left(\frac{ID}{ID + L}\right)^{1/2} \qquad \ldots \quad (7)$$

$$= 0.01 \left(\frac{9.70}{10.1835}\right)^{1/2}$$

$$= 0.009762$$

$$S_3 = \left[\frac{P(0.4835)}{2(0.009762)}\right] = 24.8P$$

2. Meridional Bending Stress Due to Pressure, S_4

$$S_4 = \left[\frac{P(L)^2}{2(T_P)^2}\right] (C_{pu}) , \qquad \ldots \quad (8)$$

where:

$$C_{pu} = \text{funct} \left[\frac{q}{2L} , \frac{q}{2.2(d_p T_p)^{1/2}}\right]$$

$$q = \text{convolution pitch}$$

$$\approx 0.20$$

$$\frac{q}{2L} = \left[\frac{0.20}{2(0.4835)}\right] = 0.207$$

$$d_p = ID + L = 9.7 + 0.4835 - 10.1835$$

$$\left[\frac{q}{2.2\sqrt{d_p T_p}}\right] = \left[\frac{0.20}{2.2(10.1835 \times 0.009762)^{1/2}}\right]$$

$$= 0.289$$

$$C_{pu} \approx 0.86 \text{ (Figure 1, Reference 3)}$$

$$S_4 = \left[\frac{P(0.4835)^2}{2(0.009762)^2}\right] (0.86) = 1055P \quad .$$

3. Meridional Membrane Stress Due to Deflection, S_5

$$S_5 = \left[\frac{E T_p^{\,2} \delta}{2L^3 N C_{fu}}\right] \qquad \ldots \qquad (8)$$

where:

$$C_{fu} = \text{funct}\left[\frac{q}{2L}\ ,\ \frac{q}{2.2(d_p\ T_p)^{1/2}}\right]$$

$$C_{fu} \approx 1.31 \text{ (Figure 2, Reference 3)}$$

$$E = 29 \times 10^6 \text{ psi}$$

$$S_5 = \left[\frac{29 \times 10^6\ (0.009762)^2 \delta}{2(0.4835)^3\ 10(1.31)}\right] = 931\delta$$

4. Meridional Bending Stress Due to Deflection, S_6

$$S_6 = \left[\frac{5E\ T_p \delta}{3L^2\ N C_{du}}\right]\ , \qquad \ldots \qquad (9)$$

where:

$$C_{du} = \text{funct}\left[\frac{q}{2L}\ ,\ \frac{q}{2.2(d_p\ T_p)^{1/2}}\right]$$

$$C_{du} \approx 1.3, \text{ (Figure 3, Reference 3)}$$

$$S_6 = \left[\frac{5(29 \times 10^6)\ (0.009762)\delta}{3(0.4835)^2\ 10(1.3)}\right] = (15.5 \times 10^4)\delta$$

5. Total Meridional Membrane Plus Bending Stress, f_{TOT}

$$f_{TOT} = S_3 + S_4 + S_5 + S_6\ . \qquad \ldots \qquad (10)$$

$$= (24.8 + 1055)P + (931 + 15.5 \times 10^4)\delta$$

$$= 1079.8P + 15.593 \times 10^4\ \delta\ .$$

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