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SNAP 10A COMPONENT DEVELOPMENT SUMMARY

VOLUME 2

SAFETY AND DIAGNOSTIC COMPONENTS

(Title Unclassified)

AEC Research and Development Report

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SNAP 10A COMPONENT DEVELOPMENT SUMMARY

VOLUME 2

SAFETY AND DIAGNOSTIC COMPONENTS

(Title Unclassified)

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ABSTRACT

The Systems for Nuclear Auxiliary Power (SNAP) are nuclear reactors designed to provide electrical power on space vehicles. Components were successfully developed to operate under the extreme radiation, temperature, and space environments of the SNAP 10A reactor.

This report summarizes in three volumes the design, development, and test of components used on the SNAP 10A for control, safety, operational diagnosis, and radiation shielding. The report also includes a summary of efforts for development of a ground test attachment assembly and discusses various materials and process problems pertinent to the program.

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Figure 1. SNAP 10A Control and Reflector Assembly

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I. INTRODUCTION

The Systems for Nuclear Auxiliary Power (SNAP) are nuclear reactors designed to provide electrical power on space vehicles. The SNAP 10A reactor is intended for use as a primary power source on satellites or space vehicles that require a minimum net electrical power of 500 watts. The heat generating system is a liquid metal (NaK) cooled uranium-zirconium, hydride fueled reactor.

This report summarizes the development of components used on the SNAP 10A reactor assembly. The need, or function, of each component, along with the environmental and functional requirements, is covered. A developmental history, with test results and descriptions of the devices is included. The complete summary is composed of three volumes. Volume I summarizes components, Volume II safety and diagnostic components, and Volume III summarizes the shield, ground test drum drive assembly and materials applications.

General requirements for the devices are listed in Volume I, Section II but are not listed in Volumes II and III. However, the detailed performance requirements for each component are included with the specific component discussion.

Figure 1 shows the reactor control and reflector assembly mounted around a reactor core.

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II. SUMMARY

Safety and diagnostic component were successfully developed to meet the SNAP 10A flight requirements. One of the safety components is an electrically actuated band release device (EABRD) which causes reactor disassembly. The device utilizes a heater to break a fusible link. Development of a back up design using exploding bridge wire squibs in pressure-operated pin-pullers was also pursued.

A program to enable the use of a fusible band which normally holds the reactor together, but which breaks during reentry thereby causing dispersal of reactor parts, was completed. A low melting braze lap joint was initially developed but abandoned when analysis showed a jointless band would cause disassembly with only a small sacrifice in performance.

Another of the safety components developed is a temperature actuated device (TABRD) which causes automatic disassembly of the reflector from the reactor core when the NaK outlet temperature drops due to failure in the system. The resulting differential expansion device gave consistent analytical and test data results, the rupture member had repeatable rupture loads, and calibration of the device on reactor assemblies was repeatable.

A timer was developed which, when triggered from a malfunction determination source, causes a disassembly sequence. After some initial production control problems, an improved design which met flight requirements was evolved.

A system to measure control drum angular position and condition the information for telemetry transmission was developed. The main areas of development were sensor bearings and demodulation component irradiation. A system consistent with flight requirements resulted.

Limit switches were developed to check the positions of various components at selected times during the mission. Commercial switches were selected, tested and modified to meet the SNAP 10A conditions.

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III. SAFETY COMPONENTS

The safety components are a group of devices designed to shut down the operating reactor or to increase the shut down margin of the system when it is not operating. These components also provide an end-of-life capability that will disassemble the reflector and control units from the reactor and allow for a more efficient reentry burnup. The devices may be operated by a command signal from the ground or from the reactor.

The reactor safety system has four basic components: the reflector retaining band, an electrically actuated band release device, a malfunction timer, and a thermally actuated band release device. (See Figure 1)

The reflector assembly is composed of two halves which pivot at the base and are held together at the top by a retaining band. Springs mounted at the base of each half exert a sufficient force against the reflector to eject the reflector half unless this is restrained by the retaining band. The band can be released by electrically energizing a heater device which melts a joint in the band. The heater may be energized by telemetry signal or by a malfunction occurs if the malfunction persists no longer than one minute.

The band can also be released by a temperature actuated device that severs a bolt joint in the band. This may be called an end-of-life device in that the actuator arms or cocks as a result of system temperature increase and severs the retaining bolt when the system temperature decreases.

A. TEMPERATURE ACTUATED BAND RELEASE DEVICE (TABRD)

To allow for decay of radioactive materials before reentry, the reactor must be capable of automatic disassembly while still in orbit. This disassembly involves removal of the reflectors, which are spring-loaded and held to the reactor by a retaining band. Release of the band allows the reflectors to pivot out and away from the reactor. This capability must exist even in the event of a loss of telemetry signals.

In the event the reactor suffers a NaK coolant loss or a NaK pump failure, the reactor would be unable to produce any usable power. The battery-powered electrically actuated band release device would then be employed to disassemble the reactor.

Should this device fail, the temperature actuated band release device will operate automatically to detach the retaining band and cause the reflector halves to be ejected from the reactor.

1. Requirements

The TABRD is attached directly to the NaK outlet pipe in the area just below the retaining band. The TABRD bolt holds the two ends of the band together. The band tension of 165^{+15}_{-10} pounds must be resisted by the bolt (in shear) for the entire life of the reactor.

The NaK outlet temperature is $1000^{\circ}\text{F}^{+30}_{-20}$ and the initial temperature drop rate (in the case of catastrophic coolant system failure) is $25^{\circ}\text{F}/\text{minute}$ decreasing as the NaK line approaches equilibrium temperature. This equilibrium temperature is approximately 530°F during a sun-orbit and approximately 270°F during a shade-orbit. During rapid cooling, the TABRD temperature will necessarily lag behind that of the NaK line. The TABRD is required to release the retaining band before the maximum equilibrium temperature (530°F plus the safety factor) is reached. The drop in NaK temperature for operation will occur within 4 hr. The maximum temperature for arming the device is 950°F .

2. Developmental History

It was decided that the temperature of the NaK outlet pipe would be a very good indicator of the "general health" of the reactor since almost any major failure would decrease NaK outlet temperature. Therefore, an automatic temperature actuated device, sensing NaK outlet temperature, would fulfill the disassembly requirement as a back-up for the electrically actuated band release device.

a. Initial Concept

The TABRD concept is a rod and tube device attached to the NaK outlet pipe and holding the retaining band halves together with a bolt. The operating principle of this concept is described below. Since the inner rod had a much higher coefficient of linear expansion (α) than the outer tube, during initial start-up of the reactor the inner rod would expand at a much greater rate than the outer rod. When normal operation (and hence normal temperature) was reached, some method of latching would be employed to lock the rod and tube in their expanded positions. Any subsequent cooling of the parts would induce a

tension in the inner rod and a compression in the outer tube. The inner rod was attached to the bolt which held the band together and this tension would increase as a function of the differential temperature. A device could be designed wherein the tension would break the bolt and thus release the band.

A design consideration was to latch the rod and tube together at either the maximum temperature or at some predetermined temperature below that of normal operation. Latch at the maximum temperature has the advantage of "instant tension" from the slightest cooling. The small tension that would be induced due to normal temperature transients would be insignificant. The first latch design was the double spring loaded snubber device pictured in Figure 2.

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Figure 2. First Developmental SNAP 10A TABRD Assembly

This device allowed free expansion of the inner rod yet would jam on the slightest contraction due to cooling. It was expected that with greater tension, the holding power of the jammed snubbers would increase.

Another development area pertained to the tension-rupture bolt. The bolt must carry the 180-lb and load in shear for the lifetime of the reactor and yet rupture in tension after a reasonably small NaK temperature drop. Also, any elongation of the bolt before failure would reduce the available tension thus increasing the ΔT required to break it. It was therefore decided to notch the bolt since notching greatly reduces the elongation. The diameter at the notch was consistent with the 180-lb shear load requirement. The material chosen for the initial bolt design as shown in Figure 2 and Figure 3 was A-286 since it is rather strong and rather brittle. At 0.122 diameter, it was calculated that 1280 pounds, would be required to fail the bolt tension with a 180-lb shear load constantly applied. The elongation of the bolt at failure was expected to be 0.008 in.

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Figure 3. Notched Tension Bolt

The length of the rod and tube was made the longest possible within the physical constraints of the reactor assembly. However, the force equation shows no dependence on length as length cancels out of the equation and force is dependent on net α , ΔT , A and E. Thus,

$$\Sigma(\alpha L \Delta T) = \Sigma\left(\frac{PL}{AE}\right)$$

where

α = coefficient of linear expansion in. / in. / °F

L = length in inches

P = force induced in rod and tube - lb

A = cross sectional area of members - in.²

E = modulus of elasticity

The greater the net α , the greater the force which can be exerted for a given ΔT . The (AE) term should be optimized for both the rod and tube to exert the optimum tension for a given ΔT . For the above reasons the rod was fabricated from solid 316 stainless steel rod ($\alpha \cong 10 \times 10^{-6}$) and the tube from molybdenum ($\alpha \cong 3 \times 10^{-6}$). Net $\alpha \cong 7 \times 10^{-6}$.

This design was fabricated and is shown in Figure 2. Preliminary testing showed that the spring loaded snubber approach would not work. The device was force-limited. The strain in the snubber linkages prevented development of sufficient holding force. A step latch device, which cannot slip, was fabricated to replace the snubbers. This latch was adjusted to lock at a predetermined temperature below the maximum. Various tests were performed to determine, and adjust for, the correct latching temperature (For the remainder of this report, "latching" shall be called "arming" and the arming temperature is therefore the temperature at which the rod and tube are latched and any cooling from the arming temperature shall produce tension). With the arming temperature set at 900°F, tests were begun to prove the design by measuring the temperature drop required to rupture the bolt. Upon cooling, rupture was expected within 300°F below arming temperature. The tests were all unsuccessful in that the bolt would not rupture until 600 to 700°F below arming temperature. This led into a thorough investigation of the tensile properties of the bolt and its variation as a function of the notch radius, notch diameter, ratio of notch radius to notch diameter, and different metallic materials.

b. Bolt Analyses and Testing

The existing bolts (Figure 3) were tested in an Instron tensile testing machine. The tests were conducted as simple tension tests. For simplicity, and because the shear load is such a small fraction of the ultimate tensile strength, the 180 lb simulated band shear load was omitted. All tests were short-time, constant rate of strain (0.0002 in./min), constant temperature tensile tests. Reference to Table 1 test results will clarify why the bolts did not fail at the

TABLE 1
SHORT-TERM TENSILE TESTS ON BOLTS, MATERIAL A-286
(Refer to Figure 3)

Temperature (°F)	Notch Diameter (in.)	Notch Radius (in.)	Expected Ultimate Tensile Strength		Failure		Elongation at Failure (in.)
			(psi)	(lb)	(lb)	(psi)	
840	0.122	0.002	110,000	1280	2340	200,000	0.040
840	0.122	0.002	110,000	1280	2860	244,000	-
840	0.122	0.002	110,000	1280	2460	210,000	0.015
840	0.123	0.0015	110,000	1280	2760	230,000	0.012
840	0.123	0.0015	110,000	1280	2830	244,000	0.013
840	0.121	0.007	110,000	1280	1920	166,000	0.029
840	0.122	0.001	110,000	1280	1960	172,000	0.031
840	0.122	0.0015	110,000	1280	2140	182,000	-
840	0.122	-	110,000	1280	2450	210,000	-

TABLE 2

SHORT-TERM TENSILE TESTS ON BOLTS WITH 60° V-NOTCHES
(Refer to Figure 3 for General Configuration)

Material	Temperature (°F)	Notch Diameter (in.)	Notch Radius (in.)	Expected Ultimate Tensile Strength		Failure		Elongation at Failure (in.)
				(psi)	(lb)	(lb)	(psi)	
A-286	800	0.087	0.005	110,000	650	1340	226,000	0.017
A-286	800	0.087	0.005	110,000	650	1390	236,000	0.009
A-286	800	0.087	0.005	110,000	650	1540	260,000	0.015
A-286	800	0.087	0.005	110,000	650	1560	264,000	0.008
H-11	890	0.062	0.0015	210,000	630	560	185,000	-
H-11	890	0.062	0.0015	210,000	630	845	281,000	-
H-11	890	0.046	0.0015	210,000	335	500	301,000	-
H-11	890	0.044	0.001	210,000	335	488	320,000	-
H-11	890	0.044	0.001	210,000	335	490	322,000	-
H-11	890	0.044	0.001	210,000	335	458	315,000	-
H-11	890	0.040	0.001	210,000	264	390	317,000	-
H-11	890	0.040	0.001	210,000	264	486	389,000	-
H-11	890	0.040	0.001	210,000	264	414	329,000	-
REX-AA	840	0.040	0.001	210,000	264	216	173,000	0.003
REX-AA	840	0.040	0.001	210,000	264	219	175,000	0.003
RENE'-41	690	0.058	0.003	158,000	410	580	216,000	0.007
RENE'-41	690	0.058	0.003	158,000	410	596	226,000	0.006
RENE'-41	690	0.074	0.001	158,000	680	885	206,000	-
RENE'-41	690	0.074	0.001	158,000	680	983	228,000	-
RENE'-41	690	0.087	0.003	158,000	930	1190	201,000	-
RENE'-41	690	0.087	0.003	158,000	930	1350	230,000	-
RENE'-41	690	0.087	0.003	158,000	930	1390	237,000	-
RENE'-41	690	0.087	0.003	158,000	930	1420	242,000	-
RENE'-41	840	0.047	0.002	158,000	275	315	180,000	0.004
RENE'-41	840	0.047	0.002	158,000	275	346	199,000	0.005
RENE'-41	840	0.047	0.002	158,000	275	375	216,000	0.007
RENE'-41	840	0.047	0.002	158,000	275	388	223,000	0.006
RENE'-41	740	0.086	0.0075	158,000	930	1700	330,000	0.003
RENE'-41	740	0.086	0.010	158,000	930	1640	318,000	0.006
RENE'-41	740	0.082	0.007	158,000	930	1590	309,000	0.006
HAYNES 19	700	0.087	0.005	100,000	590	675	115,000	0.0005
HAYNES 19	700	0.087	0.005	100,000	590	660	111,000	0.0004
HAYNES 19	700	0.087	0.005	100,000	590	585	98,500	0.0006
HAYNES 19	700	0.087	0.005	100,000	590	540	91,000	0.0003
HAYNES 19	700	0.087	0.005	100,000	590	300	50,500	0.0001
HAYNES 19	700	0.087	0.005	100,000	590	230	38,800	0.0001

required ΔT . Failure was anticipated at 1280 lb and 0.008 in. elongation but did not occur until approximately 2500 lb and 0.020 in. elongation average. Also, note how unpredictable and erratic the failure load was. Various other notch diameter and radius configurations were tested. (See Figures 4 and 5). Reference to Tables 2, 3 and 4 again verifies the conclusions. The bolts were stronger (sometimes almost double) what they should have been. Again, note how unpredictable the failure load was.

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Figure 4. TABRD Tension Rupture Bolt With U-Shaped Notch

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Figure 5. U-Shaped Notch With Central Hole

TABLE 3

SHORT-TERM TENSILE TESTS ON BOLTS WITH U-SHAPED NOTCH, MATERIAL REX-AA
(Refer to Figure 4)

Temperature (°F)	Notch Diameter (in.)	Notch Radius (in.)	Expected Ultimate Tensile Strength		Failure		Elongation at Failure (in.)
			(psi)	(lb)	(lb)	(psi)	
840	0.039	0.007	210,000	250	208	173	0.0024
840	0.039	0.007	210,000	250	210	175	0.0021
840	0.040	0.007	210,000	250	232	193	0.0033
840	0.038	0.007	210,000	250	222	185	0.0029
840	0.038	0.007	210,000	250	225	187	0.0028
840	0.038	0.007	210,000	250	227	193	0.0031

TABLE 4

SHORT-TERM TENSILE TESTS ON BOLTS WITH U-SHAPED NOTCH
AND CENTRAL HOLE, MATERIAL RENE' 41
(Refer to Figure 5)

Temperature (°F)	Notch Diameter (in.)	Notch Radius (in.)	Expected Ultimate Tensile Strength		Failure		Elongation at Failure (in.)
			(psi)	(lb)	(lb)	(psi)	
840	0.074 Dia. 0.055 Hole	0.005	158,000	310	428	218,000	0.0030
840	0.074 Dia. 0.055 Hole	0.005	158,000	310	430	219,000	0.0036
840	0.074 Dia. 0.055 Hole	0.005	158,000	310	436	222,000	0.0042
840	0.074 Dia.	0.005	158,000	310	474	242,000	0.0039

This phenomenon was confirmed by literature pertaining to stress concentration factors less than 1 (rupture force increases instead of decreases due to the notch). It was observed,* that, whenever the notch radius approaches 0.005 inch, the surface finish along this radius can have varying and unusual effects on the crystal lattices at the surface. This phenomenon becomes especially important as the notch diameter decreases, thus making the surface crystals a larger percentage of the total and can be easily seen by an examination of the failure loads listed in Tables 1,2,3, and 4. (No effort was made to accurately control, to a minute degree, the surface finish at the notch during the manufacture of these bolts). Timoshenko† uses the dimensionless ratio of radius of notch to diameter of notch (R/D) in his calculations, and his data indicate that a value of R/D can be found such that the stress needed to rupture is a minimum. Assuming this to be correct, all of the data on the bolts were replotted against the R/D ratio. Rene' 41 was picked as the most promising material because of its insensitivity to small variations in notch geometry. Bolts made from other materials would exhibit erratic stress-rupture characteristics unless extreme tolerances and surface finish requirements were maintained. In Figure 6, note that the minimum tensile strength can be expected when the R/D ratio is approximately 0.055. With 0.086 in. selected as the notch diameter in order to withstand the 180 lb band load in shear, and maintaining the

*R. J. Roark, "Formulas for Stress and Strain."

†S. Timoshenko, J. M. Lessells, "Applied Elasticity," Westinghouse Technical Night School Press, 1925.

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Figure 6. Rupture Stress vs R/D Ratio of Notched Bolt

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Figure 7. Rene' 41 Notched TABRD Bolt

R/D ratio of 0.055 the correct notch radius is 0.005 in. A new bolt was designed (Figure 7) using the above dimensions. This bolt was tested to determine its tensile rupture strength and its shear rupture strength. In tension, at 700°F, the bolt ruptures at 1350 ± 100 pounds. In shear at 800°F, the bolt ruptures at 648 ± 38 pounds. Table 5 shows the uniformity of these Rene' 41 bolts in shear. The shear stress induced in the bolt by the 180 lb band load is only 33,000 psi.

c. Rod and Tube Analysis and Test

Redesign of the existing TABRD (Figure 2) was initiated. However, to analyze and predict the eventual performance of the new design, it was decided to determine how well the existing design performed in relation to theoretical values. In this analysis all known dimensional and material tolerances were accounted for to provide an indication of the confidence-band of operation. The primary equation of

TABLE 5

TABRD BOLT RELIABILITY TESTS
SHORT TERM SHEAR TESTS, MATERIAL RENE' 41
(Constant Strain Rate 0.0002 in./min)

Type Load	Temperature (°F)	Notch Radius (in.)	Notch Diameter (in.)	Rupture Force (lb)	Rupture Stress psi x 100
SHEAR	800	0.002	0.086	662	114
		0.002	0.086	670	115
		0.001	0.085	640	113
		0.003	0.086	685	118
		0.002	0.086	658	114
		0.003	0.086	682	117
		0.002	0.084	650	117
		0.003	0.086	675	116
		0.003	0.087	668	113
		0.004	0.087	688	117
		0.005	0.088	625	104
		0.005	0.087	610	104
		0.005	0.089	622	100
		0.005	0.087	610	104
		0.004	0.086	670	115
		0.004	0.087	675	114
		0.005	0.088	640	105
		-	-	670	-
		0.004	0.086	635	109
		0.002	0.086	662	112
		0.002	0.086	670	115
		0.001	0.085	641	109
		0.003	0.086	685	117
		0.002	0.086	659	114
		0.003	0.086	682	117

operation of a simple rod and tube differential temperature tension device is:

$$\Sigma [\alpha L \Delta T] = \Sigma \left[\frac{PL}{AE} \right]$$

Expanded, the equation becomes:

$$(\alpha L \Delta T)_{\text{ROD}} - (\alpha L \Delta T)_{\text{TUBE}} + (\alpha L \Delta T)_{\text{BOLT}} =$$
$$\left(\frac{PL}{AE} \right)_{\text{ROD}} + \left(\frac{PL}{AE} \right)_{\text{TUBE}} + \left(\frac{PL}{AE} \right)_{\text{BOLT}}$$

Note that terms relating to both plastic yielding and creep of the bolt are omitted from this equation. Plastic yielding will be accounted for later in the discussion.

Since this device is operating over a rather large ΔT , the variation in the coefficient of expansion (α) and in the modulus of elasticity (E) as a function of temperature for all materials must be considered. Overall data on the above are readily available from the respective manufacturers and incremental values can be derived from these data by first deriving the equations of the curves of α and E vs temperature. Since test equipment was available to determine the net thermal contraction as a function of the temperature drop from 990°F, this contraction became the first subject of verification analyses. The test was conducted by cooling the device rapidly (50°F per 10 minutes) while allowing a dial indicator to show the net contraction between the rod and tube. The bolt was omitted from this test. The basic equation was first utilized with the nominal dimensions and values of L and α , then the tolerances were arranged to provide the maximum available deflection and the minimum available deflection. The test data are superimposed on these three curves shown in Figure 8. Despite a poor temperature stabilization occurring during these tests, the correlation is excellent.

Figure 9 shows the available net free deflection to be expected from the new SNAP 10A design. The new design uses A-286 instead of 316 stainless steel for the inner rod. A-286 has a slightly lower α but offers much more strength which compensates for the lower α .

Tests precisely opposite to those above were performed wherein the total force output available was measured. The tests were conducted on the

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Figure 8. TABRD Deflection vs Temperature, Original Design 316 SS and Mo

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Figure 9. TABRD Deflection vs Temperature, A286 and Mo, SNAP 10A Reference Design

Instron tensile testing machine by allowing the device to cool rapidly (50°F per 5 minutes) while the Instron ram prevented any net deflection. The center stainless steel rod (again minus the bolt) was attached to the Instron force transducer via a pull rod and the output was pen-recorded on a strip chart. This setup (Figure 10) produced force ΔT , data, as explained above. In addition, at each incremental ΔT , the ram was moved to allow the force to momentarily return to zero and a dial indicator on the ram then showed the net deflection at that temperature. This was done as a cross-check on the deflection tests. Because of the thickness of the ram, an exceptionally long pull rod was required which materially affected the force and deflection tests. A mathematical correction factor was therefore used to validate the test data.

From these force output tests, two relationships were determined: force vs deflection and force vs temperature. Figure 11 shows the maximum and minimum force vs deflection relationship with the test data superimposed. The test data presented are an average of four tests, since the repeatability was quite excellent. The force vs temperature data are shown superimposed on

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Figure 10. TABRD Cool-Down Test

the calculated values in Figure 12. Again, the data presented are actually an average of four tests, since the repeatability was good. However, note in Figure 12 that the data parallels the calculated values but appears to be displaced from it. This indicates that there is some amount of initial lag which, when completed, allows the force to increase correctly. This initial lag varies between 50 and 100° F before any force can be built up. The cause of this lag is thread "give". The calculated operating conditions of force vs temperature for the new SNAP 10A design are presented in Figure 13. Note that these curves are based on the assumption that there is no plastic yielding

of the bolt nor initial lag which would decrease the force available.

d. Flight Configuration Analysis and Test

The final SNAP 10A reference design has the potential tension abilities enumerated below.

- 1) The available force is 780 lb per 100° F ΔT . The maximum and minimum possible values are 1060 and 530 lb per 100° F ΔT . (See Figure 13)
- 2) The available deflection is 0.0076 in. per 100° F ΔT nominally. The maximum and minimum possible values are 0.0093 in. and 0.0059 in. per 100° F ΔT . (See Figure 9)

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Figure 11. TABRD Force vs De-
flection 316 SS and Mo,
Original Design

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Figure 12. TABRD Force
Output Test, 316 SS and
Mo, Original Design

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Figure 13. TABRD Calculated
Force Output Brittle Fracture
A286-Mo SNAP 10A Design

- 3) The inherent force output of this design is 103 pounds per 0.001 in. deflection nominally, while the maximum and minimum values are 114 and 88 lb per 0.001 in. deflection.

These three relationships enumerated above are combined and presented in Figure 14 which encompasses the entire operating band of the new SNAP 10A TABRD.

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Figure 14. SNAP 10A TABRD - Theoretical Relationship of Operating Parameters, Force vs Deflection vs Temperature Drop

To determine the amount of plastic yielding in the bolt, and the amount of initial lag, stress-strain maximum and minimum curves were plotted from test data for the Rene' 41 bolts as shown in Figure 15. Note that the initial lag in the bolt threads can be as much as 0.002. Also note that the bolt appears to become stronger when the applied load is approximately 90,000 psi; however, above 160,000 psi this added strength is lost. Different notch configurations will produce strengthening at different stress levels.

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The initial lag and the plastic yielding values are combined with the force vs ΔT data of the TABRD as shown in Figure 16. Figure 16 also shows the bolt rupture strength as a cross plot. The point at which the curves cross is the predicted operating area for the new SNAP 10A TABRD. In summary, Figure 16 predicts that the bolt will rupture after a temperature drop of at least 170°F but not more than 440°F measured from the arming temperature. The most probable ΔT at rupture is 305°F. This present SNAP 10A design is shown in Figure 17.

Initial testing was begun on this SNAP 10A reference design. First, tests were conducted to determine if the arming temperature, after once being adjusted, would remain constant. The TABRD was adjusted to arm at a NaK line temperature of 870°F and the adjusting collar was pinned in place. A safety spring was installed over the notched bolt to prevent rupture during the cooling part of the temperature cycling. The NaK line on which the TABRD was attached was heated three times in vacuum to 1000°F and the various temperatures were recorded at the instant of arming, as shown below.

	<u>Temperatures (°F)</u>		
	<u>TEST I</u>	<u>TEST II</u>	<u>TEST III</u>
NaK Line	850	870	850
TABRD Outer Tube	803	845	845
TABRD Inner Rod	625	655	650

These data show that, once set, the arming temperature is repeatable. However, a large temperature difference exists between the NaK line and the inner rod of the TABRD. The outer tube effectively shields the inner rod from the heat. TABRD operation relies upon the high α material - inner rod - undergoing the greatest possible temperature change. To improve this ability, gold covers were added over the TABRD assembly to reduce heat loss. Figure 18 shows the TABRD mounted to the NaK line with the extra covers installed. While these covers slightly improve heat transfer they are not desirable in that they make it difficult to see, inspect, adjust, and arm the TABRD.

The safety spring was removed from the bolt and tests were performed to determine the temperature drop needed to cause rupture. The TABRD was assembled and mounted to a simulated NaK line and the 180 pound

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Figure 15. TABRD Bolts Test Data - Average Stress-Strain Band Rene' 41, 750°F

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Figure 16. Expected Results Bolt Stress vs Temperature SNAP 10A Reference Design Rapid Temperature Drop

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Figure 17. TABRD Actuator Assembly

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Figure 18. Installation - TABRD

band load was applied just as in the arming tests. The NaK line contained the electrical heaters to simulate actual NaK temperatures. Photos of the test fixture and TABRD appear in Figure 19a and b. The test results show that rupture occurred after temperature drops of 300°F, 270°F, 390°F, and 400°F. Reference to Figure 16 will show all these results to be within the predicted temperature band. However, the inner rod was still more than 150°F cooler than the outer tube. Note in Figure 20, which shows the TABRD after bolt rupture, that the inner rod has "backed-out" of the outer tube approximately two inches. This is due to the elastic tension in the rod at the instant of rupture which pulls the bolt out of the band. This demonstration shows that both ends of the retaining band will release and not just the one held beyond the notch on the bolt.

3. Conclusions

Development testing showed good agreement between calculations and supporting test data in that a temperature drop of 170 to 440°F causes operation of the TABRD assembly. Numerous tests on the notched bolt have demonstrated repeatability of the load to cause rupture. This coupled with success in repeating calibration of the assembly on the reactor gives high confidence in the operation of the device.

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(a)

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(b)

7622-4504b

Figure 19. TABRD on Test Fixture

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Figure 20. TABRD After Bolt Rupture

B. ELECTRICALLY ACTUATED BAND RELEASE DEVICE (EABRD)

Reactor shutdown is initiated by release and ejection of the neutron reflectors surrounding the reactor core. Ejection of these reflectors prevents reactor startup or shuts down an operating reactor. The EABRD is one device used to shut down the reactor. An electrical signal to this device will sever the band which holds the reflector halves together. Once the band is severed, the reflectors are ejected by springs.

Three concepts were initially proposed for the electrical shutdown device. These were an explosive pin-puller, a solenoid latch, and a resistance heat switch. The explosive pin-puller concept, termed the reflector band release actuator, was chosen because of the low weight, simplicity and high temperature and radiation capability. Later, however, a newer concept, called the fusible link EABRD was investigated and became the final choice.

1. Reflector Band Release Actuator (Pin-Puller) EABRD

a. Exploding Bridge Wire Squib

The exploding bridge wire (EBW), squib-powered actuator was considered as the actuator for the pin-puller because it is an extremely effective, compact pressure generator. Two electrically-fired EBW'S were used as a power source for the one-shot band release actuator in which gas energy was converted to useful mechanical output. The primer charge, which is sensitive to temperature soak, is eliminated in this type of squib. Additionally, the high voltage firing initiation requirement makes the EBW squibs insensitive to ordinary shock, stray currents and radio frequency energy.

Requirements

The significant design requirements for the EBW squibs are given below.

- 1) The all fire current shall be 2000 vdc at $1\mu f$ with the receipt of 1.5 joules minimum.
- 2) The EBW squib shall not automatically ignite after or during exposure to 800°F for one year.
- 3) No firing shall take place with an input of 500 vdc at $1\mu f$, or 220 vac with a 30 ampere source.

- 4) When fired in a 0.179 in.³ bomb chamber, the EBW squib shall generate, within 5 msec, a pressure of not less than 2400 psi and not more than 3600 psi.
- 5) The EBW squib shall be exposed to a temperature of 800°F.
- 6) Either one or both of the EBW squibs, when fired, shall be capable of producing the required actuation energy when exposed to SNAP 10A environmental conditions.
- 7) The EBW squibs shall be used in conjunction with a firing unit which, upon command to arm, is to convert a 28 vdc input to high voltage (2000 v) and store it on a 1.0 mfd capacitor.
- 8) The EBW squibs shall accept the firing unit output of approximately 1.5 joules and convert it to energy for initiating squib explosion.
- 9) Materials used for the EBW squibs shall be compatible with SNAP 10A environmental conditions. They must withstand the radiation levels associated with one year of operation in space (Vol. I, Sect. II.)
- 10) The EBW squib cavity shall be hermetically sealed.

Design Description

Figure 21 is a photo of a sectioned EBW and shows the pyrotechnic material, two connector contacts, one bridgewire, and hermetic seals. A glass header seal within the EBW seals the cavity on the connector pin end and a metal closure disc at the aft end seals the pyrotechnic charge. The purpose of the hermetic seals is to prevent deterioration of the pyrotechnic charge, as well as to eliminate corona effect between the connector pins when electrically charged. The explosive effect in the bridgewire is based on a very high current density and a very high rate of current application. The current applied to the bridgewire heats the wire beyond its melting point in less than a microsecond. The resulting phase change causes vaporization of the wire with explosive violence, thereby initiating ignition of the relatively insensitive pyrotechnic material surrounding the bridgewire.

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Figure 21. EBW Cross-section

Test Program

A number of standard, commercial EBW squibs were obtained from Aerojet General Corp., Librascope Co., and Special Devices, Inc., for evaluation tests under expected SNAP 10A conditions. In this program, the EBW squibs were tested for pressure output at ambient, high and low temperatures; at ambient pressures and vacuum; and after gamma irradiation. Insulation resistance and gap capacitance at the initiating bridge element was measured, leak tests at the seals were performed, and auto-ignition tests were conducted. Equipment used for these tests included a variable volume bomb chamber, shown in Figure 22, which was set at the optimum band release actuator volume. It was then placed into a transit box that was equipped with a heater and dry ice air cooling system.

Table 6 indicates the EWB component materials that were used by the three manufacturers. Table 7 gives the results of the EBW squib pressure tests at a chamber volume of 0.227 in.^3 , which is the volume of the band release actuator. In the EBW pressure output tests at 700°F and ambient pressure, it was

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Figure 22. Variable Volume Bomb Chamber

TABLE 6

EBW COMPONENT MATERIALS

Component	Librascope AC-80	S. D. I. 2L42-5.1	Aerojet-General
Body	B-1113 Steel	B-1113 Steel	B-1113 Steel
Pins	Alloy 52	Alloy 52	Alloy 52
Seal	Corning 9010	Compression Glass	Compression Glass
Static Disc Ring	Type 304 Cres.	Mica	-
Closure Disc	Type 304 Cres.	Tin-plated Lead Sheet	Brass
Bushing	Mullite Ceramic	Sauereisen #31	-
Adhesive	Type A-LP Astroceram	Al Oxide suspended in Astroceram Type A	(Brass disc soldered shut)
Bridge	35% Al Powder 65% Sauereisen #7	Gold Alloy - Ney-oro-G	Tophet A
Plating	Copper Flash - Silver	Copper Flash-Tin-Hot oil fused	Nickel
Explosive	15% Al Powder 85% Potassium Perchlorate	Al Flakes, BistaneK, Mg Potassium Perchlorate Cupric Oxide	Al Cupric Oxide and Teflon, Mg
Atmosphere	Argon	-	-
Spark Gap	No spark gap, but dielectric bridge is conductive above 500 v input	Al Oxide	Al Oxide
Connector End	Mates with Physical Science TIBC-2S-C Connector		

TABLE 7
EBW SQUIB PRESSURE - VOLUME TESTS

Test No.	Test Temperature	Environment Pressure	Input Voltage (v)	Time Delay (msec.)	Volume of Chamber (in. ³)	Peak Output Pressure (psi)	Remarks
1	Ambient	Ambient	2200	3.25	0.227	3000	Librascope
2	Ambient	Ambient	2200	0.25	0.227	800	S.D.I.
3	Ambient	Ambient	2200	-	0.227	-	Aerojet no pressure rise observed within
4	Ambient	Ambient	2200	-	0.227	-	Aerojet 20 msec.
5	700° F	Ambient	2200	1.0	0.227	3500	Librascope: after 3-hr soak
6	700° F	Ambient	2200	3.0	0.227	4000	Librascope: after 6-hr soak
7	700° F	Ambient	2200	1.4	0.227	4500	Librascope: after 24-hr soak
8	700° F	Ambient	2200	1.0	0.227	4300	Librascope: after 171-hr soak
9	700° F	Ambient	2200	1.6	0.227	500	S.D.I.: after 5-min. soak
10	700° F	Ambient	2200	0.5	0.227	550	S.D.I.: after 6-hr soak
11	700° F	Ambient	2200	1.5	0.227	850	S.D.I.: after 27-hr soak
12	700° F	Ambient	2200	2.0	0.227	700	S.D.I.: after 191-hr soak
13	Ambient	Ambient	2200	0.1	0.227	1100	S.D.I.: after gamma irradiation 10 ⁶ R
14	Ambient	Ambient	2200	0.4	0.227	1050	S.D.I.: after gamma irradiation 10 ⁶ R
15	Ambient	Ambient	2200	0.8	0.227	1050	S.D.I.: after gamma irradiation 10 ⁶ R
16	Ambient	Ambient	2200	1.0	0.227	3700	Librascope: after gamma irradiation 10 ⁶ R
17	Ambient	Ambient	2200	0.5	0.227	3700	Librascope: after gamma irradiation 10 ⁶ R
18	Ambient	Ambient	2200	0.7	0.227	4000	Librascope: after gamma irradiation 10 ⁶ R
19	Ambient	Ambient	2200	0.4	0.227	1200	S.D.I.: after gamma irradiation 10 ⁷ R
20	Ambient	Ambient	2200	-	0.227	-	S.D.I.: no trace
21	Ambient	Ambient	2200	0.3	0.227	1050	S.D.I.: after gamma irradiation 10 ⁷ R
22	Ambient	Ambient	2200	0.7	0.227	4000	Librascope: after gamma irradiation 10 ⁷ R
23	Ambient	Ambient	2200	1.2	0.227	4700	Librascope: after gamma irradiation 10 ⁷ R
24	Ambient	Ambient	2200	1.7	0.227	3600	Librascope: after gamma irradiation 10 ⁷ R
25	Ambient	Ambient	2200	0.3	0.227	900	S.D.I.: after gamma irradiation 10 ⁸ R
26	Ambient	Ambient	2200	1.3	0.227	1000	S.D.I.: after gamma irradiation 10 ⁸ R
27	Ambient	Ambient	2200	2.0	0.227	900	S.D.I.: after gamma irradiation 10 ⁸ R
28	Ambient	Ambient	2200	0.3	0.227	3500	Librascope: after gamma irradiation 10 ⁸ R
29	Ambient	Ambient	2200	1.2	0.227	3700	Librascope: after gamma irradiation 10 ⁸ R
30	Ambient	Ambient	2200	2.5	0.227	3250	Librascope: after gamma irradiation 10 ⁸ R

noted that the seals of all squibs had partially melted though their function was not affected. EBW's of both Librascope and Special Devices were subjected to gamma irradiation dosages of 1×10^6 , 1×10^7 , and 1×10^8 r at a rate of 1.15×10^6 r/hr at ambient temperature and ambient pressure conditions. After this exposure, the EBW's were fired by application of a 2200 volt pulse to the bridgewire. The Librascope EBW squibs generated peak pressures of 3250 to 5700 psi and the Special Devices, Inc. EBW's had peak pressures of 900 to 1200 psi. A typical EBW squib pressure/time curve is shown in Figure 23.

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Figure 23. EBW Squib — Fired 7-28-62

These results indicated that, of the three types of EBW's tested, only the Librascope EBW's developed pressure peaks of sufficient magnitude for consideration as an energy source for the band release actuator. Nineteen Librascope EBW's squibs were tested for insulation resistance by application of 500 vdc potential, for one second, between each of the two pins and the case. The results of these tests are given in Table 8. The resistance values of the EWB's were inconsistent. Gap capacitance test results are shown in Table 9 and all values were found to be within permissible limits. In the leak test for seal integrity, the EBW Squibs were subjected to the appropriate gas pressures and the results are shown in Table 10. Three Librascope EBW's were subjected to auto-ignition tests for one week at 900°F and no auto-ignition took place. Examination, however, disclosed that physical changes had occurred in the EBWs. It was found that the glass header seals at the connector pin side had partially melted, grown and expanded in height. Since no auto-ignition had taken place during the period of high temperature exposure, an unsuccessful attempt was made to fire these EBWs by applying currents of 2200 and 2500 volts. Failure to fire was attributed to the deteriorated seals. Figure 24 shows the EBW's after exposure to auto-ignition tests at elevated

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TABLE 8

INSULATION RESISTANCE OF LIBRASCOPE AC-80 SQUIBS
(500 v for 1 second from pin to case)

Serial No.	Insulation Resistance (Mohm)	
	Pin No. 1	Pin No. 2
1	shorted	shorted
2	200,000	400,000
4	3,000	1,750
5	5,000	4,000
7	70,000	70,000
8	shorted	shorted
10	25,000	20,000
11	50,000	200,000
12	shorted	shorted
13	shorted	shorted
16	shorted	shorted
17	50,000	50,000
18	shorted	shorted
20	shorted	shorted
30	shorted	shorted
31	290,000	450,000
36	60,000	∞
37	shorted	∞
33	Insulation cracked, pins not shorted; returned to vendor.	

temperatures. The evaluation tests subjected the EBW's only to gamma radiation of a comparatively low level dosage and to no neutron radiation. Literature information has indicated that the potassium perchlorate pyrotechnic material, used for the base charge, is unstable under irradiation dosage levels of SNAP 10A environment.

b. Development of Pin-Puller

The development testing of the EBW squib-actuated reflector band release actuator (pin puller) was integrated with the EBW squib evaluation program.

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TABLE 9
GAP CAPACITANCE OF LIBRASCOPE AC-80 SQUIBS

Serial No.	Capacitance (μf)
1	63.9
2	63.9
4	63.9
5	64.0
7	63.9
8	62.2
10	64.1
11	63.2
12	63.9
13	63.9
16	63.8
17	64.1
18	63.9
20	63.9
30	63.8
31	63.2
33	63.9
36	64.0
37	63.8

The pin puller, with its test fixture, is illustrated in Figure 25 and Figure 22 shows the type of variable volume chamber used in the test. The disassembled actuator is pictured in Figure 26. Static tests determined that the force required for complete actuation was 275 pounds, maximum. Pressure/volume tests were conducted with Librascope EBW's and the pin puller, which had an adjustable volume chamber attached to it. Upon EBW firing, the piston rod of the actuator disconnected the reflector band fitting. The volume in the variable volume chamber of the pin puller was gradually increased until failure to completely release the band fittings occurred.

TABLE 10
LEAK RATE OF LIBRASCOPE AC-80 SQUIBS

Gas concentration, pressure and exposure time appropriate for sensitivity of 1×10^{-8} cc/sec (STP)			
Serial Number	Leak Rate in cc/sec (STP)	Serial Number	Leak Rate in cc/sec (STP)
1	1×10^{-6}	13	5×10^{-6}
2	$> 1 \times 10^{-8}$	16	3×10^{-6}
4	$< 1 \times 10^{-8}$	17	$< 1 \times 10^{-8}$
5	$< 1 \times 10^{-8}$	18	$< 1 \times 10^{-8}$
7	$> 1 \times 10^{-5}$	20	$> 1 \times 10^{-5}$
8	$< 1 \times 10^{-8}$	30	$< 1 \times 10^{-8}$
10	$< 1 \times 10^{-8}$	31	1×10^{-5}
11	4×10^{-8}	36	5×10^{-6}
12	3×10^{-6}	37	$< 1 \times 10^{-8}$

In this manner, the maximum volume for successful operation of the pin puller was 2.816 in.³ at 1800 psi pressure. The minimum volume was 0.227 in.³ at 3000 psi chamber pressure.

The pin puller successfully passed the following thermal cycle/vacuum tests:

- 1) Five thermal cycles of 30 to 700°F temperature. (120 minutes to heat, 75 minutes to cool)
- 2) Vacuum soak at 10^{-6} mm Hg pressure at 30°F temperature for 24 hours.
- 3) Vacuum soak at 10^{-6} mm Hg pressure at 700°F temperature for 24 hours.

The pin puller housing (less piston) was subjected to a high pressure proof test of 13,500 psi in order to check the strength of the walls. See Figure 6. Since no rupture occurred, this value represents a safety factor of 3:1 over the maximum observed pressure of 4500 psi in the assembled pin puller.

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c. Conclusions

The test results indicated that the band release actuator was suitable for flight operation. However, the squibs evaluated were off the-shelf squibs from several vendors and would have required additional development to meet the requirements of SNAP 10A. The fusible link EABRD that had been

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Figure 24. Auto Ignition Test at Elevated Temperatures

carried as a back up device was therefore given the primary emphasis and resulted in a satisfactorily operating device reported below.

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Figure 25. Pinpuller with Test Fixture

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Figure 26. Disassembled Band Release Actuator

2. Fusible Link EABRD

A second EABRD concept consisted of two concentric hollow cylinders joined together with a low melting point braze alloy and with a heating element encapsulated inside these cylinders to provide internal heat generation. This concept was designed to meet the following requirements:

- a) Operate at 28^{+1}_{-6} volts.
- b) Actuate in 5 seconds or less after voltage is applied.
- c) Operate with a maximum of 1000 watt-sec energy input.
- d) Withstand a tensile load of 165^{+15}_{-10} lb at 500°F for 1 year.
- e) Meet the general requirements of Vol I, Section II.

Figure 27 is a drawing of one of the first EABRDs built for developmental testing. This EABRD was not built to withstand the structural loads but only to check out EABRD actuation capabilities. This particular design required 12 seconds and 1400 watt-seconds energy to actuate. Additional bench testing of

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Figure 27. Feasibility EABRD Design

this design proved the concept would work but indicated development was necessary to refine the design to meet the performance and environmental requirements.

a. EABRD Heater Development

To generate enough heat to melt the braze alloy, the use of a low resistance, stable heater material was necessary. Ni-chrome (70% nickel, 30% chromium) wire was first tried because it is the most widely used heating element material and its properties are well known. The design of the heater coil incorporated a helical shape for efficient and uniform heating. The amount of ni-chrome wire needed for optimum heat generation was calculated and a quantity of test samples were fabricated. The coil test samples were potted into EABRD prototype housings and fired at 22 to 28 volts. The EABRDs actuated with good reliability at 22 v, but as the voltage was raised to 28 v, a high number of coils burned out before actuation. (See Table 11).

Seven commercial heater manufacturers were contacted as sources of counsel and as potential fabricators of the EABRD heater. Only one company

TABLE 11
COMPARISON OF PROPERTIES OF HEATER MATERIALS

Heater Material	Number of Tests	Average Time for Actuation (sec)	Average Energy Input (watt-sec)	Success* (%)	Remarks
Ni-chrome	32	6.5	1300	60	Very easy to fabricate heaters using this wire, but high number of burn-outs
Kanthal	16	6.0	1200	60	Same as nichrome
Commercial	3	9.5	1800	67	Much excess mass made energy input high
Thermocoax	5	9.0	700	60	Termination of heater wire a problem
Tungsten 30 gauge	15	5.5	900	80	Higher resistance caused slow response
32 gauge	60	4.1	820	95	Best material tested

*Indicates percent EABRDs that successfully separated.

appeared to possess the required experience and fabrication techniques required to meet specifications. However, the first tests of their heater failed to meet our maximum energy requirements and the manufacturer explained that considerable development would be required to meet the requirements. Figure 28 is a sketch of the commercially manufactured heater. The results of tests on this heater are shown in Table 11.

A Thermo-coax heater element was also tried. This is a steel-sheathed nichrome wire with MgO swaged between the sheath and the element. The advantage of this wire is that no encapsulating material is needed. The disadvantage is that power density is too low to cause rapid EABRD separation. See Table 11 for the test results.

Another heater material, Kanthal, (nickel alloyed with 25% chromium) was tried because of its higher melting point and higher power density capacity. Results of a series of tests with this material indicated more reliability than the plain ni-chrome but again a high percentage of burn-outs occurred. It was concluded that the melting point of the nickel-chromium materials was too low to use under the relatively high temperatures experienced.

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Figure 28. Watlow EABRD Heater Design

Pure tungsten was the next heater material to be tested. Tungsten has a melting point of approximately 6100°F (as opposed to 2400°F for nichrome). After considerable testing, tungsten was found to be far superior to the other heating materials. The only disadvantages of tungsten are that it readily oxidizes in air and is somewhat brittle. Since the SNAP 10A will be in the vacuum of outer space, and the heating element is operated for such a short time, the oxidation will not be a problem. Table 11 is a comparison of the properties and test results of the heater materials tried.

The SNAP 10A flight heater design drawing is shown in Figure 29. Figure 30 shows the EABRD in three stages of fabrication and Figure 31 shows the evolution of the EABRD and heater development from the conceptual design to the final design.

b. Encapsulating Material Development

The selection of an encapsulating material was based upon the three primary considerations of (1) minimum specific heat, (2) maximum thermal conductivity, and (3) maximum electrical resistivity. Of these considerations, the property of specific heat is the most critical. According to calculations, the EABRD design requires a minimum theoretical energy of 540 watt-seconds to

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Figure 29. Heater Design EABRD

FEASIBILITY DESIGN

FOLLOW-UP DESIGN

OPTIMUM DESIGN

BRAZE JOINT

1600 watt-sec
14 sec ACTUATION

HOUSING BEFORE CRIMPING

HEATER INSIDE HOUSING

COMPLETE ASSEMBLY

850 watt-sec
4 sec ACTUATION

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Figure 31. EABRD - Development Stages

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Figure 30. EABRD Fabrication Stages

heat the braze alloy to its melting point. Approximately 20% of this energy is absorbed by the encapsulating material.

Experimental results of a number of tests conducted on different materials indicate that thermal conductivity has little or no effect on the performance characteristics of the EABRD. For example, an EABRD potted with BeO required approximately the same or more time and energy to actuate as an EABRD potted with silica or asbestos materials. BeO has a conductivity of $114 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ as compared to the conductivity of approximately $1.5 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ characteristic of the other materials tested.

To find an encapsulating material which has the desired characteristics, a number of commercial materials were tested. After initial development testing it was found that most commercial materials with excellent electrical properties exhibited poor thermal properties. To achieve better thermal properties, an effort was initiated to develop a new encapsulant by combining two or more known materials. After preliminary screening tests, three such compounds were found which would meet the firing energy requirements. These compounds were asbestos cement and sodium silicate, asbestos cement and sodium phosphate, and silica powder and aluminum phosphate. Table 12 is a comparison of the test results of all the encapsulating materials tested.

The tests in Table 12 were conducted using the set-up shown in Figure 32. The EABRD was mounted in the fixture and loaded with a 20 lb dead weight. A variable dc power supply and a memo-scope to measure the current and voltage were connected to the EABRD heater lead wires. The encapsulating materials were then evaluated by comparing the electrical energy input needed to actuate each EABRD at ambient conditions. As shown in Table 12, AI-10 was the best material on the basis of energy input.

Encapsulant AI-10 is a mixture of asbestos cement and sodium silicate thinning liquid in the proportion of five parts by weight of asbestos to one part by weight of liquid. By a "cut and try" method, the best curing time and temperature for this compound was found to be 240°F for 30 minutes in air. This curing procedure produces a strong cement with good electrical resistance.

TABLE 12
COMPARISON OF ENCAPSULATING MATERIALS

Code Name	Commercial Name	Composition	Number of Tests	Average Time for Actuation (sec)	Average Energy Input (watt-sec)	Ease of Application*
AI-11	Asbestos and Saureisen 7	Magnesium and sodium phosphate	10	4.5	900	Good
AI-10	Asbestos and Saureisen 14	Magnesium and sodium silicate	40	4.1	820	Good
AI-7	Thermoplaze and P solvent	Mica and aluminum phosphate	15	4.7	950	Good
AI-6	Thermoplaze and Saureisen 14	Mica and sodium silicate	15	5.0	1000	Excellent
AI-5	PBX powder and P solvent	Silica and aluminum phosphate	20	5.0	1000	Excellent
AI-4	Aluminum oxide	Aluminum oxide	5	5.5	1100	Fair
AI-3	Beryllium oxide	Beryllium oxide	8	6.0	1200	Fair, hazardous
AI-2	Zircon	Zirconium	4	5.0	1000	Poor

*Ratings are based on how well the materials mixed, how well they adhered to the heater wire, and how well they adhered after bake-out.

After conducting the performance tests on all of the encapsulating materials listed in the table, five materials were chosen for thermal endurance tests. The purpose of this test was to evaluate the electrical characteristics of these materials as a function of temperature, vacuum, and time. The test samples were laboratory fabricated EABRDs with a uniform thickness of encapsulant of 0.005-in. Figure 33 illustrates electrical resistance as a function of time for each material tested. The equipment and the test samples mounted in the fixture are shown in Figure 34.

As Figure 33 indicates, AI-10, 11 and 7 degraded only slightly in resistance in 200 hours. AI-5 considerably degraded and AI-6 did not degrade with time but degraded significantly with temperature. At the end of 210 hours, each test sample was removed from temperature and vacuum, mounted in the fixture shown in Figure 32, and fired with 28 volts dc. All five materials were successfully actuated, as is shown in Figure 35.

From the results of the performance bench tests and the thermal endurance tests, AI-10 was chosen as the original flight design encapsulating material.

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Figure 32. EABRD Actuation Test Setup

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Figure 33. EABRD Electrical Insulation Resistance vs Temperature

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Figure 34. EABRD Vacuum Test Fixture

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Figure 35. EABRD Environmental Performance Test 3, Fired at Atmospheric Conditions

During fabrication of the EABRD heaters, a critical problem developed. It was discovered that the sodium silicate-asbestos (Al-10) encapsulating material was chemically attacking the flexible sleeving during bake-out, causing the sleeving to become brittle and prone to cracking.

Two approaches were taken to solve this problem. The first was to substitute an encapsulating material which would not attack the sleeving and the second was to completely redesign the heater to eliminate the flexible sleeving. Three encapsulant compounds were tested, using various bake-out cycles. Table 13 shows the results of these tests. Of the three compounds, PBX-alkophos attacked the sleeving the least. All three showed about equal thermal properties.

Due to the unpredictability of the chemical attack of the first approach, the decision was made to completely redesign the heater assembly. This new

TABLE 13

TESTING OF EABRD BOBBIN AND ENCAPSULATION MATERIALS

Test Number	Housing Material	Heater Core	Potting	Load (lb)	Temperature (°F)	Air Vacuum	Time	Energy (watt-sec)
1	17-7	Bobbin	Alkaphos + ASB	5	500	Air	4.0	860
2	17-7	Bobbin	PBX	5	500	Air	4.5	1230
3	17-7	Bobbin	PBX	5	500	Air	4.8	1290
4	17-7	Sleeving	Alkaphos + ASB	180	500	Vacuum	4.2	940
5	17-7	Sleeving	Alkaphos + ASB	180	500	Vacuum	4.0	828
6	17-7	Bobbin	Alkaphos + ASB	5	500	Air	4.0	990
7	17-7	Bobbin	Alkaphos + PBX	5	500	Air	4.0	1090
8	17-7	Bobbin	Alkaphos + PBX	5	500	Air	4.0	1020
9	17-7	Sleeving	Alkaphos + PBX	5	500	Air	3.3	820
10	Rene-41	Bobbin	PBX	5	500	Air	6.2	~
11	Rene-41	Bobbin	Alkaphos + PBX	11	500	Air	5.3	~
12	17-7	Bobbin	Alkaphos + PBX	11	500	Air	3.8	1080
13	Rene-41	Bobbin	Alkaphos + PBX	11	500	Air	4.3	~
14	Rene-41	Bobbin	Alkaphos + PBX	60	500	Air	2.6	690
15	Rene-41	Sleeving	Alkaphos + ASB	100	500	Vacuum	3.6	871
16	17-7	Sleeving	Alkaphos + ASB	100	500	Vacuum	3.0	726
17	Rene-41	Bobbin	Alkaphos + PBX	100	500	Vacuum	6.7	911
18	Rene-41	Bobbin	Alkaphos + PBX	100	500	Vacuum	3.0	720

heater design differs from the previous design in the following ways:

- 1) A rigid bobbin replaces the flexible sleeving.
- 2) The heater coil wire is terminated with a weld-cup.
- 3) An alternate encapsulating material is used.

The rigid bobbin design is shown with a heater coil in Figure 36. The bobbin is machined from unfired lavite and then fired to produce a hard surface. The first advantage of a rigid bobbin is that it simplifies the fabrication of the heater. The original flight design EABRD heater must be wound undersize and allowed to spring back to the correct diameter. The second advantage of the bobbin is that it offers a positive means of separating the coils, thus reducing the chance of a short circuit.

Due to the difficulty of terminating tungsten wire by brazing, a method of weld termination was designed. This method consists of crimping the tungsten

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Figure 36. Bobbin Heater Assembly

wire into a hollow copper collar. The collar is then percussion welded to the lead wire, as shown in Figure 37.

After extensive testing, the results of which are shown in Table 13, the bobbin heater was made the primary flight design and the flexible sleeving heater was made an alternate design.

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Figure 37. Heater Wire Termination

c. Structural Design and Development

As discussed earlier, the EABRD is required to withstand a structural load of 165^{+15}_{-10} lb during the shock and vibration of launch and at 500°F for one year after launch (during reactor operation). Also, the EABRD structure, including the braze joint, has a limitation of 0.1% creep in 10,000 hours. In addition to these requirements, the following factors were taken into consideration in the EABRD design:

- 1) Weight or mass
- 2) High temperature tensile and creep strength
- 3) Machinability
- 4) Weldability
- 5) Brazability

(1) Original Design

The original EABRD design consisted of two sections of 17-7 PH stainless steel tubing brazed together in an overlap fashion. One end of the tubing was crimped and butt-welded to a flat washer, and the other end was welded to a flat washer, and the other end was welded to a clevis. 17-7 PH stainless steel was selected for its high tensile and creep strength, its good braze and weld properties, and its availability in tubular form. To minimize the mass, which in turn would minimize the energy required to heat the EABRD, the device was welded rather than machined. Due to fabrication problems, the clevis weld was eliminated and a machined section substituted.

Incusil 15 was chosen as the braze material. This alloy is composed of 61% silver, 24% copper, and 15% indium. Incusil 15 was chosen primarily because of its melting point, 1350°F, and its high temperature tensile and creep strength. Because there is very little braze materials strength data available, the braze joint design was based on the results of tests conducted on flat, lap joints. These lap joints were designed for use on the SNAP 10A re-entry band and were brazed with Incusil 15. Figure 38 shows the calculated stress distribution of the 17-7 PH EABRD design.

Approximately 50 developmental EABRDs were fabricated for SNAP 10A developmental testing requirements. The detailed parts were fabricated and assembled to the drawing on Figure 39. The brazing was done in a

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Figure 38. 17-7 PH EABRD Calculated Stress Distribution @ 500°F

hydrogen furnace and the brazing surfaces were nickel-plated to facilitate wetting. Since there was a considerable amount of uncertainty in the brazing technique, the EABRDs were brazed in small lots and detailed evaluations made of the joints after each braze run. Upon completion of the fabrication a complete study was undertaken to establish the quality of these parts. The conclusions of this study are enumerated below.

- Because the 17-7 PH tubing used in the fabrication was in the fully hardened condition, crimping of the welded end caused stress corrosion cracking around the weld joint.
- Pitting corrosion occurred in the tubing during fabrication due to inadequate surface protection.
- Welding of the tubes to the washers showed inadequate process or quality control causing a high number of rejections; also, welding changed the 17-7 PH physical properties.
- Satisfactory brazing was accomplished by the addition of nickel plating to the mating surfaces.

Based on the results of this study it was evident that the difficulties with weld control and base metal problems made 17-7 PH stainless steel unsuitable for use in a welded assembly.

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Figure 39. 17-7 PH EABRD Assembly

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Figure 40. EABRD Tensile Strengths

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As a further verification of this evaluation, short-term tensile tests were conducted on a number of these EABRDs. Figure 40 illustrates load as a function of temperature from 70 to 800°F. As can be seen from the figure, each EABRD tested failed in the weld zone. In comparison with the theoretical strength, these tests showed the weld joint to be approximately 50% understrength.

The evaluation clarified the need for a number of structural design changes. The first change was elimination of the weld joint by machining the EABRD out of solid bar stock rather than tubing. This change increased the mass of the EABRD but the increase was justified since strength was the more important factor.

The second change was the substitution of Rene' 41 for the 17-7 PH stainless steel. This change was recommended because the brazing temperature was higher than the aging temperature for 17-7 PH steel and caused overaging of the 17-7 PH. The optimum values for aging 17-7 PH are 1-1/2 hours and 1050°F, but brazing temperature is approximately 1400°F. These are short-time operations, but overaging results as aging time decreases with increasing temperature. The end result of brazing is an overaged material with poor physical properties. The metallurgical analysis is discussed in Vol. III, Sec. V.

The third and last major change in the EABRD design was the addition of dimples to the female section. This change was made to allow positive control of the braze clearance and to eliminate the need for "pre-placing" the braze alloy in the joint. The use of dimples allows the EABRD to be assembled before being placed in the brazing furnace. The braze alloy wire is wound adjacent to the joint and flows into the joint by capillary action. A seat at the bottom of the joint keeps the braze from flowing out the bottom. Figure 41 is a drawing of the revised EABRD design.

(2) Rene' 41 Brazed EABRD Design

Twenty-five developmental EABRDs of the Rene' 41 design were fabricated. These parts were made under critical process and quality control to avoid the problems experienced with the 17-7 PH design.

The brazing technique followed the same general pattern as before with small lots being brazed and then evaluated before going on to the next lot. Figure 42, x-rays, shows one of the first lots brazed. As the figure shows, there is a large amount of void area where the braze did not wet.

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Figure 41. Rene' 41 EABRD Design

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Figure 42. EABRD X-Rays
(Initial Braze)

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Figure 43. EABRD X-Rays
(Final Braze)

The addition of a thin silver flash over the mating surfaces improved the quality of the braze, as shown in Figure 43. However, it was found that the braze coverage was not consistent from one batch to another. Tensile tests, at temperatures up to 900°F, showed that strength of the braze joint was 300% or more in excess of the design loads. Also, satisfactory separation of the brazed halves was accomplished when the EABRD heater was energized. However, the production control difficulties in obtaining repeatable braze area, inspection for braze area and bonding between the braze material and EABRD bodies prompted the investigation of the use of a no-braze EABRD design.

(3) Rene '41 Single Tube EABRD Design

A single tube Rene '41 EABRD housing was designed to eliminate the need for brazing. In this design, band release results from rupture of the thin tube-wall when the heater is energized, as opposed to melting a brazed joint in the previous design. The experience gained from development of the previous designs was factored into the new design. Figure 44 shows the assembled EABRD and also an EABRD housing and heater before final assembly.

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Figure 44. Reference Design EABRD Assembly and Component Parts

At this time the test conditions were changed to meet the more rigid system requirements as follows:

- a) Circuit voltage: - 22 volts minimum
- b) Circuit resistance exclusive of the EABRD heater:
 - 0.69 ohms at launch condition (ambient temperature)
 - 1.69 ohms at end-of-life condition (500°F)
- c) Tensile load: -155 lb at launch condition (ambient temperature)
 - 120 lb at end-of-life condition (500°F)
- d) Time to separation after voltage is applied: -30 sec maximum
- e) Energy input: - 3000 watt-sec, maximum.

Numerous performance tests were conducted on the single tube Rene '41 EABRD design at these test conditions. The tests resulted in acceptable separation time and energy input; the maximum values obtained were 17 sec to separate with 1320 watt-sec input energy. The first few tests of this design resulted in fracture of the heater bobbin, followed by unwinding of the heater wire during EABRD separation. This mode of separation was caused by the elongation and attendant contraction of the Rene '41 tube around the bobbin just prior to fracture. This condition was corrected by reducing the bobbin diameter by 0.015 in. and potting only 25% of the bobbin length into the tube.

To determine the structural quality of the single tube design, it was subjected to a short-term tensile test. The pull-test was conducted at 700°F (140% of the expected operating temperature). Rupture of the housing occurred in the end fitting at a tensile load of 690 lb (380% of the nominal design load).

A method of supporting the heater cable to survive launch loads was investigated. Several types of cable restraining devices were installed on the single tube Rene '41 EABRD assemblies which were subjected to vibration and shock testing at the qualification test levels. EABRD assemblies without cable restraints were also tested. The electrical characteristics of the EABRD assemblies were not affected by the vibration and shock testing. However, chipping of the alumina adapter and movement between the adapter and the bobbin

were observed on EABRD assemblies without cable restraints. The most satisfactory cable restraint design was a U-bolt and back-up plate configuration which clamped the cable to the structural housing. This design eliminated the alumina adapter and encapsulated the ferrule which attached the cable armor to the heater bobbin inside the EABRD housing. A favorable feature of this design was that all potting material was contained inside the housing and would not fall into other reactor components if flaking occurred. In order to use the one-piece bobbin and the U-bolt cable restraint, the clevis portion of the EABRD housing was lengthened by 0.550 in.

d. Conclusions

The single tube Rene '41 EABRD assembly with the one-piece heater bobbin and the U-bolt cable restraint was selected as the reference design. The selection was based on the ease of fabrication, the elimination of critical process braze requirements, and the repeatability of performance data.

The heater design concept has been modified to eliminate the problems experienced in earlier designs. In comparison, the flight design heater using the bobbin has the following improvements over the earlier flexible sleeving design:

- 1) Positive separation of the heating element coils
- 2) Positive control of the heater coil diameter
- 3) A much simplified fabrication process
- 4) A more reliable method of heater wire-conductor termination
- 5) A more stable encapsulating material.

The single tube Rene '41 EABRD housing design was the result of evolution by development testing. Some of the improvements over the original design are as follows:

- 1) A higher strength material with improved stress corrosion resistance properties
- 2) A simplified fabrication process which avoids welding and critical process brazing operations
- 3) A design which is not creep sensitive at the normal operating temperature (500°F) and does not require creep-rupture testing

- 4) A positive restraint on the electrical cable, capable of surviving launch loads
- 5) Repeatable separation time and separation mode.

During the final development stages, the reference design EABRD assembly was subjected to the following tests:

- 1) Nineteen (19) firing tests
- 2) Two (2) short-term tensile tests at 700°F
- 3) Six (6) shock and vibration tests at the component qualification test levels.

On the basis of these tests the reference design EABRD appears to satisfy the final SNAP 10A system requirements.

C. FUSIBLE BAND LINK OF REFLECTOR RETAINING BAND

The reentry shutdown retaining band is essentially a thin metal band stretched around the reflector assembly, securing the two halves of the reflector to the core vessel. This band serves two primary functions: (1) it holds the beryllium reflector assembly against the reactor core during launch and normal operation and (2) it separates, due to the melting of the fusible link from reentry heating, allowing the reflector assemblies to be ejected away from the reactor core. Ejection of the reflectors away from the core allows more efficient and faster burn-up of the reactor assembly during reentry. Figure 45 shows the retaining band mounted on a simulated reflector assembly. The requirements for the fusible band are listed below.

- 1) The band is spring-loaded with a force of 165^{+15}_{-10} lb. (This load was chosen to overcome the force of the ejection springs at the bottom of the reflectors, to compensate for any creep in the band, and to retain the reflector assemblies during the shock and vibration of launch.)
- 2) The band is limited to 0.1% creep in 10,000 hr at an average temperature of 500°F.
- 3) The band and fusible link must be of optimum size and material to fail during reentry at an approximate altitude of 300,000 feet or more.

- 4) The band must meet all requirements and perform under the conditions described in Section II, Volume I.

1. Concept

The original reentry shutdown concept incorporated two basic designs. The first design was an overcenter band release mechanism which operated by thermal expansion of the band due to the sharp rise in temperature during reentry. Figure 46 shows this device mounted on a fixture for feasibility testing. A number of successful feasibility tests were conducted on this device but the design was dropped because of its shock and vibration sensitivity.

The second design consisted of a series of six brazed overlap sections which melt during reentry from the aerodynamic heating. The advantage of this design is that only one of the six joints must fail since, if a large temperature variation occurs due to tumbling of the reactor upon reentry, at least one joint will be normal to the airstream for a long enough time for the temperature to rise above the braze melting point.

2. Braze Materials

Initial development efforts on this design included refinement of calculations on reentry heating rates for the band and testing of various brazing alloys, such as silver copper, boron silver, and gold copper, which have melting points in the required temperature range. Very little published data existed on the yield strength, creep rate, and the high temperature vacuum compatibility of braze alloys and more complete data was necessary on the elevated temperature properties of metals which are suitable for use as a rupture link. The ideal material would have the properties of (a) constant yield strength up to the required triggering temperature and yield strength which decreases rapidly above the triggering temperature, (b) low ductility at the desired triggering temperature, and (c) no variation in yield strength and ductility from sample to sample.

The first braze material tested was an ASTM boron-silver alloy. This alloy was unsuitable because of the high vaporization of the low-melting constituents during vacuum testing.

The second material tried was Incusil 15 an alloy composed of 61% silver, 24% copper, and 15% indium. The melting point of this alloy is approximately 1350°F. Long-term vacuum tests on this material showed negligible vaporization rates of its constituents at high temperature.

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Figure 45. SNAP 10A Band Assembly Mounted on a Reactor Mockup

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Figure 46. SNAP 10A Overcenter Band Release Mechanism

3. Band and Joint Design

The original retaining band design was made of 0.016 in. thick by 0.5 in. wide corrosion resistant 316 stainless steel. The primary consideration in the braze joint design was high temperature strength. The strength of a brazed joint in general is influenced by the factors listed below.

- a) The degree to which the materials being joined are wet by and alloyed with the brazing alloy.
- b) The thickness of the brazing alloy layer in the joint itself.
- c) The strength of the metal being joined.
- d) The amount of flux inclusions or voids in the joint.
- e) The geometry of the structure.

Factors a) and d) are dependent on the method of brazing and on the process control during brazing. The first group of lap joints fabricated for testing were torch-brazed in air using a standard brazing flux. Figure 47 is composed of x-ray photographs of three such joints showing a large amount of void area. These voids were the result of improper temperature and process control.

A carbon-electrode resistance type braze method was used in the second attempt to braze these joints. Figure 48 shows three such joints using this method. As the x-ray indicates, this method resulted in much better joints.

Thickness of the braze in the joint has a definite effect on joint strength. Joints exhibit maximum strength at a thickness of 0.001-0.002 in. However, recent research on braze joints revealed that the high temperature creep rate decreases as the thickness of the joint increases. Figure 49 shows the relationship of joint thickness to tensile and creep strength.

Joint geometry is also a significant factor in the strength of the joint. The stress distribution in a lap joint shows the highest stress occurring at the ends of the joint with the minimum stress in the center. This occurs because of the higher strain at the ends of the joint as shown in Figure 50.

Another consideration in the lap-type joint configuration is the direction of the forces. Since the principal forces are displaced from a common axis, a force couple is produced, creating a state of bi-axial stresses in the joint. For greater strength capability joint eccentricity should be kept to a minimum and the length of the braze joint should be sufficient so that resulting shear and

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Figure 47. Torch-Brazed Joint
X-rays

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Figure 48. Resistance Brazed Joint
X-rays

tensile stresses are within the allowable limits. As Figure 50 indicates, lengthening the joint does not increase the strength of the joint.

Considering the above factors, the final joint design was optimized at a length of 1.0 in. and a thickness of 0.003-0.006 in.

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Figure 49. Effect of Braze Thickness on
Creep Rate and Tensile Strength

4. Braze Joint Structural Testing

Several braze joints were fabricated to the SNAP 10A reference design and tested for short-term tensile strength. Figure 51 is a graph of tensile and yield strength as a function of temperature for seven lap joints. Test specimens were:

Band material: 304 CRES stainless steel

Braze material: Incusil 15

Cross-section area of band:
0.50 in. x 0.016 in. = 0.008 in.²

Shear area of joint:
0.50 in. x 1.0 in. = 0.50 in.²

Braze thickness: 0.001 in-0.002 in.

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Figure 50. Joint Strain Distribution

Test conditions were:

Atmosphere: Air

Leading rate: 300 lb/min

Temperature soak: 30 min

The stress at each point is based on the original area at the point of failure. The stresses below 650°F are based on the band cross-sectional area. The stresses above 650°F are based on the brazed joint shear area.

The X-rays of the joint showed a significant variation in percentage of braze coverage. The seven specimens tested were the best from a group of twelve. Shown below is a tabulation of the approximate braze coverage and strength of each specimen.

Temperature	Failure Load	Coverage
100°F	608 pounds	90%
300°F	535 pounds	80%
500°F	512 pounds	85%
600°F	408 pounds	90%
700°F	425 pounds	95%
900°F	350 pounds	70%
1100°F	225 pounds	80%

A series of stress-rupture and creep tests was conducted on the lap-joint design. Figure 52 is a Larson-Miller plot of the results of these tests. The points on the curve were obtained by measuring the stress and time to failure for a number of tests. These values were then extrapolated to 10,000 hr using the Larson-Miller equation. As the graph shows, the joint stress of 350 psi

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Figure 51. Strength of SNAP 10A Band and Joint vs Temperature

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Figure 52. Incusil - Braze Joints

for 10,000 hours is well below the curve, indicating the braze joint will not fail during the life of the reactor.

5. Conclusions

A detailed analysis was conducted to determine the exact reentry altitude and temperatures required to separate the reactor retaining band. Figure 53 is a graph of band temperature as a function of altitude obtained from this analysis. As the graph indicates, the fusible link braze joint would fail at an altitude of 330,000 feet. The steel band without a braze joint would fail at 310,000 feet. Since there is a reasonable amount of uncertainty in the structural reliability of a braze joint in a radiation environment, the decision was made to eliminate the braze joint fusible link from the band. The advantage of 20,000 feet of altitude for band separation was not worth the possibility of premature failure of the joint during reactor operation.

The final band design consists of a solid 316 stainless steel band 0.5 in. wide and 0.025 in. thick.

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Figure 53. Temperature of Fusible Link During Reentry

D. MALFUNCTION DELAY TIMER

1. Objective

The objective for the timer is to provide two functions at the end of the system life. A 1-min time base is provided which times out from the instant of receipt of a malfunction signal. It resets immediately should the malfunction signal cease before the end of one minute. Once the 1-min time base has timed out, the 1-hr time base is initiated. The 1-hr time interval serves as a delay period for the acquisition of failure data. When this time base times out, a contact closure is made which initiates reflector ejection.

2. Requirements

In addition to the General Requirement of Volume I, Section II the performance requirements for the timer are summarized below.

- a) The timer shall consist of two separate timing functions. The second timing function shall be initiated upon completion of the first timing function.

- b) The first time base shall be initiated by the application of a +28 vdc signal and shall time out after a period of 1-min ± 0.1 min. If the signal is interrupted before the completion of the 1-min period, the timer shall reset to zero time.
- c) The second time base shall be initiated by an externally applied +28 vdc signal and shall time out after a period of one hour, ± 5.0 min. Loss of power or start command shall not result in a reset to zero. Reapplication of the power shall result in a continuation of the second time base to the completion of the 1-hr period.
- d) The timer shall be capable of operation at any time during a 1-yr period.

Design requirements are summarized below:

- a) The weight of the timer shall not exceed 3.0 lb.
- b) The maximum envelope shall be 3-1/2 x 2-1/2 x 6 in.
- c) The timer shall be high vacuum sealed.
- d) The timer shall operate on unregulated 28 vdc (22 to 29.5 vdc). Power consumption shall not exceed 20 watts during the 1-min period and 10 watts during the 1-hr period.
- e) Output contacts shall be rated at 28 vdc, 2 amp resistive.

The special environmental temperature requirements are:

- a) Non-operating -30 to +140°F
- b) Operating 0 to +140°F

3. Developmental History

The first requirement was for a timer which had a single time base of 10 hours. A vendor was selected and was able to produce one prototype before the requirement was changed to a single 1-hour time base. The same vendor was, however, able to modify his design to meet the new requirement.

The basis of this design was a low frequency unijunction transistor oscillator followed by cascaded magnetic core incremental counting stages which utilized unijunction transistors to sense saturation and silicon controlled rectifiers for core resetting and for relay drivers. Figure 54 shows an early prototype of this timer.

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Figure 54. Early Prototype of Malfunction Delay Timer

A unijunction oscillator was tested in the first irradiation at the Shield Test Reactor (STR-1) and it failed at approximately 3×10^{12} nvt. Simultaneously, a literature search revealed that silicon controlled rectifiers exhibited extremely poor radiation tolerance. A prototype timer was nevertheless tested in STR-3 and, as was expected from the previous findings, it failed at approximately 2.8×10^{12} nvt. Since this timer used unijunctions and silicon controlled rectifiers throughout, it was concluded that a new design was required.

Concurrently with the STR-3 tests, the requirement for the second time base (1-min) was added. Based on available information, it was concluded that an electromechanical approach would be feasible from the standpoint of radiation tolerance. Also, since the timer was required to operate only once, it was felt that the inherent complexity of such a device would not be detrimental.

A vendor was selected and his effort was followed through design verification testing and the delivery of 19 units. After delivery, however, poor quality control and difficulties with the brushes caused the whole lot to be rejected. Modifications to cure these deficiencies and steps to insure tighter quality control

have been assured on a new procurement. This timer is shown in Figures 55 and 56.

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Figure 55. Rejected Malfunction Delay Timer

4. Final Design

The final timer design utilizes a governed dc motor driving through a gearhead, two separate gear reductions, and clutches to the 1-min and 1-hr output shafts, respectively. Figure 57 shows the schematic and cam settings for the timer.

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Figure 56. Rejected Malfunction Delay Timer, Uncovered

When power is applied to pins 1 and 2, both clutches pull in and the motor begins to run. Clutch CL-1, when energized, engages the 1-min cam shaft so that the motor drives this shaft. Clutch CL-2, when energized, disengages the 1-hr cam shaft so that it is not driven. If, at any time during the first minute of operation, power to pin 1 is interrupted, clutch CL-1 will release the 1-min shaft and it will spring back to the zero position. Only if power is applied continuously will the 1-min shaft rotate to its full timed out position. At one minute, switch SW-5 will close energizing relay K and closing contacts Ka and Kb. After an additional 20 msec, nominal, switch SW-4 will close and latch relay K1 thus deenergizing clutch CL-1 and allowing the one minute shaft to spring back to the zero position. Relay K is deenergized and contacts Ka and Kb open. (The original closing of Kb latches an external relay which then applies power to pin 7.) Application of power to pin 7 energizes relay K2 which opens contacts

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Figure 57. Reflector Ejection Delay Timer Schematic

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K2a and K2b — thus deenergizing clutch CL-2 — and which closes contact K2c, reenergizing the motor. The motor will now drive the 1 hr cam shaft. After 1-hr, switches SW-2 and SW-3 will close and momentarily thereafter switch SW-1 will open and deenergize the motor. Should power be interrupted prior to completion of the 1-hr, the cam shaft holds its position. Reenergization continues the timing sequence. Resetting is accomplished by energizing pins 8 and 13 which unlatch relay K1 and energize clutch CL-2 so that the 1-hr cam shaft can spring back to zero.

The timer draws an average of 260 mamp during the 1-min period due to the motor and the two clutches. The motor current is varied by the governor as the governor resistor is switched in and out of the line on a timed basis depending on supply voltage and motor load. At the end of the 1-min period, current climbs momentarily to an average of 300 mamp as relays K and K1 are momentarily energized. Once the 1-hr time base has started, only the motor and relay K2 draw current for an average of 120 mamp. At the end of the 1-hr period the motor is switched off and only relay K2 remains energized, drawing 75 mamp as long as pin 7 remains energized.

The timer motor is direct current permanent magnet field type with a chronometric governor which controls motor speed by switching in and out a resistor in series with the motor and thus controls current. It is rated for 22 to 29.5 volts and 150 mamp maximum running current. An RFI filter is contained within the motor housing for suppression of commutator arcing.

The clutches are rated at 28 vdc and 250 mamp maximum. The relays are radiation resistant types with coils rated at 28 vdc, 250 mamp, maximum and with contacts rated at two amps resistive at 30 vdc. The cam actuated switches are precision snap-action types; SPDT, rated at 2-1/2 amp inductive, 28 vdc, 25,000 operations. The cams are aluminum and the gears are bronze and stainless steel. The hookup wire is Raychem RT No. 22 (19) V. Lubrication is with Beacon grease 325 and Windsor-Lub 252. A literature search conducted on the suitability of these lubricants for the radiation environment indicated that they were satisfactory.

5. Testing

Design verification tests were performed on timer SN 104. These tests were performed to qualification levels in shock, vibration, and acceleration.

One thermal cycle in vacuum of 10^{-6} mm Hg from 0 to 140°F was performed. Insulation resistance and sealing tests were also performed. Performance record tests at 22, 28 and 29.5 vdc were performed after each of the above tests. Radio interference tests were not performed since documented data on previous MIL-I-26600 tests on the motor was acceptable.

Two timers have completed 90-day endurance tests. The first (SN 104) was subjected to an accelerated life test where it was cycled through its two time bases twice every six hours. Test conditions were 140°F and 1×10^{-6} mm Hg. The timer completed 860 cycles during 2580 hours of testing with no malfunctions. Variance in the time bases was less than 1%. The second timer (SN 120) was placed on a "soak" test where it was maintained, with no power applied, for 90 days. Test conditions were 80°F and 1×10^{-5} mm Hg. After the soaking period, the timer was operated and no degradation in performance was noted.

Two timers (SN 111 and 112) were irradiated to 2×10^7 r in the Co-60 source and to 3×10^{13} nvt in the STR. Performance tests were conducted during the irradiations and no malfunctions of the timers were observed. The test setup in the STR is shown in Figure 58.

6. Conclusions

Despite the successful verification of the design, numerous difficulties were experienced with production timers. Four were rejected after failing the low level vibration acceptance test. Two timers on qualification test also failed after limited testing. As a result of the failures, several timers were opened for inspection. Numerous cases of poor workmanship were noted including such things as solder splashes, split wire insulation, improperly adjusted clutches and relays, gears not staked, and faulty motor connections. These examples of poor workmanship were called to the attention of the vendor and a strict enforcement of quality control is planned for future procurements.

In addition, one basic design deficiency was discovered as a result of this testing. It was found that the carbon brushes were wearing very rapidly and that carbon material was building up excessively in the slots between the commutator bars. This buildup is shown in Figure 59. It is believed that this problem was caused by contamination of the commutator with bearing lubricant which was pulled from the bearings during the pump-down prior to back filling

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Figure 58. Timer Irradiation Test Setup

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Figure 59. Carbon Buildup

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and sealing. This lubricant on the commutator caused the carbon particles worn from the brushes to stick to the commutator and thus further accelerate wear and buildup. A new process for bearing impregnation and pump-down is planned to eliminate this problem.

Correction of the bearing problem and tighter quality control has produced a satisfactory timer. Two timers of the final design have completed 1000 cycles without degradation in performance.

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IV. DIAGNOSTIC COMPONENTS

Other special components are required to provide diagnostic information on the position status of the various components of the reflector assembly. The fine control drums are fitted with position sensors and an auxiliary demodulator in the instrument compartment to supply the telemetry system with signals to identify the angular position of the drums. Limit switches are provided on the full-out position of all drums and on the full-in position of the coarse drums to monitor the release of drums during startup.

A. POSITION SENSOR AND DEMODULATOR

1. Objectives

It is necessary to monitor the position of the SNAP 10A reactor control drums during the operating life of the system. This information provides a continuous record of reactivity changes in the reactor caused by temperature changes, fuel burnup, and/or hydrogen loss. Drum position data is also useful in diagnosis of malfunctions or failures of the drum drives or other portions of the system.

This function is accomplished by the position sensor-demodulator system. The position sensor is mounted on the reflector assembly with its rotor shaft coupled to the control drum shaft. The demodulator package supplies the sensor with regulated 400 cps ac voltage, and converts the sensor output ac signal, which varies in amplitude and phase as the drum is rotated, to a dc ramp voltage compatible with the flight vehicle telemetry system. The demodulator is mounted below the shield to protect its electronic components from severe radiation.

2. Requirements

The general requirements for the position sensor and its demodulator are outlined in Section II, Volume 1. Specific requirements are listed below in Table 14.

TABLE 14
POSITION SENSOR AND DEMODULATOR REQUIREMENTS

Requirement	System	Sensor	Demodulator
1. Angular range	135°	135°	-
2. Temperature range	-	30 to 500°F	0 to 140°F
3. Accuracy	±3%	±2.5	±0.5%
4. Linearity	-	±4% (±2% zero base)	-
5. Repeatability (as function of temperature)	-	±20 min (at fixed temperature)	±1.0% (through 0 to 140°F)
6. Repeatability (vs power supply variations)	±3%	-	±1% (with ±10% variation on 28 vdc and ±5% on 115 vac supplies)
7. Torque	-	4 in.-oz	-
8. Electrical power requirements	-	26 vrms ±1% 1ϕ 400 cps ±0.02%	2 va, 115 ±2.3 vrms 400 cps ±0.02% 1.5 w, 28 ± 0.56 vdc
9. Electrical output	-	3.8 ± 0.2 vrms 1ϕ 400 cps ±0.02% at zero and 135° electrical null at 67.5°	0 to 5 vdc in 135° (coarse) 0 to 5 vdc in 30° (fine)

3. Design Selection

Many different concepts of sensing systems were investigated and evaluated for the SNAP 10A reactor application. These are listed in Table 15 together with the advantages and disadvantages of each.

The variable reluctance concept was selected based primarily on the advantages listed above. However, considerations of cost and delivery time were also taken into account.

4. Description and Operation

a. Sensor Design and Materials

The sensor is a variable reluctance electromagnetic device and is best described as a rotary differential transformer. It consists of two main sub-assemblies, the stator and rotor. The stator contains the sensor windings and the journal bearings. There are three windings, of the simple bobbin-wound

TABLE 15

EVALUATION OF SENSING SYSTEM CONCEPTS

Type	Advantages	Disadvantages
Potentiometer	Minimum need for demodulator circuitry.	Self-welding problems with wiper-element contact.
Synchro-resolver with control transformer and servo amplifier	Relatively insensitive to temperature variations.	Complexity and weight. Self-welding problem with rotor wipers. Cost.
Variable capacitance sensor	Simplicity of construction. Ruggedness.	Possible effects due to cabling capacitance. Complex demodulation circuitry.
Digital magnetic pickup plus digital to analog converter	Simple sensor construction. Insensitive to temperature variations.	Complex and bulky electronics converter package. High system weight.
Variable reluctance sensor with ac to dc demodulator package.	Simple rugged construction of sensor (no wipers or contacts).	Sensor temperature-sensitive. Relatively complex demodulator.

type. The rotor consists of a non-magnetic shaft and a magnetic rotor shaped so that the mutual coupling between the primary and one secondary is at a maximum when the coupling with the other is at a minimum. The secondary windings are connected electrically in series with opposing polarity. A cross section of the sensor and a partially disassembled sensor are shown in Figures 60 and 61.

The magnetic portions of the sensor are fabricated of Relay No. 5 steel and 416 stainless steel. The non-magnetic portions are of titanium. The bearing surfaces on the shaft are of flame-sprayed and ground alumina, working against CDJ-83 graphite journal bearings. The bearing nearest the shaft extension is both a radial and thrust bearing. MoS_2 dry film lubricant is applied to the rubbing surfaces during the assembly process. A split-washer adjusting disc is used to establish the rotor position and the sensor null point and to insure adequate linear output range.

The windings are of ceramic insulated nickel-clad copper wire (AWG No. 32), encapsulated with phosphase-bonded ceramic potting compound. Fiberglass tape is used for coil form insulation. A high temperature electrical connector is used.

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Figure 60. Cross-Section of SNAP 10A Variable Reluctance Position Sensor

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Figure 61. Partially Disassembled Sensor Showing Belleville Spring, Adjusting Washer, and Alumina Bearing Surfaces

b. System Operation and Signal Relationships

If the sensor primary winding is excited with ac current and the rotor turned, the secondary windings (in series) produce an ac output voltage the amplitude of which varies linearly with shaft rotation. A voltage null and phase reversal occurs at the mid-point of the range, as shown in Figure 62a. However, the SNAP 10A flight test vehicle telemetry system is designed to accept only dc signals. A demodulator is, therefore, needed to convert this amplitude and phase varying ac signal from the sensor to a dc voltage proportional to drum position for telemetry input.

a. SIGNAL FROM TRANSDUCER

b. SIGNAL FROM DEMODULATOR

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Figure 62. Sensor Signal Relationships

The required output swing is 0-5 vdc. The output signal from the demodulator related to the input from the sensor is shown in Figure 62b. Note that both a coarse (full scale in 135°) and fine (full scale in 30°) output are provided. This is done to increase the sensitivity of the system in the range of drum position of greatest interest during reactor life.

Another function of the demodulator is to provide regulated excitation of the proper voltage level to the sensor.

c. Demodulator Design and Operation

The demodulator contains a voltage regulator, an ac signal amplifier, and a phase sensitive bridge demodulator, as shown in the system block diagram, Figure 63. The circuit wiring diagram is shown in Figure 64, with the functional sections indicated.

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Figure 63. Block Diagram of Demodulator

The regulator is of magnetic design utilizing a non-dissipative magnetic amplifier series regulator. The resulting third harmonic content is filtered by means of a fourth-order filter. Regulation is achieved by sensing the ac output and comparing this voltage, after rectification, to a zener diode reference source.

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Figure 64. Demodulator Wiring Diagram

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The ac input from the sensor is amplified by a 2-stage transistorized signal amplifier using a high degree of degenerative stabilization. This amplified signal is rectified and converted to a dc voltage by the phase-sensitive bridge demodulator. Adjustments are provided on the gain and output zero-level for both the fine and coarse channels.

5. Developmental History

a. Sensor

Initially, bids for complete sensory systems were solicited. Bids were received for a synchro type transmitter with control transformer and variable reluctance systems. With the decision to develop the demodulator in house a variable reluctance sensor was chosen.

The first sensors received were acceptance tested and installed on the DRM-1 reactor. Figure 65 is a photograph of the DRM-1 reactor showing the sensors installed.

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Figure 65. SNAP 10A DRM-1
Reactor Showing Position
Sensor

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Figure 66. Sensor Output vs Axial Shaft Load

Calibration and repeatability tests on the first development units showed a sensitivity of the sensor to axial shaft load. Figure 66a and b are graphs of output signal versus shaft load, both in tension and compression, for sensor No. 1007.

The test setup used is shown in Figure 67. This axial loading effect

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Figure 67. Test Setup for Axial Loading of Position Sensor

may be explained by study of Figure 60 which shows that the air gaps linking the primary to secondary windings through the rotor are changed in terms of projected area by the rotation of the shaft, but can also be changed in width by axial motion of the rotor. The much higher sensitivity to compressive load is due to the fact that, when in this condition, the only force restraining rotor motion is the Belleville loading spring, whereas, in tension, the motion is resisted by the graphite bearing.

Figure 68 shows the effect of maintaining the shaft under tension load on error band or repeatability versus error band with the shaft unloaded. In obtaining these data, an attempt was made to obtain zero shaft loading. However, the shift of the nominal signal, as well as the widening of the error band,

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Figure 68. Error Band for Loaded and Unloaded Position Sensor Shaft

indicates that some compressive loading was inadvertently obtained. Based on these results the design of the shaft coupling was modified to include a bellows type coupling and the installation procedure revised to specify that the coupling, and hence the sensor shaft, must be placed under not less than 500 grams tension.

The original mounting yoke on the reactor assembly caused difficulties in calibration of the sensors in place and resulted in excessive response of the sensor-yoke combination during vibration tests. The sensor mounting yoke was redesigned to increase its stiffness and reduce lateral motion.

The sensors mounted on the DRM-1 reactor successfully passed vibration and shock and temperature-vacuum tests. However, two sensors (SN 1011 and 1012) were found to be defective after qualification tests, due to the excessive shaft torque. A third sensor (SN 1008) was accidentally subjected to an excessively steep temperature ramp (30°F/min) during acceptance testing (specification requirement is 10°F/min). Bearing damage was also caused in this test, due to inability of the rotor axial loading Belleville spring to absorb the differential expansion between stator and rotor during this transient. As a result of these difficulties the Belleville spring was redesigned. The spring characteristics before and after redesign are shown in Table 16.

TABLE 16
BELLEVILLE SPRING CHARACTERISTICS

Design Parameter	Initial Design	Redesign
Thickness	0.014 in.	0.0065 in.
Diameter	0.70 in.	0.70 in.
Camber	0.016 in.	0.025 in.
Maximum load (flattened)	23.0 lb	7.30 lb

The redesigned springs were installed in all sensors and design verification tests were successfully rerun. A change was also made in the original torque setting (hence, in the spring load at assembly) to minimize the possibility of torque buildup due to wear.

As part of the component qualification program, two sensors were irradiated with the drum drive actuators. Figure 69 is a photograph of the irradiation fixture and components. Test conditions were 500°F and 10^{-5} mm Hg pressure. Measurements were made of sensor coil and insulation resistance, input and output impedance, and output signal vs angle.

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Figure 69. Test Setup for Irradiation Fixture and Components Pretest Checkout

In this test, two sensors operated successfully for over 2500 hours, during which time they accumulated 51 cycles through the angular rotation range. The radiation dose (integrated) was 4×10^{18} nvt (fast) and 6.5×10^9 r gamma. Insignificant variations were found in coil resistance, input and output impedance and sensor null-point and sensitivity (hence, output vs angle). The degradation of coil insulation resistance is shown in Table 17. The sensors were considered to have successfully passed this test.

TABLE 17

POSITION SENSOR COIL INSULATION RESISTANCE
DURING RADIATION TEST

Sensor	Input Winding		Output Winding	
	Start of Test	End of Test	Start of Test	End of Test
Upper	75 Megohm	2.54 Megohm	160 Megohm	2.80 Megohm
Lower	63 Megohm	19.9 K ohm	94 Megohm	23.5 K ohm

In a series of calibration tests of sensors at various temperatures, it was found that the sensor experienced zero or null point shift with temperature. Figure 70 is a representative curve showing this effect. The shift is not consistent from one sensor to the next, i. e., it may be positive, negative, or change from positive to negative through the temperature range. The inconsistency of zero shift between sensors was attributed to variation of the air gaps due to differential expansion. The variation from sensor to sensor is due to the fact that the total air gap is not necessarily divided equally between the two air gaps thus causing a variation in temperature sensitivity between the two secondary windings. The size of the zero shift indicates that the sensor temperature must be known or maintained within 100°F of that expected during measurements, to meet the system accuracy requirements.

After qualification vibration and shock tests sensor SN 1012 exhibited torque in excess of that allowed in the specification. However, due to the design of the test fixture used, the sensor received accelerations up to 200 g in this test. In development testing, sensor No. 1017 was mounted directly on the vibration table. Torque tests in air and room temperature on this unit after vibration and shock showed torque to remain within specification for up to 20 revolutions, which far exceeds the expected service even through qualification testing.

After the vibration and shock tests described above, sensor No. 1017 was installed in a vacuum chamber and tested for torque requirements at various temperatures. Acceptable values were found, as shown in Table 18.

Figure 70. Position Sensor Output Signal vs Temperature, Showing Zero Shift

b. Demodulator

Based on sensor test data and system requirements, the demodulator circuit shown in Figure 64 was designed and breadboarded. For radiation resistance, wire wound or metal film resistors were used. Only capacitors with ceramic, glass or mica dielectric were used. Data were not yet available from the transistor and diode irradiation screening tests at the time of finalization of design. The 2N736 transistor was selected for the ac amplifier based on its desirable electrical characteristics including high gain-bandwidth product, which generally indicates that the device should have good resistance to gain degradation in a radiation environment.

TABLE 18
TORQUE TEST DATA - POSITION SENSOR NO. 1017 AT 500°F

Date	Time	Breakaway Torque		Torque (oz/in.) Operational		Vacuum (mm Hg)	Temperature (°F)
		(CW)	(CCW)	(CW)	(CCW)		
4-3-64	3:00 PM	1.5	1.0	1.5	1.00	5×10^{-6}	75
4-6-64	1:00 PM	3.5	3.0	2.5	2.50	4×10^{-5}	500
4-7-64	9:00 AM	4.75	4.25	2.5	2.00	4×10^{-6}	500
4-8-64	9:45 AM	2.50	2.00	1.5	1.50	6×10^{-7}	500
4-8-64	2:45 PM	2.25	2.00	1.5	1.50	5.4×10^{-7}	500
4-9-64	10:45 AM	2.00	3.25	1.25	1.30	4×10^{-7}	500
4-10-64	9:30 AM	4.50	2.50	1.25	1.00	3.8×10^{-7}	500
4-13-64	4:00 PM	2.00	2.00	1.50	1.50	2.9×10^{-7}	500
4-14-64	2:15 PM	2.00	2.00	1.75	1.50	2.8×10^{-7}	500
4-16-64	9:00 AM	2.25	2.25	1.75	1.50	2.8×10^{-7}	500
4-20-64	8:15 AM	2.00	2.50	1.75	1.75	3×10^{-7}	500
4-21-64	10:30 AM	2.00	2.00	1.50	1.75	3×10^{-7}	500
4-22-64	2:30 PM	2.50	2.25	1.50	1.75	2.7×10^{-7}	500
4-27-64	11:00 AM	2.00	2.25	1.50	1.75	3.6×10^{-7}	500
4-29-64	1:20 PM	1.85	3.00	1.50	1.75	-	500

Electrical tests were performed on the demodulator using a sensor as input signal source and varying the ac and dc power supplies through the expected range during operation. Results of these tests are given in Table 19. The circuit met all specification requirements in these tests.

The breadboard was subjected to a temperature range of -0°F to +140°F. The overall stability of the coarse channel output was found to be within 0.08 volts (equivalent to ~2° sensor rotation). Test data are shown in Table 20.

Due to schedule requirements, fabrication of production units was initiated prior to receipt of radiation test data on the piece parts used on the demodulator breadboard. A specification and control drawings were prepared based on the breadboard circuit. These documents were released for bid covering the packaging of production units and the contract was subsequently granted.

TABLE 19

DEMOMULATOR OUTPUT VOLTAGE vs
CHANGE IN INPUT VOLTAGE

Input Voltage		Variation (%)	Output Voltage	
28 vdc Supply	115 v; 400 Supply		135°	30°
28	115	Nominal	5.0	5.0
26.6	109.25	-5%	5.0	4.95
29.4	120.75	+5%	5.0	5.10

TABLE 20

OUTPUT OF SENSOR AND DEMOMULATOR vs TEMPERATURE
(Input voltages constant)

Temperature (°F)	Sensor Output (rms)	115 v 400 cps Supply	28 vdc Supply	26 v 400 cps Regulated	135° Output (dc)	30° Output (dc)
-4	4.11	115	28	26.00	5.06	4.956
-13	4.11	115	28	26.00	5.05	4.950
-22	4.11	115	28	26.00	5.05	4.940
-30	4.11	115	28	26.00	5.05	4.934
+5	4.11	115	28	26.00	5.05	5.001
+32	4.11	115	28	26.00	5.09	5.046
+50	4.10	115	28	26.00	5.05	5.114
+68	4.10	115	28	26.00	5.05	5.182
+86	4.12	115	28	26.00	5.02	5.117
+104	4.12	115	28	26.00	5.10	5.121
+122	4.11	115	28	26.00	5.10	5.078
+140	4.11	115	28	26.00	5.10	5.084

Total coarse channel output error over temperature range of 0° to +140°F is 0.08 volts corresponding to a sensor rotation error of 2.12°. Equivalent fine channel data is 0.248 volts and 1.43°.

Subsequent irradiation tests of the 2N736 transistor showed much more severe gain degradation than had been assumed in the design of the demodulator circuit. Figure 71 is a graph of the irradiation data (gain vs nvt) showing the spread on 20 samples. Analysis of this data indicated that the stability of the

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Figure 71. Irradiation Data, Gain vs Nvt, Transistor 2N736

demodulator circuit would not meet specification requirements. Irradiation of the breadboard unit verified this fact as is shown in Figures 72a, b, c, which are graphs of output signals vs nvt (various inputs remaining constant). Table 21 summarizes the results of the analysis of the test, with regard to the sources of the degradation. At the time of this analysis, data on more radiation-resistant components were available. A design review and analysis were made, indicating that, should a redesign be made, the circuit changes and parts replacements as shown in Table 21 would be made. However, since fabrication and delivery of the flight packaged units had already started, it was decided not to redesign the demodulator. This decision was considered justified on the following technical bases:

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Figure 72. Position Sensor Output Signal vs Nvt Following Irradiation of Breadboard

TABLE 21*

RELATIVE DEGRADATION IN VARIOUS PORTIONS OF POSITION SENSOR
DEMODULATOR FOLLOWING IRRADIATION

Breakdown of Circuitry	Degradation Referenced to Fine Channel		Degradation Referenced to Coarse Channel		Components Responsible for Degradation	Replacement or Other Corrective Action
	1×10^{13} (nvt)	3×10^{13} (nvt)	1×10^{13} (nvt)	3×10^{13} (nvt)		
All sections combined Total Degradation (%)	5	35.2	2	7.2	See Below	See Below
Power supply Total Degradation (%)	4.6	12.4	7.4	20.8	1N3544 Diodes CR1 and CR2	Replace with 1N914 diodes
Amplifier Total Degradation (%)	44.4	32.6	70.6	54.7	2N 736 Tran- sistors, Q1, Q2, Q3	Replace with 2N1493 transistors and add amplifier stage. Use multipath feedback loops and bootstrapping techniques
Demodulator Output Total Degradation (%)	54	55	22	24.5	2N736 Tran- sistors, 1N3547 Diodes, Q4, Q5, Q6 and Q7	Replace CR8 bridge with two 1N914 diode in series for each 1N3547. Elim- inate Q5 and Q6 by amplifier redesign and relocating coarse control at output term

*Reference: NAA-SR-8994 Page 58

- 1) The expected radiation integrated dose at the demodulator, based on the latest isodose plot, ranges between 3×10^{12} and 1×10^{13} nvt. The most serious degradation of output occurs after 1×10^{13} nvt.
- 2) Using even the qualification level nvt figure (3×10^{13}) insignificant degradation would be observed during the 72 hour reactor stabilization period.
- 3) Since the control drums will not be moved after the stabilization period, a sensitivity ratio for determination of incremental motion when the control system is energized later can easily be obtained by comparing signal at the beginning and end of the static period.

In packaging the flight demodulators, the most critical semi-conductors were located in the most favorable position with respect to the isodose plot of the instrument compartment, i. e., against the mounting surface toward the center of the APU. Photographs of the packaged assemblies appear in Figures 73 a and b. Welded circuitry and modular construction were used.

Qualification irradiation tests were run on SN 06 and 18 showing similar results to that from developmental tests. Data on No. 06 is shown in Figure 74. Upon completion of the neutron irradiation, the average deviation from specification was approximately 0.1 volts output, which is equivalent to approximately four degrees drum rotation. Other environmental and electrical tests are now in progress.

Qualification thermal cycling and vibration and shock tests on the demodulators are now in progress.

6. Conclusions and Recommendations

The position sensing system meets the objectives for operation during the SNAP 10A flight. The information required during flight is whether the drums are moving, approximate control drum position from which radiation scatter estimates can be made, approximate control drum position from which the rate of reactivity insertion can be determined, and the changes of reactivity

3-19-63

a. Encased

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3-19-63

b. Case Removed

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Figure 73. Demodulator Flight Package

during the three-day stabilization period. The present accuracy and resolution of the system supply this information so that it is recommended that the system be used to monitor drum position on the SNAP 10A reactor.

B. LIMIT SWITCHES

1. Objective

Limit switches are required on the SNAP 10A reactor for the purpose of indicating control drum full-out and full-in position, and to indicate reflector assembly ejection at end of the life of the system. Signals from the switches are delivered to the telemetry system and transmitted to ground receiving stations for diagnostic purposes. These signals are in the form of zero-to-five volt dc voltage level changes. The circuit used to energize the switches and produce the appropriate voltage change with switching action is shown in Figure 75.

2. Requirements

Since the switches are mounted on the reflector assembly in close proximity to the reactor, they must be capable of withstanding a high radiation environment and a temperature of 700°F. Performance requirements are list as follows:

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Figure 74. Irradiation Qualification Tests on Demodulators 6 and 18
(Qualification 3.8 Vac Input After Dose of 2×10^7 r)

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Figure 75. Limit Switch Connections

a) Voltage 28 vdc unregulated.

b) Current (conducted and switched) 2 ma.

c) Load - resistive

d) Connection

Drum full-out- normally unactuated

Drum full-in-normally unactuated

Reflector half ejection-normally actuated

e) Number of actuations

Actual service 1

Qualification 1000

f) Operating Force

Switch 14 ounces maximum

Actuator 18 ounces maximum

g) Pretravel

Switch plunger 0.047 in. maximum

Actuator 0.060 in. maximum

h) Overtravel

Switch plunger 0.031 in. minimum

Actuator 0.031 in. minimum

i) Insulation Resistance - 1 Megohm at operating temperature.

j) Contact Resistance - 1.0 ohm maximum

k) Envelope Dimensions - 0.40 x 0.625 x 1.364 in.

3. Developmental History

The development program consisted of surveying commercially available switches, evaluating promising ones, modifying the designs and comprehensively testing the final designs. Several commercially available high temperature limit switches were evaluated to determine whether any appeared capable of modification to meet the environmental requirements of the SNAP 10A reactor application. The switches evaluated are listed in Table 22 together with comments on the capabilities, desirable and undesirable characteristics of each.

The V3-1301 switch, manufactured by the Microswitch Division of Minneapolis Honeywell Corporation, was selected as the most promising for

TABLE 22

LIMIT SWITCHES CONSIDERED IN PRELIMINARY SURVEY FOR SNAP 10A

Catalog No.	Manufacturer	Rated Operating Temperature (°F)	Remarks
V3-1301	Microswitch Division Minneapolis Honeywell Corp.	600	Adaptable to SNAP 10A by substitution of higher temperature, higher vacuum materials in original design.
61151	Haydon Switch Inc.	700	Both switches rejected because of early difficulties with pin to metal case potting compound.
61392	Haydon Switch Inc.	700	
1HT1	Microswitch Division Minneapolis Honeywell Corp.	1000	Size of switch exceeds allowable envelope for SNAP 10A.

development modification to meet the requirements. The switch is shown in Figure 76. It is a snap-action switch using a pre-stressed leaf spring to produce this action. A roller actuator is normally used with the switch, to prevent side loading of the plunger due to cam friction. The materials used in the unit as manufactured are:

- a) Body, cover and plunger - Supramica 550 (a glass-bonded synthetic mica).
- b) Leaf Spring - Haynes 25 alloy.
- c) Contacts - Silver
- d) All other parts - Cadmium-plated brass.
- e) Actuator - 17-7 PH stainless steel.

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7622-5538

Figure 76. Microswitch, V3-1301

Tests were conducted on the off-the-shelf switch; improvements were incorporated in the design and the modified switch was tested further.

Temperature-vacuum tests were performed on the V3-1301 to evaluate the suitability of the materials. Figure 77 is a photograph of a switch after 89 hours at 800°F and 10^{-6} mm Hg pressure.

The case material showed gross distortion. Also considerable outgassing of the cases material and contact support parts was observed. This was traced to lead and zinc in the Supramica material and to the cadmium plating on the metal parts.

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1276-5507

Figure 77. High Temperature, High Vacuum
Test of V3-1301 Microswitch

Based on these tests, the following materials replacements were made:

- a) The case, cover and plunger material was changed to Supramica 560. This material has a higher softening temperature than the 550, and does not contain the high vapor pressure contaminants found in the latter material.
- b) All metal parts with the exception of the spring were changed to type 304 stainless steel.
- c) A third change was made to minimize the possibility of contact or roller self-welding in a harder vacuum. The fixed contact was changed to PO3HT graphite, and the actuator roller to Purebond P 5N graphite.

The switch as modified was designated the V3-1302.

High temperature-hard vacuum tests were run on the V3-1302 switch (800°F and 10^{-9} mm Hg pressure). Figure 78 shows the fixture used. No out-gassing, distortion, or other degradation was observed in 350 hours of test.

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Figure 78. Limit Switch Ultra High Vacuum Test Setup

However, the case showed brittleness in that fractures occurred at the corners of some switch bodies due to mechanical stress produced by the mounting screws. Figure 79 shows a typical failure of this type.

Tests were also run at 800°F temperature in moderate vacuum (10^{-5} to 10^{-6} mm Hg). In these tests, an increase in contact resistance to approximately 1 ohm was observed, attributed to superficial oxidation of the surface of the fixed graphite contact. However, this contact resistance is acceptable, due to the high impedance of the readout circuit. The effect on output signal is negligible.

Vibration and shock tests were performed on the V3-1302 switch, with no apparent failure or degradation.

Eight V3-1302 switches were subjected to the following test sequence: Acceptance level vibration, thermal cycling in vacuum, shock, vibration and acceleration. Of the eight switches, two were found to have fractured corners on the body at the end of the shock, vibration and acceleration. Operation of the defective units was not impaired by the case breakage.

As shown in Figure 80a, the actuated switch failed when the contacts opened after 1120 hours of test. The unactuated switch successfully withstood the test. However, as shown in Figure 80b, the contact resistance was increasing rapidly near the end of the run. It is not known whether this was caused by

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Figure 79. Switch Case Failure
Due to Excessive Torque of
Mounting Screws

relaxation of the spring or accelerated oxidation of the graphite contact. The cause of its failure is not known but the actuated switch will undergo hot cell examination. However, it is known that the leaf spring is more highly stressed in the actuated position, which could have caused accelerated relaxation.

As a result of the case and cover breakage previously described, and similar difficulties encountered in mounting the switches on the reactor, an evaluation was made of possible modifications which could be made to the switch and its mounting procedure to eliminate this problem. The procedures recommended are shown in Figure 81 and are enumerated below.

- a) Milling of the corners of the cover.
- b) Manufacture and installation of alumina bushings in these corners to transmit mounting loads directly to the case rather than through the weaker cover.
- c) Replacement of the Supramica plunger with alumina.
- d) Use of 1/16 in. thick flat stainless steel plates between which the switch is held to distribute the loads imparted by the mounting screws.
- e) Use of a 1/16 in. layer of fiberglass between the metal plate and the switch.

Two switches were irradiated in the Battelle Memorial Institute reactor. One was unactuated and one was held in the actuated position. Test conditions were 700°F, and 10^{-5} mm Hg. During the 1120 hour test the switches were subjected to integrated radiation doses of 5×10^{18} nvt (fast) and 2×10^{10} r gamma. Measurements were made of insulation resistance to ground through the case and circuit resistance through the contacts. Figures 80a, b show the latter measurements.

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a. Limit Switch 105

7623-0457-2

b. Limit Switch 104

Figure 80. Electrical Contact Resistance of Limit Switches, High Flux Capsule 6 Irradiation Experiment

However, due to schedule difficulties only items d and e were implemented. As a result, breakage has been reduced but not eliminated; however, the switch function should not be affected by the breakage.

4. Conclusions

Development testing of the SNAP 10A limit switch has shown the device to be capable of withstanding the required temperature and vacuum environment. As discussed above problems were encountered in cracking of the case during installation and in contact resistance during irradiation.

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Figure 81. Revised Switch Mounting Design

Review of the switches performance in relation to their function in a SNAP 10A flight gives high confidence in their operating as intended.

It has been found that if switches are installed without causing cracks, the switches do not develop cracks in subsequent use. Switches with improved features have been procured for installation before flight if this is found necessary. Also, each switch function is redundant in being backed up by another switch or

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the position sensor. The radiation testing case some doubts on the switch performance but the test was inconclusive. Actually most switches operate during the early hours of the flights before significant irradiation.

With these conditions in mind, it is recommended that the present switches be used in the SNAP 10A flight reactor.

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