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S8DR ACTUATOR

INTERIM REPORT

AEC Research and Development Report

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

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S8DR ACTUATOR

INTERIM REPORT

By

W. G. LONG

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The author has collected and distilled the labors of a group of people. Prominent among the contributors to the development of the SNAP 8 Actuator was A. Marcus, who was responsible for the testing of the developmental models. E. L. Gardner later assumed these duties. The design of the actuator was performed by Messrs. J. Cusamano, A. Marcus, and L. E. Donelan. The developmental activity has been supervised by E. Matlin. Many other persons have contributed, to a greater or lesser degree, to the success of the actuator development. The author is especially grateful to Mr. Gardner, who served as consultant throughout this writing.

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ABSTRACT

High-temperature, radiation-resistant, rotary actuators have been developed for use in the control system of SNAP Reactors. These actuators are electromagnetic, variable-reluctance, stepping devices with integral, spring-loaded brakes. Fifteen developmental models have been built and tested to the requirements of the SNAP 8 Prototype System (S8DR). A comprehensive program has been conducted to evaluate the actuators under simulated operating conditions.

Developmental actuators have successfully performed for 10,000 hr at 1025°F, the maximum predicted service temperature for an actuator in reactor service. Two actuators performed in accordance with system requirements, when tested in an irradiation environment simulating actual operating conditions of temperature, pressure, and irradiation.

As a result of coil failures experienced at 1125°F, 100° in excess of the design temperature, modifications have been made in the coil materials. Actuators fabricated with the new materials are now in long-term testing. This latter phase of the program will be covered in the final actuator report.

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I. INTRODUCTION

Future space missions of long duration will require an electrical power source in the kilowatt range. To meet this requirement, Atomics International, under contract to the Atomic Energy Commission, has developed a series of Systems for Nuclear Auxiliary Power (SNAP) reactors. These reactors provide thermal energy which can be converted to electrical power.

The first generation of these reactor systems, designated SNAP 10A, produced over 500,000 w-hr of electrical power in 43 days of uninterrupted space operation. The advanced reactor system, SNAP 8, has a greater power capability, with resultant higher temperatures and more complex research and development problems.

The SNAP 8 reactor is designed to produce 600 kw of thermal power at 1300°F. The control system for this reactor is similar in concept to the SNAP 10A. The reactors are controlled by regulating the neutron leakage from the reactor core. This regulation is accomplished through the reactor control system by accurate positioning of the beryllium reflectors which surround the reactor core. Upon command from a programmed controller,⁽¹⁾ an electromagnetic actuator drives the reflectors through a gear train.

The control drum actuators are electromagnetic, variable-reluctance, stepping devices with integral, spring-loaded brakes. By its proximity to the reactor core, the actuator is subjected to high operating temperature and fast neutron and gamma irradiation. The operating temperatures of the reactor control components have increased with the increased power ratings of the reactor system. A comprehensive development program has been carried out to produce a highly reliable prototype actuator for the SNAP 8 Reactor System.⁽²⁾ This actuator will be tested under the operational environment during the SNAP 8 Development Reactor (S8DR) Test.

Figure 1. Tooth Alignment in Adjacent Stator Poles

II. DESIGN DESCRIPTION

A. OPERATING PRINCIPLES AND ACTUATOR FUNCTION

The S8DR actuator is an eight-pole, electromagnetic, variable-reluctance device. Torque is produced from the interaction of magnetic forces between stationary teeth on a fixed pole and notched teeth cut into a cylindrical rotor, as shown in Figure 1. As a pole is energized electrically, the rotor moves to minimize the magnetic flux flow path, producing a small rotary step. As this rotation takes place, the teeth in the adjacent pole are misaligned by one-half tooth. This position produces the maximum aligning force as the pole is energized. Thus, the maximum torque is produced for each stepping sequence.

The brake which restrains the rotor between stepping sequences operates on the tractive electromagnetic principle. The armature has a toothed ring attached which engages a mating disk attached to the rotor. The brake surfaces are coated with a sodium silicate bonded dry film lubricant to prevent adherence.

B. S8DR ACTUATOR DESIGN

An exploded view of the S8DR actuator is shown in Figure 2. This design is an improved version of the earlier actuator models. Some of the changes which have been effected in this later model to improve the actuator's performance at higher temperatures are listed in Table 1. A principal change was effected in the rotor design, when a solid rotor replaced the earlier design of a rotor pressed onto the shaft. Hiperco 27,^{*} a cobalt-iron alloy, is utilized for both the magnetic and structural members. This feature eliminates the differential thermal expansion which was a source of rotor misalignment in the SNAP 10A actuator.

The air gap between the rotor and the stator was increased to 0.008-in. from the 0.004-in. nominal clearance in the SNAP 10A machine. The 0.008-in. value was established to accommodate the maximum tolerance buildup in the actuator housing. The electromagnetic design was then developed with the 0.008-in. air gap.

The coils for the S8DR actuator stator were fabricated from 26 AWG glass-fiber insulated, chrome-plated copper conductors, alumina bobbins, and a

^{*}Westinghouse Electric Corp.

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Figure 2. S8DR Actuator

TABLE 1
DESIGN COMPARISON OF SNAP ACTUATORS

	1.8° Step Actuators			
	Permanent Magnet (S10A)	Solid Rotor Wet Wound Brake (S8DRM-1)	Solid Rotor Wet Wound Stator (S2DRM-1)	Solid Rotor Wet Wound Stator and Brake (S8DS Original Design)
Design Considerations				
Principle	Magnetic reluctance stepper			
Permanent Magnet	In rotor	None		
Electromechanical Brake	Yes	None	Yes	
Weight (lb)	4.5	5.5	5.5	15.75
Maximum Diameter (in.)	3.5	3.5	3.5	4.125
Maximum Length (in.)	7	6	6.25	8.325
General Configuration	Cylinder			
Step Size (°)	1.8	1.8	1.8	1.8
Phase — Winding Pulse Sequence*	AB	A	A	A
	BC	B	B	B
	CD	C	C	C
	DA	D	D	D
Materials				
Magnetic	Silicon steel and Alnico	Silicon steel		Hiperco
Electrical	Glass-covered copper	Glass-covered chromed copper		
Insulation	PBX†	SAP II§		
Bearings	Carbon graphite and Al ₂ O ₃			
Brake Surfaces	Al ₂ O ₃ and chrome	None		Hiperco and dry lube
Structural	Titanium	Inconel-X	Titanium	Hiperco

*A, B, C, and D refer to phase-windings for pairs of poles in clockwise sequence

[†]Commercially available high-temperature encapsulant

[§]Atomics International developed high-temperature encapsulants

phosphate-bonded encapsulating cement. The brake coils were made from the same materials, but employed 24 AWG wire. The cement, designated SAP II, was introduced in the coils by a technique called wet winding. Using this method, the glass-fiber served copper conductor is pulled through a slurry of cement. Sufficient cement is picked up to provide mechanical separation between individual turns on the coil. The cement is then cured at high temperature, forming a solid, rigid mass.

The actuator rotor turns on bearing surfaces of aluminum oxide in contact with carbon-graphite bushings. This combination of materials produces a low friction torque throughout the operational temperature range.

The system requirements for the S8DR actuator are given in Table 2.

TABLE 2
CONTROL DRUM ACTUATOR REQUIREMENTS
FOR S8DR SYSTEM OPERATION

Maximum Temperature (°F)	1025
Operating Life (hr)	12,000 (originally 10,000)
Maximum Pressure (torr)	10^{-5}
Maximum Irradiation	10^{20} nvt ($E > 0.1$ Mev) 3×10^{10} R, gamma
Thermal Cycles (Room Ambient to 1025°F)	55
Dynamic Torque (oz-in.)	37
Brake Holding Torque (oz-in.)	88
Step Size (°)	1.8
Maximum Stepping Speed	One two-step sequence/2.5 sec
Supplemental Requirements: (According to NASA Specification 417-2)	Shock, vibration, and acceleration of launch; humidity protection; storage (2 yr)

III. ACTUATOR EVALUATION

The objective of the actuator testing program was to evaluate the performance of the actuator under simulated operating conditions. Service conditions were simulated as closely as practicable. Testing was performed on actuators manufactured essentially in accordance with production drawings and specifications.

A. TEST EQUIPMENT

The equipment used in the development and evaluation of the S8DR actuator included vacuum chambers for space simulation, the test reactor facility at Battelle Memorial Institute, and shock and vibration devices. Stainless steel sheathed helical heaters provided test temperatures, and were regulated with typical laboratory controllers.

The space simulation chambers typically were glass bell jars equipped with oil diffusion vacuum pumps. One chamber employed an ionization pump. Extreme care was taken with the oil diffusion systems, to prevent contamination of the test actuators.

The test apparatus at Battelle is shown in schematic in Figure 3. Testing

Figure 3. Apparatus for Irradiation Environment Test

TABLE 3
COMPOSITE TEST RESULTS

Actuator SN	Type of Test	Temper- ature (°F)	Thermal Cycles	Time (hr)	Revolu- tions Stepped	Brake Actuations	Load Stepped (oz-in.)
1	Thermal-vacuum	1025	10	10,373	110	11,000	40
2	Thermal-vacuum	1025	10	10,373	36	3,600	40
3	Irradiation	1025	6	2,313	25	2,500	40
4	Irradiation	1025	6	2,313	44	4,400	40
5	Scram kit	900	200	13,100	13,890	1,389,000	40
6	Thermal-vacuum	1025	6	5,876	21	2,100	120
7	Shock and vibration test unit						
8	Scram kit	900	108	11,645	9,460	946,000	40
9	Startup and thermal cycle	1025	15	450	500	50,000	40
10	Startup and thermal cycle	1025	208	5,800	1,248	124,800	80
11	Startup and thermal cycle	1025	208	6,300	1,242	124,200	40
12	Scram kit	1000	111	5,270	9,890	989,000	40
13	Thermal-vacuum	1025	7	190	8	800	40
14	Thermal-vacuum	1025	1	300	5	500	40
15	Thermal-vacuum	1025	10	5,367	60	6,000	40

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was accomplished at 1000°F and 10^{-7} torr pressure in a fast neutron and gamma environment, simulating service conditions during reactor⁽³⁾ test.

Torque measuring devices included a dynamometer for room-temperature determinations, and a weight-arm arrangement for operating temperatures in vacuum. The insulation resistance and coil resistances were read on megohmmeters and Wheatstone Bridges.

B. ACTUATOR PERFORMANCE

The ability of the S8DR actuator to satisfy the design requirements has been demonstrated in bench tests, as well as in long-term operation at service temperature. Each type of test has been performed on a number of actuator units, to give a greater confidence level in the results. A total of 15 developmental S8DR actuators, as listed in Table 3, have been built and tested in this program. Most of the elevated-temperature evaluations were conducted under vacuum without irradiation, but two were carried out in an irradiation facility under vacuum. The latter simulated the actual service environment.

The actuator has also been subjected to the stresses of shock and vibration expected in launch. Three units were incorporated into a scram test assembly, and four units were tested in a consecutive startup and thermal cycle performance mode.

1. Actuator Torque

The relationship of output torque to field current is shown in Figure 4 for room ambient conditions. These curves represent the average performance characteristics of 28 actuators, including 15 developmental and 13 production units. A field current of 4.8 amp at 28 v produces a dynamic torque of ~400 oz-in. at 78°F. The dynamic torque, as shown, is ~70% of the peak (static) torque over the normal output range. These bench readings were taken with a precision dynamometer, as shown in Figure 5.

A different technique was required for relating torque to field current in the vacuum and temperature environment. The method used involved attaching a weight to the actuator shaft; for these determinations, a weight providing either 40 or 80 oz-in. was employed. An S8DR actuator with this arrangement, located in a vacuum-temperature chamber, is shown in Figure 6.

Figure 4. Actuator Torque

Figure 5. Torque
Measurement With
Dynamometer

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Figure 6. Weight Arm Attached
to Actuator Shaft

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The weight and arm, in this photograph, are in a horizontal plane. With the weight in this position, current was impressed on the field coils to produce a stepping action. The current was gradually reduced until the stepping action could not be accomplished, and the weight and arm fell free. The minimum current which would step the motor with the weight in the 90° position was recorded. The values of current produced in this manner have been very reproducible, and show no significant change with time at temperature. A set of values is given in Table 4 for Actuator SN 011, which was typical for all of the actuators tested.

TABLE 4
PERFORMANCE VARIATION OF ACTUATOR SN 011

Test Condition	Start of Test		After 200 Thermal Cycles		After 200 Thermal Cycles Plus 5000 hr	
	78°F	1025°F	78°F	1025°F	78°F	1025°F
Minimum Current to Step Load (40 oz-in.)	1.05	0.90	1.0	0.95	1.0	0.95
Brake Pull-In Current (amp)	0.57	0.54	0.58	0.69	0.6	0.58

2. Actuator Brake Performance

The magnetic force produced in the brake must overcome the spring force of 11 to 12 lb. A design margin is required to free the brake, in the event of adhesion of the mating surfaces. In functional tests on S8DR actuators, the dry film lubricant applied to the brake surfaces has prevented any significant adherence.

The current required to release the brake of Actuator SN 011 is shown in Table 4. This performance is typical for all of the actuators tested in the development program. The design S8DR current in the brake at 1025°F is 0.9 amp. This value gives a design margin of ~50% over that which is required to effect release of the brake.

3. Endurance Tests

a. Vacuum-Temperature

As part of the reliability study, four actuators have been endurance tested at the S8DR actuator operating temperature of 1025°F in vacuum. The 10,000-hr service life has been attained at 1025°F on two units. The other two units have been at 1025°F for the times indicated in Table 5. The thermal cycles were typically between 400 and 1025°F, and were incorporated into the test schedule to simulate reactor startup and shutdown conditions.

TABLE 5
ENDURANCE TESTING

Actuator SN	Number Thermal Cycles	Time at 1025°F (hr)	Minimum Current to Step Load (amp)	Current Required to Release Brake (amp)	Average Phase Resistance at 1025°F (Ω)	Insulation Resistance to Ground (kΩ)
1	10	10,073	1.15	0.55	17.2	108
2	10	10,373	1.16	0.60	17.2	100
6	6	5,876	1.7	0.50	17.1	11
15	10	5,367	0.95	0.50	17.3	230

The following parameters were monitored, with readings taken daily at the beginning of the test and then weekly until the test was completed:

- 1) Minimum current to step 40 oz-in. load
- 2) Current required to release brake
- 3) Average phase resistance
- 4) Insulation resistance to ground.

Only the initial values are reported in Table 5. There was no significant change noted in these values during the test period. These long-term test results indicate that no significant deleterious effects are produced in vacuum at service temperature. These tests also served as a basis for evaluation of similar actuator units under irradiation at 1025°F.

Figure 7. S8DR Scram Drive Mechanism

b. In-Pile Performance⁽³⁾

The performance of two S8DR actuators was determined in pile, simulating the total environment which the actuator experiences in service. The two actuators were coupled with a position sensor and limit switches in a functional test configuration. The duration of test was 3110 hr at service temperature and 10^{-7} torr vacuum. Of this time, the test capsule containing the actuators was removed from the reactor core for ~ 800 hr, but the test temperature and pressure were maintained. Thus, 2310 hr were accumulated next to the reactor core. The accumulated irradiation levels were 1.16×10^{19} nvt ($E > 0.1$ Mev) and 3.9×10^{10} r, gamma. The design point requirements for the S8DR actuator are 10^{20} nvt ($E > 0.1$ Mev) and 3×10^{11} r maximum.

Each actuator - position sensor assembly successfully completed 61 functional operations (equivalent to 61 reactor startup cycles) during the irradiation phase of the test at 1025°F . One unit was actuated through 128 steps in each direction during each operation.

c. Scram Drive Mechanism

The S8DR control drum drive system employs the gear-reduced, 1.8° stepping actuator and a scram mechanism for each of the six control drums. This arrangement provides a means for quickly shutting down the reactor by outward rotation of the control drum. The actuator's function is to wind up a torsional spring in the scram mechanism, as well as to rotate the drum. The spring is held by an electromagnetic, toothed clutch. Scramming occurs when electrical power to the clutch is interrupted and the spring rotates the control drum outward. The test assembly is shown in Figure 7.

The actuator must produce ~ 37 oz-in. of dynamic torque to complete the winding of the scram spring. The performance of these actuators is demonstrated in the data of Table 6.

d. Consecutive Startup and Thermal Cycle

Two S8DR actuators have been evaluated in a schedule which simulates reactor startup. The test mode is as follows:

- 1) The actuator is stepped to effect the equivalent of the drum rotation experienced in a reactor startup. This is accomplished in vacuum at room temperature with a 40-oz-in. or an 80-oz-in. load.

TABLE 6
ACTUATOR PERFORMANCE DURING SCRAM
MECHANISM EVALUATION

Drive and Scram Test Assembly Number	Maximum Temperature (°F)	Number Thermal Cycles	Total Time (hr)	Number Scrams	Actuator Revolutions Stepped
1	900	200	13,100	1,389	13,890
2 *	900	108	11,645	946	9,460
3 *	1000	111	5,270	989	9,890

*The tests of No. 2 and No. 3 assemblies are continuing.

- 2) The actuator is then heated to 1025° F.
- 3) The actuator is stepped again as in (1).
- 4) The actuator is allowed to cool to room temperature.

The performance of the two units tested in the development program is summarized in Table 7.

TABLE 7
STARTUP AND THERMAL CYCLE

Actuator SN	Thermal Cycles	Time (hr)	Revolutions Stepped
010	208	5800	1248
011	208	6300	1242

The stresses introduced in the actuator during thermal cycling are representative of the most destructive forces which the S8DS actuator will experience. Thermal cycles and stepped revolutions exceed the number which an S8DS actuator will be required to undergo in normal reactor service. S8DR system operational requirements call for a maximum of 55 thermal cycles during the reactor life. The number of stepping sequences is not defined.

4. Shock and Vibration

The capability of surviving the stresses of launch, as specified in NASA Specification 417-2,^{*} was one of the design objectives for the S8DR actuator. However, this capability was not a performance requirement, as the S8DR system is intended only as a ground test unit. The design objective was included to be consistent with the overall program of designing, building, and testing hardware for space application.

A preliminary determination was made on an assembly consisting of actuator coils terminated to electrical connectors. The coils and terminations withstood 5-min dwells at resonant frequencies with full 35-g inputs. This test demonstrated the integrity of the electrical wiring subsystem for the S8DR actuator.

One S8DR actuator unit was subjected to the simulated shock and vibration conditions contained in NASA Specification 417-2 and listed in Table 8. The actuator was built according to specifications, and was typical of other actuators in the test program. The test on the actuator duplicated the earlier tests on the coil assemblies, with the addition of a random vibration sequence. The Hiperco 27 rotor fractured close to a bearing area near the end of the rotor shaft during random vibration. Coincident with the fracture was the rupture of the graphite bearing in the actuator end bell. This information on performance in shock and vibration testing will be factored into future actuator designs, but did not result in any design changes in the S8DR actuator.

5. Dynamic Performance

A series of tests was conducted at room temperature on an actuator to evaluate dynamic performance under various conditions of phase overlap and pulse width. A variable input controller was used, with a dynamometer employed for loading. The results of these tests, as shown in Figures 8 and 9, indicate that:

- 1) The phase overlap may be set as low as 2-1/2 msec, with no appreciable loss in dynamic or stepping torque. The output torque will fall off as much as 50% without phase overlap (this relationship is shown in Figure 8).

^{*}"Environmental Specification for SNAP 8 Electrical Generating System"

TABLE 8
SNAP 8 ACTUATOR ENVIRONMENTAL DESIGN CRITERIA

	Storage Through Launch	Space Operation	Space Nonoperation
Shock			
Level	35 g	3.0 g	±3 g along X, Y, and Z axes
Number	3 in each direction of X, Y, and Z axes (18 total)		
Input Shape	One of the following pulses: Triangular 10 msec Half-sine 8 msec Rectangular 5 msec	Half-sine, 1 msec	One of the following pulses: Triangular 10 msec Half-sine 8 msec Rectangular 5 msec
Vibration			
Sweep	10 min logarithmic		
Number	Once in each direction		
Direction	X, Y, and Z axes	X, Y, and Z axes	Along X, Y, and Z axes
Level	16 to 100 cps, 6.0-g peak 100 to 180 cps, 0.0118-in. double amplitude 180 to 2000 cps, 19.0 g	5 to 2000 cps, 0.25-g peak	5 to 2000 cps, 0.25-g peak
Resonance			
Dwell Point	Resonance points from sweep		
Level	1/2 sweep amplitude		
Duration	5 min at each dwell point		
Random			
Number	Once in each direction, X, Y, and Z axes		
Level	20 to 200 cps at 2 db/oct 200 to 700 cps at 0.64 g ² /cps 700 to 900 cps at -17.5 db/oct 900 to 2000 cps at 0.15 g ² /cps		
Duration	5 min		
Acceleration			
Level	+7.0 g to 3.0 g along X axis +4.5 g along Y and Z axes	±1 g along X axis ±1/4 g along Y and Z axes	±3.5 g along X axis ±1 g along Y and Z axes combined
Duration	5 min		
Pressure	Sea level to 10 ⁻¹² torr vacuum	10 ⁻¹² torr or lower	
Temperature	0 to 200°F	1025°F maximum	
Humidity	20% relative humidity, maximum		
Time at Temperature and Humidity	2 years (storage)

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Figure 8. Effect of Phase Overlap on Actuator Torque

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Figure 9. Effect of Phase Overlap and Pulse Duration on Actuator Torque

- 2) A pulse duration of ~ 300 msec is required to stabilize the output torque. A minimum pulse duration of ~ 20 to 30 msec is required to produce any significant torque. With a phase overlap of 5 msec, a pulse duration as short as 58 msec will produce the design output torque required by system design (Figure 9 presents this information graphically).

The S8DR test controller supplies pulse lengths of 400 msec and a phase overlap of 50 msec.

6. Post-Test Examination

All actuators tested were subjected to a normal post-test examination. This examination consisted mainly of visual inspection of the actuator interior for material transfer or other phenomena produced in endurance testing. Following the testing of Developmental Actuator SN 005, a dimensional analysis was conducted, in addition to the visual examination. This actuator was part of the first scram mechanism tested. The test temperature was $\sim 900^{\circ}\text{F}$ for the actuator and brake. The duration of the test was $13,100$ hr at temperature, with 200 thermal cycles. This is the longest single test conducted in the actuator program.

The free standing height of the brake spring remained unchanged. The difference in dimensions of the other mechanical parts was on the order of 0.0005 in. or less, which was considered insignificant.

At the conclusion of the $13,100$ -hr test, the brake teeth of Actuator SN 005 were badly worn. Views of two segments of the teeth are shown in Figure 10. The teeth edges were somewhat damaged; in spite of this condition, the brake functioned satisfactorily in the test.

C. INSULATION AND COIL RESISTANCE

1. Insulation Resistance

The insulation resistance, as measured on an actuator, takes into account leakage through the coil leads, through the bobbin wall, and through the associated lead wiring in the space simulation chamber. The readings are taken from one coil lead to ground.

a. Segment A

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b. Segment B

7695-55180

Figure 10. Brake Teeth on Actuator SN 005

The minimum acceptable value of insulation resistance is $1\text{ M}\Omega$ at room temperature and $0.05\text{ M}\Omega$ at 1025°F . These values were established from typical values taken on previous SNAP actuators. The room-temperature value is employed principally as a quality control tool. If a newly manufactured unit fails to meet the room-temperature insulation resistance requirements, it is ordinarily an indication that a fault is present somewhere in the insulation system. Occasionally, an actuator exposed to room ambient conditions will absorb sufficient moisture to adversely affect the insulation resistance value. This defect is quickly remedied by heating to 200°F for a short time to drive off the moisture. When this treatment fails to produce the desired insulation resistance, the actuator is considered to be out of specification.

The minimum specified values far exceed the level at which actuator performance is affected. Actuators have performed at 1025°F under irradiation with insulation resistance as low as 240Ω . Typical values for insulation resistance in long-term tests at 1025°F range between $10\text{ k}\Omega$ and $1\text{ M}\Omega$.

The insulation resistance was extremely sensitive to minor amounts of hydrocarbon-type contamination. This sensitivity has been well defined in tests on developmental coils in the insulation development program.⁽⁴⁾ Sources of hydrocarbon included fingerprints, machine oils, lubricants, vacuum greases, and oil from vacuum pumps. The latter source was the most prominent offender in long-term tests conducted in chambers evacuated by oil diffusion pumps.

During manufacture, precautions were taken to minimize contamination. All parts were thoroughly cleaned. All handling was done by personnel wearing white gloves. During test, actuator units which were known to have received abnormal amounts of oil vapor deposition, due to improper or faulty operation of the vacuum equipment, showed a steady decrease in insulation resistance. The insulation resistance of one such actuator phase decreased from an initial value of $0.5\text{ M}\Omega$ at 1025°F to $11,000\Omega$ in 5876 hr of operation in vacuum. Immediately following this period, oxygen was admitted to the vacuum chamber while the actuator was maintained at 1025°F . This technique has proven effective in oxidizing contaminants and restoring high levels of insulation resistance. In this test, the insulation resistance was increased by oxidation to $33\text{ M}\Omega$.

2. Coil Resistance

The coil resistance values have remained extremely stable in all actuator endurance tests. The minor changes experienced are believed to be due to measuring errors, rather than any fundamental material change of the chrome-plated copper conductor.

IV. DISCUSSION OF PROBLEM AREAS AND DESIGN MODIFICATIONS

One of the main purposes of conducting a component development program is to optimize the component's reliability. This consideration entails periodic reviews of the design, with a goal of strengthening weak areas. During the course of the initial S8DR actuator development program, the following problem areas were discovered, and design modifications were made to the actuators tested.

A. COILS

During the fabrication of the coils for the first six of the 15 developmental actuators, coil fabrication techniques were continuously optimized. The wet-winding method of forming coils was the main area of consideration. Variables, such as wire stress during winding, termination techniques, and coil drying time, were constantly examined and improved. The prime reason for this effort was to reduce or eliminate the infantile mortality of coils. Rupture of coil wires had been experienced very early in the actuator evaluation at temperature and vacuum. Some ruptures occurred during the normal curing and thermal cycling associated with coil production. As these fabrication techniques were improved, the infantile mortality was reduced. A narrow piece of mica was originally used as a pad under the termination joint in the final turn of wire. It appeared that the pad was acting as a stress riser, with the effect that fracture of the wire was noted in a few coils. The design was changed to the present arrangement, as shown in Figure 11. The mica strip separates the final turn from the body of the coil. Following Actuator SN 006 in the development sequence, no further coil failures were experienced in actuator testing at design temperatures.

However, coil failures did occur in beyond-design-point thermal cycle testing to 1125°F. These failures led to a change in the selection of both the conductor and the encapsulating material, to provide an increased design margin. Based on accelerated thermal cycle testing of "test beds," made up of S8DR configuration phase and brake coils assembled in S8DR actuator stator and brake housings, the coils are now being fabricated of stainless-steel-clad copper wire, encapsulated with AI-1. The latter is a phosphate-bonded cement, recently developed by Atomics International. The failures referred to, as well as the

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Figure 11. Revised Method of Insulating and Protecting Stator Coil Start and Finish Lead Wires

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details of the redesign and the test results, will be documented in the final actuator report. This report discusses only the performance of the original copper-wound actuators under rated conditions.

B. ROTOR

The brittle nature of Hiperco 27 magnetic material dictates that special care be exercised in handling and assembling actuator components. The rotor, in particular, is susceptible to damage due to its geometry. Under normal handling in assembly and disassembly, no problems have arisen. Two actuator rotors fractured as a result of being dropped during actuator assembly. The fractures occurred in the rotor shaft at changes in the cross section. Although increased fillet radii would have reduced failure potential, no change was made in the design of the S8DR actuator rotor, since fabrication of the rotors had been completed.

C. CONNECTOR FEEDTHROUGH

The original design of the actuator provided for the termination of the coil wires at an electrical connector which was mounted in the actuator wall. A mating electrical connector, attached to the cable harness, served as a disconnect in the circuit. The weakness of this technique was the dependence on spring contacts to maintain continuity. At elevated temperature in long-term tests, the spring relaxation was excessive. In general, the reliability of the connector was not acceptable.

The mating connector was eliminated, and cable harness conductors were terminated directly to the receptacle pins.

D. BRAKE SURFACE COATINGS

A colloidal graphite suspension was sprayed on the brake surfaces of the early SNAP 8 actuators. The film formed acted as a cold welding preventive. However, the material used had a poor adherence, and was replaced with a sodium silicate bonded dry film lubricant (Molykote X-15)* which is extremely reliable at 1025°F. Molykote X-15 is used throughout the S8DR system to prevent cold welding and to reduce friction.

*Dow Chemical Co.

V. SUMMARY

A prototype electromagnetic rotary actuator has been designed for service at 1025°F on the S8DR system. Fifteen developmental models have been built and tested to meet the performance requirements of the S8DR system. A comprehensive program has been conducted to evaluate the actuator's performance in conditions simulating actual reactor service.

Developmental actuators have successfully performed in 10,000-hr life tests at 1025°F, the predicted service temperature on the reactor. Two units were evaluated in an irradiation environment simulating actual operating conditions of temperature, pressure, and irradiation. These two components performed in accordance with units tested out of pile for correlation.

Other functional experiments with the S8DR actuator include three units tested with the scram mechanism, and two units in a simulated reactor startup and thermal cycle mode.

Minor modifications to the design of the actuator have been made throughout the developmental phase of this program. These modifications were made to increase reliability, and were the normal changes which would be experienced in a component development program. As a result of coil failures experienced at 1125°F, 100° above reactor service temperature, changes in coil materials were made to improve the design margin of the actuator. Long-term tests are now being conducted at 1125°F to determine the design margin with the new coil materials. The final report of this series will describe the 1125°F testing, the details of the actuator redesign, and the results of long-term testing of the reworked actuator.

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