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**S8DR ACTUATOR
FINAL REPORT**

AEC Research and Development Report

Atoms International
North American Rockwell

P O Box 309
Canoga Park, California 91304

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By

L. E. DONELAN

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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.

Five actuators were built, and four of these have been tested successfully to the environmental and performance requirements of the SNAP 8 Development Reactor (S8DR) Program. These tests have been concluded; the final results are reported here.

The five actuators were modifications of the originally designed units, the testing of which has been reported previously. These modifications were made as a result of design-margin tests which were conducted at 1125°F (100°F above maximum design temperature). This report details the results of the design verification tests that were conducted on the modified actuator.

The results of the tests indicate that the modified actuators meet all environmental and performance requirements for the S8DR Program.

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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 Zirconium Hydride Reactor Systems, of which SNAP 8 represents the current hardware generation, have a greater power capability, with resultant higher temperatures.

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 that of 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 reflector drums which surround the reactor core. Upon command from a controller,⁽¹⁾ an electromagnetic actuator drives the reflector drums 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 progressively advance the art of control drum actuator design, under the SNAP Program, to meet the increasingly more stringent environmental and performance requirements.⁽²⁾ The actuator developed for the SNAP 8 Reactor system has successfully satisfied all design verification test requirements, as well as performing flawlessly under actual high-temperature nuclear reactor environment during the recently completed S8DR Test.

The first Interim Report⁽³⁾ of this series described the design and the satisfactory performance, under the design condition, of the original design S8DR actuator. The failure of some actuators to withstand the higher-temperature design margin tests, and the design modification incorporated, were discussed in the Second Interim Report.⁽⁴⁾ This concluding Final Report covers the results of the design verification tests conducted on the modified-design S8DR actuators.

II. DESCRIPTION OF THE ACTUATOR DESIGN

A. OPERATING PRINCIPLES AND FUNCTIONS

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 a distance equal to one-half of a tooth width, into position for the next step.

The brake which restrains the rotor between stepping sequences operates on the tractive electromagnetic principle. The armature, which is restrained rotationally, has an attached toothed ring which, when the brake is de-energized, engages a mating disc attached to the rotor. The brake surfaces are coated with a sodium silicate bonded dry film lubricant to prevent adherence.

B. MECHANICAL AND ELECTRICAL DESIGN

The eight equally spaced stator poles are bolted to the stator shell, capturing the coil between the shaped pole face and the shell. A nonmagnetic Inconel 600 chip shield fills the space between the poles, and fits into grooves in the end bells. The poles, shell, end bells, and rotor are all constructed from Hipercor 27,^{*} a cobalt-iron high-temperature magnetic alloy. The homogeneous construction is used to minimize the effects of thermal expansion. The actuator rotor turns on bearing surfaces of aluminum oxide in contact with carbon-graphite bushings, for minimum friction torque at operational temperature. The radial clearance between the rotor and the stator poles is a nominal 0.008 in. The carbon-graphite bushings are sized to be loaded in compression by the end bells, for temperatures through 1025°F. Design requirements for the control drum drive, and comparison to other actuators, may be found in Reference 3.

The coils for the S8DR actuator stator are wound with 24-AWG Oxalloy 28[†] wire. Oxalloy 28 consists of a copper core, clad with a chrome-iron alloy

^{*}Westinghouse Electric Corp.

[†]Sylvania Electric Products, Inc.

Figure 1. Tooth Alignment in Adjacent Stator Poles

(Type 410 stainless steel). This cladding material is bonded to the conductor, and occupies 28% of the wire cross-sectional area. The cladding will not rupture or crack under the most severe bends, providing protection for the copper core. The encapsulant used is AI-1, a phosphoric acid based cement with silica filler, developed by Atomics International. This encapsulant material is completely compatible with the cladding material, in both its liquid and its cured forms. The brake coils are wound with the same Oxalloy conductor materials, except of 20-AWG size. The actuator contains four phases, with two coils in each phase, connected in parallel.

An exploded view of the S8DR actuator is shown in Figure 2. The unit weighs 15.75 lb, and is 8.325 in. long and 4.125 in. in diameter. The actuator drives the control drum through a 13.8 to 1 stepdown gear train. The integral drive pinion can be seen on Figure 3.

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Figure 2. Exploded View of Actuator

Figure 3. Actuator After Acceptance Testing

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III. DESIGN VERIFICATION TESTS

A. PERFORMANCE

The ability of the modified S8DR actuator to satisfy the design requirements with margin was demonstrated by testing four actuators. These actuators were designated as Dev. 010, Dev. 011, Dev. 013, and Dev. 016. The previous test history on the reused mechanical parts was as follows:

<u>Actuator Number</u>	<u>Previous Test Hours</u>
Dev. 010	5,800
Dev. 011	6,310
Dev. 013	5,340
Dev. 016	10,073

Actuators Dev. 010, Dev. 011, and Dev. 013 were tested to the production acceptance test requirements after assembly and prior to endurance testing. An additional actuator, Dev. 014, was also fabricated; but it was transferred to the status of a spare actuator for the production actuators. Actuator Dev. 016 was connected with all the phase coil leads brought out external to the housing, so it could be used as a Performance Mapping Unit.

1. Performance Mapping Test

The performance mapping actuator, Dev. 016, was assembled identically to the other actuators, except for the final connection. The coils were connected to low-temperature wiring, and both coil leads of each coil were brought outside the housing. This allowed for testing in the normal arrangement, as well as allowing simulation of the effects of failures in various coils.

Development actuator Dev. 016 produced 70 and 82 oz-in. torque at its rated current of 4 amp, depending upon the direction of rotation, when tested with all phase coils energized. Testing was then performed with one coil open, two coils open, three coils open, and four coils open, with various combinations of open coil location. This included adjacent coils being open, as well as coils widely separated being open. The total range of torque values obtained

at rated current was 70 to 87 oz-in. No appreciable change of output torque or performance was detected, as long as the current to each phase was kept at a constant 4-amp value.

2. Design Verification Test

Three developmental actuators, Dev. 010, 011, and 013, were placed on a long-term design verification test at 1125°F. The test sequence for these actuators was:

- 1) 54 thermal cycles
- 2) 1000-hr endurance (includes 12 thermal cycles)
- 3) 1000-hr static dwell
- 4) 3000-hr endurance (includes 36 thermal cycles)
- 5) 1000-hr static dwell
- 6) 4000-hr endurance (includes 82 thermal cycles)
- 7) 2000-hr static dwell
- 8) 16 thermal cycles
- 9) Post-test calibration and inspection.

The thermal cycle consisted of heating the actuator from ~300°F to 1125°F, at the rate of 15°F/min, stabilizing at 1125°F, and then cooling back down to 300°F. On alternate thermal cycles, the actuator was operated at rated input current, at the speed of one step sequence (3.6° rotation) every 2.5 sec, for 25 min prior to the heatup, and again after temperature stability at 1125°F was achieved. Prior to each startup at 300 and 1125°F, the following data were recorded:

- 1) Phase and brake coil resistances
- 2) Phase and brake coil insulation resistances
- 3) Minimum phase coil to step 40 oz-in. in clockwise and counterclockwise rotation
- 4) Minimum brake coil current for brake magnet pull-in and drop-out.

The 25-min operation of the actuator at this speed is equivalent to the operation required to drive the S8DR control drum from the Full Out position to the Full In

position. The startup cycle test was conducted with 4.0 amp to the phase and 2.0 amp to the brake, up through the 3000-hr endurance phase. Subsequently, the current was increased to 5.4 amp to the phase and 2.2 amp to the brake, to correspond more closely to the output of the actual controller being used to operate the actuator on the S8DR test system.

During the endurance run, the actuator was maintained at 1125°F, except for the two thermal cycles (including 1 startup cycle) which were conducted once per week. In the static dwell phase, the actuator remained undisturbed while being maintained at 1125°F. The minimum current to the brake coil to release the mechanical brake was measured prior to, and after, the dwell period.

The test history of the three actuators is shown on Table 1. The performance of the actuators was, in general, stable and satisfactory throughout the test period, as indicated by the summary test data listed on Table 2. All units completed the testing electrically without any difficulty, verifying the expected increase in design margin. Mechanical binding in actuator Dev. 011, probably attributable to the over 6000 hr of prior testing, necessitated interim shutdown, and finally prevented the last few startup cycles.

TABLE 1
S8DR ACTUATOR DESIGN VERIFICATION TESTING
(Test status at end of testing)

Totals	Actuator Serial Number (S/N)		
	Dev 013	Dev 011	Dev 010
Test Hours	13,776	13,956	13,711
Hours at 1125°F	11,738	11,625	11,867
Thermal Cycles	201	200	201
Startup Cycles	100	97	100
Stepping Time (min)	6,250	6,062	6,250
Equivalent Revolutions of Rotor	1,600	1,552	1,600

TABLE 2
ACTUATOR PERFORMANCE AT 1125°F

	Actuator S/N	Brake Current		Stepping Current*		Insulation Resistance	
		Pull-in (amp) (min)	Release (amp) (max)	Clock- wise (amp) (min)	Counter- clock- wise (amp) (min)	Brake (M Ω)	Phase (M Ω) (min)
Start of Test	011	1.55	0.35	2.9	2.9	7.0	0.300
After 1st 1000-hr Dwell		1.80	0.35	2.9	3.1	2.0	1.3
After 2nd 1000-hr Dwell		1.62	0.32	3.2	3.1	1.5	1.4
After 2000-hr Dwell		1.44	0.32	2.5	2.5	0.0368	0.075
End of Test		1.42	0.34	2.4	2.5	0.045	0.075
Start of Test	013	1.44	0.68	3.9	2.8	7.5	5.0
After 1st 1000-hr Dwell		1.56	0.6	2.8	2.7	0.700	3.0
After 2nd 1000-hr Dwell		0.94 [†]	0.56	2.7	2.6	0.900	4.0
After 2000-hr Dwell		1.68	0.36	2.8	2.7	0.400	2.0
End of Test		1.58	0.6	2.8	2.8	0.370	2.25
Start of Test	010	1.28	0.34	3.0	3.2	10.0	0.200
After 1st 1000-hr Dwell		1.72	0.34	2.7	2.7	3.0	1.2
After 2nd 1000-hr Dwell		1.6	0.34	2.7	2.7	1.4	1.6
After 2000-hr Dwell		1.62	0.34	2.7	2.7	0.800	1.2
End of Test		1.46	0.34	2.6	2.7	0.700	1.2

*To step 40 oz-in. load

[†]Brake not fully seated during dwell

Detailed performance curves were generated as the testing proceeded. In general, only insulation and winding resistances, shown typically on Figures 4 and 5, exhibited any significant variation trends, as the test progressed. Minimum current-to-step, brake pull-in, and brake release current values remained within the constant scatter bands.

The decreasing trend of the insulation resistance may, as had been found in the past insulation tests, be due to contamination by the carbonization of oil, back streaming from the diffusion pump. The minimum recorded insulation resistance test value was $37,000 \Omega$ on S/N Dev. 011. This low value is probably attributable to low resistance in the pigtail cable, which was handled extensively during the failure investigation on this unit. This handling presents an abnormal condition which would not be present in an actual application. The value of $37,000 \Omega$ is still well above the minimum required resistance. The minimum required resistance of a power circuit is defined by the maximum allowable leakage loss. For the established leakage loss of 1%, the minimum insulation resistance is 800Ω for the brake, and 300Ω for the phase coils.

The coil resistances have increasing trends. The average of the phase resistance changes at 1125°F (12 phases, 24 connected coils) during the test period was 6.8%, with a minimum change of 3.5% and a maximum change of 10%. The average of three brake coil changes was 9.7%, with a minimum of 7% and a maximum of 11%. This increasing trend may, in part, be due to elongation and diameter reduction of the conductor by a thermal ratcheting mechanism. Ratcheting is caused during thermal cycle by the differential thermal expansions between the stainless steel cladding and the copper core of the conductor.^(4,5) Up to the design temperature of 1025°F , thermal ratcheting and coil resistance change should be negligible, as confirmed by Design Modification Proof Tests performed on sets of eight coils at 1025, 1125, and 1225°F .^(4,5) These tests, for 203 thermal cycles, indicated that the resistance changes were 0.0% for coils cycled to 1025°F , 3.3% to 1125°F , and 14% to 1225°F .

The maximum winding resistance increase measured at the cable terminals was 30%, and occurred between bench measurements taken before and after testing. As observed on other units, the ambient temperature resistance increase is always greater than the increase in resistance at elevated temperature. One explanation for this difference may be a change in grain boundary

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Figure 4.
Insulation Resistance Trend Curve

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Figure 5.
Winding Resistance Trend Curve

resistance at the different temperature. The differential thermal expansion between copper core and stainless cladding tends to cause the core to be in compression at temperature, and in tension when cooled to room temperature.

B. POST-TEST EVALUATION

1. Mechanical Investigation

a. Dev. 010

Actuator Dev. 010 was completely disassembled for inspection after testing. Visual inspection revealed a small chip in the root area of a tooth of the rotating brake disk, as shown on Figure 6. This chip deformed the crest of all teeth on the stationary flexure assembly (Figure 7). The chip appears to have been on the teeth from the start of testing, possibly as a particle covered over by the dry film lubricant applied to the brake disc. The chip has been identified by x-ray fluorescence as Hiperco 27, the brake disc material, by the relative amounts of iron and cobalt. Other than the effects of this chip, the visual inspection did not show significant evidence of wear or operational damage.

The post-test measurements on this disassembled actuator indicated all fits and clearances to be within drawing tolerances. A slight taper on the rotor, and between opposing stator poles (2 and 6), were noted. The tapers effectively decreased the minimum gap (0.008 in., nominal) between the rotor and the poles ~ 0.001 in. at the brake end.

b. Dev. 011

Actuator Dev. 011 failed to step after 3291 hr of the 4000-hr endurance phase. Failure occurred during the initial attempt to rotate the actuator at 300°F. At the time of failure, the actuator had accumulated 10,527 test hours and 151 thermal cycles, of which 74 were startup cycles. The failure appeared to be mechanical in nature, as the rotor could be oscillated $\sim 2.3^\circ$, and the coil current readings were normal; controller failure was ruled out by other tests.

Testing of the brake operation indicated the pull-in current had decreased and the drop-out current increased. This type of response would be expected for a condition in which one of the two magnetic rings on the brake magnet assembly moved to decrease travel of the brake flexure assembly (magnet

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Figure 6. Brake Disk From Actuator Dev. 010

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Figure 7. Flexure Assembly From Actuator Dev. 010

armature). Sufficient movement of the magnetic ring could prevent the complete disengagement of the brake teeth, and cause the observed binding.

To check actuator operation at elevated temperatures, the actuator temperature was raised to 700°F. At this temperature, although the brake pull-in and drop-out currents did not change, the actuator stepped normally. The binding did not reoccur when the actuator temperature was lowered to 300°F or to room ambient.

The brake was disassembled from the stepper motor, and the parts visually inspected. Because the rotor rotated freely, and no evidences of malfunction were visually evident, the stepper section was not disassembled. Inspection of the brake magnet assembly showed that two of the three tack welds on each magnetic ring were broken, and the outer brake ring had moved outward. Tests on this brake magnet assembly with a fixed armature, at temperatures to 1125°F, demonstrated that the brake ring could shift sufficiently to cause the observed actuator binding. Thus, it was concluded that the probable cause of actuator failure was the brake ring movement, which prevented the complete disengagement of the brake teeth.

The brake ring was repositioned and the retaining spot welds were made. The actuator was returned to test, and all operations were normal. After 429 hr of additional testing, including 10 thermal cycles, the actuator again failed in a mechanical mode. This failure occurred at 1125°F, at the end of the 25-min continuous run of the startup cycle. Disassembly of the actuator assembly revealed the cause of failure to be rubbing, and finally physical interference between the rotor and the stator teeth. A projection on a rotor tooth, ~0.005 in. high, located 5/8 in. from the brake end of the rotor, appeared to be the point of interference with the rotor. Both the rotor and stator were scored. The rotor was scored 360°, while the stator was scored for 180°. The minimum measured diametrical difference between the stator pole bore and the rotor was ~0.002 in. less than the design minimum due to a slight taper between opposing poles on the stator. By radial deflection measuring techniques, the diametrical clearance bearings at the brake end appeared to exceed the allowance by ~0.0004 in. It was postulated that a small protrusion had existed on the tip of a tooth on the rotor. With the loss of radial clearance, by a combination of

pole tapering, bearing clearance increase, and thermal distortion, initial rubbing took place. This rubbing became progressively aggravated, causing material distortion on both the stator and rotor, resulting in the final lockup. It is also possible that an intermediate lockup, due to this rubbing action, rather than the brake magnet ring movement, was responsible for the original failure.

After cleaning and dressing the rotor and stator, the stepper was reassembled. Detail checking of the assembly, under various conditions of shaft loading, could not re-establish evidence of rubbing. The actuator was then reassembled and reinstalled for test, and the test was resumed.

The final thermal cycle testing requires 15 thermal cycles and eight startup cycles, in order to obtain the desired 200 thermal cycles, including 100 startup cycles. During this phase of testing, after accumulating 13,885 test hours (11,603 hr at 1125°F) and 197 thermal cycles, the unit failed again. Failure occurred during the 98 startup cycle, while the minimum current to step in the counterclockwise direction at 1125°F was being determined. The remaining thermal cycles were accumulated without the last two startup cycles. Disassembly revealed that interference had reoccurred between the stator and rotor, ~1/4 in. axially closer to the brake end from the previous binding location. The visual appearance of the new interference area was the same as the previous one, and the interference particle was attached to a stator tooth. Figures 8 and 9 show views of the stator and rotor with the two distinct rub areas. Figures 10 and 11 are enlargements of the interference particle on the stator tooth and torn metal on a rotor tooth. A detailed investigation determined that the loss of rotor-stator clearance was mainly due to tilting of the stator poles and bearing wear. Tilting of the poles was evidenced by a decrease in diameter between Tooth No. 6 of opposite poles, as compared to that between Tooth No. 1 of the same set of poles, and by profile measurement along the tops of the teeth. This indicated that the poles were not well seated in the stator housing. Seating of the poles is accomplished by two machine screws and two dowel pins inserted into the base of the pole, which is 0.400 in. wide. The diameter of the contact surface between the 0.400-in. width of each pole and the housing is 3.563 in.

It cannot be determined when the distortion in the pole seating occurred. It is known that, at the time of initial machining and subsequent inspection, the stator bore and bearings were aligned and within drawing tolerances. Subsequent

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Figure 8. Stator From Actuator Dev. 011
(After test)

Figure 9. Rotor From Actuator
Dev. 011 (After test)

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Figure 10. Detail of Stator Teeth From
Actuator Dev. 011

Figure 11. Detail of Rotor
Tooth From Actuator
Dev. 011

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to that time, the poles were disassembled and reassembled with the original coils, the actuator tested for 6310 hr, and then the poles were disassembled and reassembled to replace the original coils with the redesigned coils. Checks for pole alignment were not made after initial inspection, as trouble with pole alignment had not been encountered previously.

It is likely that deformations from previous testing, disassembly, and assembly affected the alignment of the poles. Thermal stresses, induced during multiple thermal cycles, could also have caused movement of material in the high-stressed areas. Extended stepping runs (25 min) apply unequal heating to the coils and to their respective poles, and could cause further distortion. Measurements taken of the individual teeth of Actuator Dev. 010 also indicated similar variations in the stator pole tooth radius. In general, the variations were less than in Actuator Dev. 011. The wear on the graphite bearings for the rotor shaft, particularly at the brake end, was confirmed by measurement after complete disassembly. The net effect of the wear was to increase the diametric clearances as much as 0.005 in. above the design maximum of 0.002 in.

c. Dev. 013

Actuator Dev. 013 was selected for continued testing to 20,000 hr, as part of the Zirconium Hydride Reactor Development Program. In keeping with the philosophy of minimum disturbance during testing, the actuator remained undisturbed in the test chamber until the testing was restarted, on July 25, 1969.

2. Coil Electrical Investigation

The coils from Actuator Dev. 011 were selected for coil examination and evaluation. Coils removed from Phase A are shown in Figure 12. Visually, these coils appear to be in fine shape, and do not exhibit the cracking and flaking of the encapsulant associated with the elongation due to thermal ratcheting action, found on similar coils tested to higher temperatures. The average room-temperature resistance of the coils, measured at coil leads, increased 20% due to testing, while the insulation resistance decreased to $\sim 10\%$ of the pre-test value. The difference between these resistance changes and those reported earlier for the actuator assemblies (Section III-A-2) is due to the resistance changes in the pigtail cables.

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Figure 12. "A" Phase Stator Coils From Actuator Dev. 011
(After test)

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Figure 13. Conductor Wire From Actuator Dev. 011 "A" Phase Stator Coil
(After test)

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Figure 14. Lead Wire From Actuator Dev. 011 "A" Phase Stator Coil
(After test)

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Figure 15. Weld Joint of Lead Wire to Conductor From Actuator Dev. 011
"A" Phase Stator Coil (After test)

The coils of Phase A were disassembled for visual inspection and tensile testing. The visual quality of the conductor wire and lead wire was very good, being smooth and regular without appreciable change in appearance from new wires, as shown in Figures 13 and 14. The quality of the weld joints between the lead wire and conductor wires, as shown on Figure 15, also appeared very good, being of full section with no appreciable change in appearance from new welds. Tensile strengths were within the range of 12.5 to 13.5 lb, which compares very well with the value of 15.5 to 16 lb for untested conductors.

Photomicrographs showed the conductors were in good condition, showing no evidence of fracturing of the cladding material or rupture of the core material. Some distortion of the cladding material, as well as partial separation of the cladding material from the core copper, were noted.

3. Coil Burnout Tests

Actuator Dev. 011 was reassembled with the remaining three phases and brake, and prepared for the coil burnout tests at 10^{-6} Torr vacuum and 1125°F. The purpose was to determine the current-life characteristics of these coils. Various values of constant current were continuously applied to the coil until the coil failed. The results were as follows:

<u>Phase Amperes</u>	<u>Time to Initial Failure</u>
5	No failure
7	55 min
8	13 min
10	2.5 min
<u>Brake Amperes</u>	<u>Time to Initial Failure</u>
8	2.5 min

The maximum voltage reached, prior to burnup, was ~35 v for the phase coils, and 90 v for the brake coil. The winding resistance increased ~75% for the phase coils, and ~50% for the brake coil. Based upon an extension of the copper resistance curve, the average coil temperature at burnup was 2150°F for the phase coils, and 1800°F for the brake coil. The coil failure mode, as may be expected, was by local melting of the conductor, causing

Figure 16. Phase Coil Burnout

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Figure 17.
Burnout Testing

AI-AEC-12925

progressive shorting between coil turns followed by open circuit. Figure 16 is a photograph of a typical coil failure.

The coil burnout current-burnout time characteristic is shown graphically in Figure 17. The maximum continuous phase current without burnout appears to be 6.8 or 6.9 amp. Using the value of 6.8 amp, and considering that the two coils, each wound with No. 24 AWG, were connected in parallel, the maximum allowable continuous current density is 10,700 amp/in.² To account for variations between coils, and to provide a safety factor, a safe continuous rating would be 5350 amp/in.², or 3.4 amp/phase. Considering the duty cycle of a phase under continuous normal stepping to be somewhat >25% but <50%, the maximum recommended phase current for two coils in parallel is 6.8 amp. The 2.5-minute data point for 8 amp for the brake, when extrapolated in accordance with the data for the phase coils, indicates a maximum continuous brake current without burnup to be 5.5 amp. Therefore, the expected burnup density for the No. 20 AWG coil is 6900 amp/in.², indicating a reduced heat dissipation capability of this coil enclosed within the brake housing. Because the brake coil duty cycle during normal stepping is high, the maximum recommended current is 2.75 amp (its continuous rating). The design operating currents of 5.4 amp for the stator phases, and 2.2 amp for the brake, are well within the recommended maximum current ratings.

7695-55510

Figure 18. Actuator Dev. 011 in Test Chamber,
Ready for Thermal Shield

7695-55509

Figure 19. Actuator Dev. 011 in Test Chamber,
With Thermal Shield in Place

IV. METHODS USED AND DESCRIPTION OF TEST EQUIPMENT

The three actuators (Dev. 010, 011, and 013) were acceptance tested, prior to the start of these tests. Electrical readings (insulation and resistance) of the actuator windings were taken on the bench, prior to installation in the vacuum test chambers and after assembly into the vacuum test chambers. The test chambers were of the oil diffusion pumped vacuum type, with coiled sheath heaters for controlling actuator temperatures. The actuators were mounted horizontally on a test fixture, utilizing the mounting flange of the actuator. Four layers of reflective metallic thermal shielding surrounded the heater and actuator to reduce the heat loss.

A torque arm, consisting of a weight and pointer, was installed on the shaft beyond the mounting face. The weighted torque arm provided torque load on the actuator, up to 40 oz-in. Actuator temperature was measured by sheathed thermocouples attached to the outside of the actuator. One thermocouple was used to control a cam-type temperature controller. The other thermocouples were used to record temperature on multipoint recorders. Figure 18 shows Actuator Dev. 011 mounted in the test fixture, while Figure 19 shows the test setup, complete with thermal shield.

Oil diffusion pumps reduced the pressure of the test chamber well below the maximum allowable pressure of 1×10^{-6} Torr, as measured by nude ion gauges installed in the vacuum chambers. The test system was protected by interlocked electrical circuits, to prevent exposure of the test actuator to excessive temperature or high test environment pressure while at elevated temperature.

Actuator operation was controlled by an electronic laboratory controller. Operational sequence (rotation) and step rate were manually set on this laboratory controller, unlike the automatic operation of the S8DR test system controller. The controller and power supplies were mounted and moved among the actuators under test, as required to obtain the test points.

7759-40234

Figure 20. Actuator Brake From 1125° F
Test Bed S/N 002
(After 12,235-hr testing)

Figure 21.
Phase Coils From 1125° F
Test Bed S/N 002
(After 12,235-hr testing)

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V. EXTENDED TEST BED EVALUATION

The expected temperature margin of the improved S8DR actuator coil design was initially demonstrated by accelerated thermal cycle test conducted on three test bed actuators. The three units were subjected to 203 thermal cycles from 400 to 1025°F, 1125°F, and 1225°F respectively. As discussed in the previous report,⁽⁴⁾ all coils successfully passed these tests without any failure, although coils cycled to 1125°F and higher were significantly distorted.

One unit, Test-Bed No. 002, with six phase coils and the brake assembly, was tested for an additional 12,235 hr (10,264 hr at 1125°F) and 338 thermal cycles. The total test on these coils was 13,867 hr (10,568 hr at 1125°F) and 541 thermal cycles. In addition, each coil had been subjected to five thermal cycles, as a manufacturing test, after curing and prior to assembly in the test bed.

During this second phase of testing, the average 1125°F phase coil resistance changed from 4.967 to 5.004 Ω , or 0.75%, and the 1125°F brake resistance changed from 15.095 to 15.950 Ω , or 5.66%. After the first 203 thermal cycles, the average phase coil resistance change was 3.3%, and the brake coil resistance change was 1.3%. The total phase resistance change averaged 4.1%, and the total brake change averaged 7.0%. Insulation resistance of the phase coils continued to decrease during this extended test, to a minimum of $\sim 50,000 \Omega$, but the brake coil insulation increased to 26 M Ω . The total change was a decrease to 36% for the phase coils, and an increase to 520% for the brake coil.

Disassembly after the test revealed that the outer magnet ring of the brake assembly had moved outward, similar to the occurrence on Dev. 011. The magnet ring on this brake assembly had been held by shrink fit, and was not spot welded, as can be noted in Figure 20. Because the brake coil was never energized during either test, the ring movement must be attributed only to thermal action. The bench measurement of this assembly indicated a winding resistance of 5.287 Ω , and insulation resistance of 25 M Ω at 50 v.

To visually inspect the quality of this coil, the housing was machined off. The cavity was, as expected, filled with encapsulant, but the encapsulant did not adhere to the coil itself. Differential thermal expansion effects probably

accounted for the lack of bond between the coil and encapsulant. The coil was restrained from rotation by mechanical interference between the coil and the encapsulant. The coil appears to be of original quality, unaffected by the test time or thermal cycles.

The phase coils showed a definite physical effect due to the testing. As can be seen in Figure 21, the sides of the coil had pulled away from the bobbin. This is very visible in the coils from Poles 3, 4, 6, and 7. The coil from Pole 1 had a bare conductor that extended a considerable distance from the coil.

The room-temperature winding and insulation resistance of these coils were:

Pole	Winding Resistance (Ω)	Insulation Resistance (M Ω)	
		50 v	500 v
1	1.5195	650	40.0
2	1.5143	95	5.0
3	1.5457	60	6.5
4	1.5430	70	25.0
5	1.5360	22	1.5
6	1.6656	45	3.5
7	1.6589	60	4.0

Tensile testing of the conductor used in the coil from Pole 4 and the coil from Pole 7 (12 samples from each coil) was performed. The average strength of the conductor from Pole 4 was 11.6 lb, with a spread of 11.5 to 12 lb, while the conductor from Pole 7 produced an average of 12.1 lb and a spread of 12 to 12.5 lb. Tensile testing of the conductor used in the brake coil (12 samples) produced an average of 19.1 lb, and a spread of 18.5 to 19.5 lb. The average initial strength of the conductor wire used for the phase coils was 15.5 lb, with a spread of 15 to 16 lb.

The overall results of the test bed program suggest that the performance limits of Oxalloy-wound coils are determined only by thermal cycles, and not by the total time at steady temperature, at least to 1225°F. The thermal cycle limits are dependent upon the coil configuration, as noted by the post-test

appearance difference between the rectangular phase coils and the circular brake coils. The following tentative limits of Oxalloy-wound coils are recommended:

<u>Operational Condition</u>	<u>Rectangular Coil</u>	<u>Circular Coil</u>
Maximum Steady Temperature for 20,000-hr Life	1225°F	1225°F
Maximum Thermal Cycles — 1025°F	500	1000
— 1125°F	250	500
— 1225°F	125	250

VI. S8DR TEST SYSTEM ACTUATORS

Seven actuators of the original design, already acceptance tested, were rebuilt to the modified configuration for use on the S8DR Test System reactor. These units were reacceptance tested, and six units were installed on the S8DR reactor. One unit was inadvertently damaged during the installation, necessitating the designation of Dev. 014 unit as a system spare. During the thermal vacuum environment acceptance test of the reactor, all six actuators were operated an equivalent to a minimum of 40 reactor startups and shutdowns. The decision to increase the controller current to the phase and brake coils, as noted earlier (Section III-A-2), was made during this test. The reactor installation checkout and preliminary tests required additional actuator operations. The power operation of the S8DR Test System was recently concluded, with over 7000 hr at or near the rated temperature, producing power up to 1 Mw. In addition to the normal drum shimming operation, each actuator operated for a total of 16 startups and shutdowns.

Throughout these series of tests, equivalent to well over 56 startups and shutdowns, all actuators operated flawlessly, with no indication of malfunction. The performance of these actuators under the actual reactor operating environment confirms the capability demonstrated by the development actuators.

VII. FUTURE TESTING

Actuator Dev. 013 is currently undergoing further testing under the original test conditions. As of January 20, 1970, this actuator had completed 18,022 hr of testing, 237 thermal cycles, of which 120 were startup cycles, and 15,618 hr at 1125°F. This test is currently scheduled for a total of 20,000 hr.

VIII. SUMMARY

The successful completion of the 12,000-hr thermal-vacuum test at 1125°F (100°F above design), conducted on three development units, verifies the built-in design margin of the modified S8DR actuator. Extended proof testing on actuator test bed has indicated that the life of the modified coil assembly, at temperatures up to 1225°F, is limited only by the number of thermal cycles and current density. The flawless operation of the six modified units during the 7000-hr test of the S8DR Test System confirms the adequacy of this actuator design.

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