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Price $1.50. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.
OMR CONTROL–SAFETY ROD
COMPONENT DEVELOPMENT TESTS

BY
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ABSTRACT

A magnetic-jack control-safety rod is under development for the 45.5 thermal megawatt Organic Moderated Reactor. The rod is "unitized," i.e., the poison element, drive, position indicator, and shock absorber are contained in a compact assembly which is inserted in a regular fuel channel opening in the core. Since all components of the rod are immersed in the reactor coolant, they must operate at or above the reactor inlet temperature, 550°F. Tests to develop components capable of operating under these conditions are described and results are reported.

Tests with anodized-aluminum magnet coils have shown that sustained operation in air at coil temperatures up to 1000°F is feasible but resistance to voltage breakdown from coil to ground is greatly reduced by immersion in hot Santowax. Hence, it is necessary to seal the magnet structure against entrance of organic into the coils.

Tests have produced a spring capable of performing in air at 600°F for the required number of snubbing operations. Tests of a Belleville spring shock absorber have shown that it also will operate satisfactorily at 600°F.

Several types of electromagnetic position indicators have demonstrated their inherent sensitivity to temperature fluctuation. A method was devised in which temperature effects on the coil transducer are automatically compensated by an integrally-mounted tungsten thermistor. Excellent signal stability for slow temperature changes was obtained; however, due to a difference in temperature relaxation time between the coil-thermistor assembly and the steel rods, a time delay is required after a step change in temperature to reestablish equilibrium. Short differential transformer coils were tested for use as a rod "up" and "down" position indicators and as temperature-independent check points at the midpoint on the long-coil indicator.
I. INTRODUCTION

Reactor control and safety elements must enable accurate control of power level, as well as accomplish emergency shutdown when required. For a central station power plant, reliability of performance of these functions for long periods of time with a minimum of maintenance is of prime importance.

Another requirement is that control elements and their drives must not, due to physical size or location, interfere with or complicate refueling operations. This latter stipulation is usually met by locating the control rod drive mechanisms below the reactor in a special "rod drive" room, or use of removable drives located above the upper biological shield. The lower drive room, however, constitutes a significant addition to plant cost, and removable "top" drives contribute undesirable procedural complications during fuel handling.

The 45.5-thermal-megawatt Organic Moderated Reactor is designed with the core placed near the bottom of a tall reactor tank. The space above the core in this tank serves as a mixing plenum for the inlet coolant. A control and safety element which could be installed inside the reactor tank and immersed in the coolant above the core would eliminate some of the disadvantages inherent in the top or bottom drives. Other advantages which could be realized with such an arrangement would be (1) flexibility of loading in number and location of control elements, and (2) elimination of need for penetration of the reactor tank through seals or re-entrant thimbles. A control-safety rod utilizing an electromagnetic drive has been designed for this unitized concept and is described in Section II.
II. OMR UNITIZED CONTROL-SAFETY ROD

The control assembly can be inserted into a standard fuel element cell opening, with the weight of the assembly supported by the core upper grid plate. The outside diameter of the assembly above the core is limited to 6.25 inches to allow clearance for refueling operations. Another grid plate near the top of the control rod maintains its vertical alignment and provides support and protection for electrical power and instrumentation leads. These leads are connected to the top of the rod assembly by means of a cable quick-disconnect, and taken out through a pressure seal in the tank wall. A sketch of the assembly is shown in Figure 1.

The movable parts of the rod, consisting of the poison element, the rod extension, and the movable armature are contained inside a sealed, pressurized thimble. Use of the thimble prevents flux peaking in the moderator and overheating of adjacent fuel elements upon withdrawal of the poison element, which might occur if the rod operated in contact with the organic.

The control rod drive used is the electromagnetic jack, similar to the type that has been under development at the Argonne National Laboratory for about five years.* The drive consists of the movable armature previously mentioned and a fixed armature, both contained inside the pressure thimble. The control rod extension passing through the hollow armatures is a hollow steel tube (1-1/2-inch OD, 3/8-inch wall) divided longitudinally into four segments.

External to the pressure thimble, four sets of stationary electromagnet coils encircle the armatures. The two large coils are used to move the movable armature up or down between its end stops (0.1-inch to 0.2-inch motion). The two sets of smaller coils, termed "hold" and "grip" coils, when energized, magnetically attract and hold the segments of the rod extension against the inside bore of the fixed or movable armatures, respectively. In this manner, the drive rods are gripped by the movable armature when it is moving or are held stationary while the armature is returned for another step. By energizing the grip, lift, hold, and pull-down coils in the proper sequence, the rod is

Figure 1. Unitized Control Rod Assembly
raised or lowered in step motion, at rates up to 180 steps per minute. Automatic
switching of direct current to the coils is accomplished with a motor-driven cam
switch which activates microswitches and relays.

The control rod also serves as a safety rod, as it can be released at any
position in its travel to shut down or "scram" the reactor. Release of the poison
element is accomplished simply by de-energizing all coils. When the current
is interrupted in the coils, the rod falls with an acceleration approximating free
fall, due to the large clearance between the drive rods and the armature bore.

A stiff spring is used to absorb the kinetic energy of the falling rod at the
end of its travel to protect the rod and its support structures from excessive
shock loads. The spring consists of a stack of beveled rings, the angle of the
bevel being approximately 14 degrees from vertical. Alternate large and small
rings have the bevels on the inside and outside, respectively; thus, an axial load
induces respective tension and compression stresses in the rings. Another
feature of the ring spring is the fact that compression of the stack causes rubbing
between mating beveled surfaces. The energy absorbed in the friction between
the surfaces reduces the reaction or unloading force of the spring. Thus, the
bounce of the safety rod after snubbing is reduced.

Sensing of the rod position by electromagnetic means is possible since the
rod extension is of magnetic steel. The guide tube for the rod extension above
the drive is fabricated of nonmagnetic stainless steel. A coil slightly longer
than the rod travel is wound on this guide tube. The length of rod extending
inside the coil is determined from the impedance of the coil.

Since the entire unitized control rod is immersed in the coolant pool above
the reactor core, mechanical and electrical parts must be capable of sustained
operation at or above the inlet temperature of the organic (550°F minimum).
Heat generation from resistance losses in the electromagnet coils may raise
their operating temperature to 750°F or above. Due to the requirement that
components must operate at these elevated temperatures and in a radiation field,
development tests were necessary to determine their characteristics and life-
times under these conditions.
III. COMPONENT DEVELOPMENT TESTS

A. MAGNETIC JACK DRIVE

As previously mentioned, this type of drive has been under development at Argonne National Laboratory for some time. In ANL designs, the drive was mounted external to the reactor tank, with the electromagnet coils cooled by forced air circulation. The movable parts of the rod operated in contact with the coolant, inside a thimble bolted to the reactor tank. The OMR unitized control rod operating conditions listed below differ considerably from those of the ANL rod, and are more severe, particularly with respect to operating temperature of the electromagnet coils.

1) Environment: The movable parts of the rod operate "dry," i.e., in a sealed inert-gas-filled thimble instead of in contact with the coolant. The coils must operate in an ambient of organic at 550°F with natural convection cooling only. Heat generation from resistance losses in the wire may raise the operating temperature to 750°F or above. In addition, the electromagnets will, due to proximity to the reactor core, be subjected to neutron and gamma radiation.

2) Space Limitation: To prevent interference with fueling operations, the drive is restricted in outside diameter to 6-1/4 inches. Also, the drive is designed to keep the length of the assembly to a minimum.

3) Speed Requirement: The magnetic jack was developed for and apparently had been limited to rod speeds below 6 inches per minute. However, in the early stages of operation of each new reactor, during investigations of such characteristics as temperature coefficient, system stability, etc., it is desirable to provide a margin in available rod speed. For this reason, experiments were conducted to exploit the capabilities of the jack with regard to maximum rod speed.

1. Coil Lift Tests

To obtain information on the characteristics of operation of the electromagnet coils at expected operating temperatures, a furnace containing a simulated lift magnet section of the jack was designed and built. A sketch of the
assembly is shown in Figure 2. All parts of the magnetic circuit such as support tube, fixed and movable armatures, coil form, etc., were fabricated of 1020 carbon steel. To prevent undesirable effects on the coil magnetic circuit from the furnace tube and coil support fixtures, these parts were fabricated of type 300 stainless steel.

Tests were performed to determine relationships between load on the movable armature, distance of armature motion (step length), and coil current. Load on the armature was changed by stacking bags of lead shot on a table attached to an extension rod below the armature. Variation of step length was accomplished by means of the screw assembly attached to the upper fixed armature. Adjustment of current was made with variable resistors in series with the coil. Figure 3, curve A, is a graph of load lifted vs coil current for a step length of 0.1 inch. This test was performed without a cushion washer in the air gap.

The lift coil which was tested is similar to the final design selected for prototype tests. The load vs deflection characteristics of the cushion washers above the movable armature have a large effect on the lift capabilities of the coil; i.e., if not completely flattened during pull-in, the washer increases the air gap without increasing lift distance. Curve B of Figure 3, obtained with a washer of excessive thickness and pre-formed deflection, illustrates this effect. Thickness and pre-formed deflection of the magnetic and nonmagnetic washers must be optimized empirically for a particular design of lift coil. The curves, therefore, represent only typical characteristics of a tractive solenoid of the type which will be used in the jack.

It was considered necessary to determine whether the magnetic properties of the steel would be affected deleteriously by elevated temperatures within the range of interest. For a fixed lift distance and armature load, measurements were made of the coil current required for lifting vs the temperature of the assembly. From room temperature to 800°F, no significant increase in the current required to lift was found.

2. **Coil "Dry" Life Tests**

The highest temperature rating (continuous duty) presently given to magnet wire by the AIEE is Class H (350°F). Therefore, a magnet wire to be
Figure 2. Lift Coil Test Furnace
used in an application where temperatures are above this figure must be subjected to exhaustive tests at those temperatures.

Several types of magnet wire presently available have been considered feasible for the OMR unitized control rod conditions, namely, copper wire with glass fibre insulation, copper wire coated with ceramic, and aluminum wire coated with an anodic oxide film. The latter material, recently marketed, is claimed by its manufacturers to be capable of continuous duty at 800°F. The first "dry" life test (with the coil not in contact with organic) was made in an atmosphere of air in the lift-coil furnace. Since glass or ceramic-covered copper wire would be seriously affected by oxidation at elevated temperatures in air, a coil wound with anodized aluminum wire was selected for the first test.

A coil wound with AWG 16 anodized aluminum wire (Aluminium Limited of Canada, type 100) was installed in the furnace with a thermocouple embedded in the center of the coil to measure its maximum temperature. A photograph of the test assembly is shown as Figure 4. A d-c power supply employing a motor-driven cam to operate microswitches and relays was used to pulse the coil so as to perform lift cycle operations at the rate of 30 per minute. A schematic of the power supply circuitry (for one set of coils) is shown in Figure 5. The power supply was operated ungrounded. The weight lifted was 125 pounds and the length of lift motion was 0.075 inch. Furnace temperature was maintained with external resistance heaters.

The coil was operated successfully for a total of 2940 hours (5.4 million lifting cycles) at coil temperatures ranging from 700 to 1100°F. Operating times and temperatures are shown in Table I. Assuming a 0.1-inch step length for the magnetic jack, this number of cycles of continuous operation represents a control rod travel of 40,000 feet. Related to the 45.5-thermal-megawatt OMR reactor, this is equivalent to 10,000 times the 4-foot control rod stroke.

After 475 hours operation at 900°F (total operating time, 2150 hours) a series of measurements was made of resistance from coil to ground vs temperature through a temperature range from 250 to 950°F. Figure 6, curve A, is a graph of the results. Measurements from either end of the coil to ground at
Figure 3. Lift Magnet Lifting Force vs Coil Current (Data were obtained using a coil of 900 turns of anodized aluminum wire)
Figure 4. Lift Coil Dry Life Test Furnace
Figure 5. Original One-Coil Magnetic Jack Power Supply Circuit

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<td>900</td>
<td>475</td>
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950°F indicated a short at approximately the center of the coil. However, since the coil power supply was not grounded, the short had no effect on the operation of the coil.

The successful long-term operation of this coil indicates that from the standpoint of temperatures, electromagnets with useful lifetime under expected OMR control rod conditions are feasible. With a power input to the lift coil of 450 watts (pulsed), the difference between coil temperature at 800°F and average furnace air temperature was approximately 125°F.
Figure 6. Resistance Measured from Coil to Ground vs Coil Temperature Using Anodized Aluminum Wire on an Anodized Aluminum Spool (1 mil oxide coating on the spool)
Figure 7. Electromagnet Test Autoclave
Tests were performed to determine the breakdown voltage (short time) vs temperature of aluminum anodic coatings in air. Aluminum rods 1/2 inch in diameter and 12 inches long, were hard anodized (Sanford process) to thicknesses of 1, 3, and 6 mils. Anodized aluminum wires were fastened tightly against these rods in the longitudinal direction. The probes were inserted in a furnace and breakdown from wire to rod obtained by battery voltage. Due to the small radius of the wires, hence increased voltage stress concentration, the values obtained are considerably lower than figures usually published for anodic coatings. Values ranged from approximately 300 volts per mil at 600°F to approximately 100 volts per mil at 900°F.

3. Autoclave Tests

Tests of coils immersed in organic coolant (Santowax R) were made. The objectives of these tests were to obtain information on: (a) heat transfer characteristics of the coil configuration when cooled by organic in natural convection, (b) effects of the organic on magnet wire insulation, potting compounds or cements, and electrical connectors, (c) effects on magnet wire and coil form insulation breakdown voltage and resistance characteristics due to water and other possible contamination in the organic, and (d) additional life-test data for use in predicting operational reliability. An autoclave, as shown in Figure 7 was used in these tests. The autoclave was designed to accommodate two "lift" coils and two "grip" coils. Two Conax fittings in the autoclave head were used for leads to thermocouples to measure coil and organic temperature and for power leads for each coil. Also installed in the autoclave head were a bleed valve to allow escape of air and dissolved gases during initial heat-up, and a pressure gage and diaphragm-type safety head for overpressure relief.

A heat transfer experiment was conducted on four coils installed in an autoclave containing Santowax R. The terphenyl mixture was in the as-received condition and contained approximately 0.01 percent by weight water. The assembly consisted of two "lift" coils, one wound with AWG No. 12 anodized aluminum wire, and one with AWG No. 16, and two "grip" coils, one wound with AWG No. 16 anodized aluminum wire and one with AWG No. 18. All coils were wound on anodized aluminum spools (oxide layer thickness 0.001 inch). Either Foster Cement No. 30-43 or Saureisen Cement No. 31 was used to hold the wire in place in the coils.
Figure 8. Power Dissipated in Electromagnet Coils vs $\Delta T$ from Coil to Organic
Each coil contained a thermocouple embedded in its center to measure its maximum temperature. Measurement of coolant temperature was obtained with three thermocouples located at different depths in the organic. The organic coolant temperature was raised to an average of 500°F. The coils were energized with various values of direct current (not pulsed), and records were obtained of steady-state coil temperature and organic temperature. The results of this test are shown in Figure 8, which is a graph of watts dissipated in each coil vs AT from coil to organic. The power required when the coils are moving the control rod or holding it at one position is indicated on the curves. The power levels indicated for lifting and gripping while the rod is in motion are steady-state values equivalent to appropriate pulsed values, taking into account the duty cycle of the coils. The power values shown are for a rod (neutron absorber) weight of 60 pounds.

Measurements were taken of resistance from coils-to-ground vs temperature, with results plotted on curve B, Figure 6. It can be seen that the values were markedly less than those measured in air. Efforts were subsequently initiated to improve the characteristics of the coils with regard to resistance from ground and breakdown voltage to ground. Methods which were investigated include:

a) Sealing the pores of the oxide coating with a vitreous ceramic material to prevent entrance of organic into the insulation layer, and

b) Investigation of methods of "canning" the coils, either as a group or by sealing each set of coils inside its steel magnetic structure.

Techniques were developed for coating aluminum with a vitreous ceramic material (Solar Aircraft Spec. No. 8004). Tests were performed on various thicknesses of the coating to determine its resistance to high temperature. Coating thicknesses of 1, 3, and 5 mils were applied to 1/2-inch diameter aluminum rods. Anodized aluminum wires were fastened tightly to the rods. The probes were immersed in Santowax R in an autoclave and breakdown values vs temperature were obtained. Values ranged from approximately 300 volts per mil at 400°F to approximately 40 volts per mil at 800°F.
The voltage breakdown values obtained with the vitreous coatings decreased markedly at temperatures above 700°F indicating softening of the material; also, the values obtained on the basis of these data were inconsistent. The ceramic was rejected as a coil-form insulation for the anodized wire. It was therefore thought desirable that, in the prototype tests of the magnetic jack, the electromagnet coils be sealed against entrance of organic by means of a steel can enclosing the entire jack.

4. Time Response Measurements

In view of the possible requirements for rod speeds higher than those previously obtained with the magnetic jack, measurements were made of the time response characteristics of a lift coil assembly to explore the maximum potential rod speed obtainable with the drive. A lift coil assembly was instrumented to provide transient measurements of coil current, armature position and acceleration, and to allow monitoring of these measurements on an oscillograph recorder.

Measurements of armature position were obtained as follows: a steel plate was attached at one end to the coil support table and at the other end to the movable armature extension shaft. A strain gage was cemented on one side of the steel plate; and the gage was connected as one leg of a balanced bridge circuit. Bending of the plate, hence change of resistance of the gage, unbalanced the bridge and produced an electrical signal proportional to armature motion. This signal was amplified and fed to the recording oscillograph. A signal proportional to coil current was obtained with a small resistor in series with the coil. An accelerometer attached to the armature measured its acceleration during pull-in.

Data from early test runs showed considerable time delay between the beginning of current rise and completion of armature motion. This was attributed to the extremely long time constant \( \frac{L}{R} \) of the rectifier-coil circuit, hence the delay in establishing the required flux to lift. Analysis of these data indicated that considerable improvement in current rise time could be obtained by changes in coil circuitry, such as addition of resistance \( R \), and capacitance \( C_1 \) (Figure 9).
Addition of \( R \), of course, required an increase in rectifier voltage to maintain the same steady-state current flow through the coil. It was also found that by addition of capacitance \( C_2 \), the shape of the coil pulse could be altered to provide a large pull-in current while maintaining the same holding current. Figure 10 shows the effect of varying external resistance and capacitance \( C_2 \) on pull-in time of the lift coil.

![Diagram of Magnet Jack Power Supply Circuit with Pulse-Shaping Capacitance and Resistance Added](image)

As can be seen, considerable improvement in time response was accomplished with this technique. Armature peak acceleration was not increased appreciably, hence the possibility of slipping between armature and drive rods was not increased. On the basis of the favorable results obtained from the lift coil tests, a power supply for the prototype magnetic jack was designed and built containing provision for varying (a) rectifier voltage, (b) external resistance and capacitance in coil circuit, (c) time sequence of energizing for four sets of coils, and (d) duration of coil pulse to each set of coils. Due to the difficulty in
Figure 10. Lift Coil Pull-In Time vs Resistance and Capacitance in Circuit
calculating optimum values for these variables, the effect of each variable on the rod speed obtainable with the jack must be determined empirically.

B. SHOCK ABSORBER

The requirement that moving parts of the control-safety rod operate inside a gas-filled thimble was mentioned in Section II. This requirement eliminated consideration of a hydraulic shock absorber and indicated the need for either a pneumatic-, friction-, or spring-type device. The pneumatic cylinder idea was rejected, due to space and arrangement considerations. Other possible shock absorbers were investigated as follows.

1. Ring Spring

To investigate the feasibility of using spring-type shock absorbers, analyses were performed to determine the amount of bounce of the safety rod permissible after snubbing without causing dangerous flux oscillations. It was found that a rod bounce of 50 percent of fall height after snubbing could be tolerated. To meet this limitation, a device incorporating both spring and friction action was needed. The "ring spring," previously described in Section II, was selected for analysis and test.

Analysis of the ring spring indicated the following desirable features of the device:

a) Efficient use of material, i.e., axial loads induce tension and compression stresses in the rings, which are evenly distributed in the ring cross section. Thus, the volume occupied by the spring stack is considerably less than that of an equivalent coil or Belleville spring, in which stresses are unevenly distributed.

b) Ability of the spring to dissipate a large portion of the kinetic energy of the falling rod, hence to reduce rod bounce after snubbing. The reduction in reaction force of the spring is due to friction between the beveled rubbing surfaces. Furthermore, the nature of the device is such that by conservative design (see discussion below) its operation should be satisfactory despite appreciable variations in coefficient of friction.
Figure 11. Ring Spring in Test Furnace
c) Ability of the device to operate satisfactorily despite slight changes in dimensions due to temperature or wear of rubbing parts. This is due to the fact that the ring spring is preloaded at the time of assembly, so that the beveled rubbing surfaces are in contact at all times.

A cross section of a ring spring stack, as installed in the furnace, is shown in Figure 11. It is desirable to stop the falling rod with the minimum peak force consistent with a practical spring length. The maximum force on the ring spring when undergoing load is given by:

$$F_{\text{max}} = W \left[ 1 + \sqrt{1 + \frac{2\pi CAE h \tan \theta}{nDW}} \right]$$

where

- $W =$ weight of rod (lb),
- $C =$ constant, which depends on the bevel angle and the coefficient of friction,
- $A =$ area of ring section (sq. in.),
- $E =$ modulus of elasticity of spring material (psi),
- $h =$ height of fall of rod (in.),
- $\theta =$ angle ring rubbing face makes with vertical (degrees),
- $n =$ number of rings in spring, and
- $D =$ average diameter of spring (in.).

The minimum value of $A$ (area of ring section) is dictated by fabrication requirements and ability of ring to maintain dimensions during heat treatment. Average spring diameter, $D$, is set by the diameter limitations of the control rod outer thimble. Figure 12 shows the effect of spring length (hence number of rings, $n$) on the reaction force of the spring for a particular material. As can be seen, an increase in spring length of over 12 to 14 inches for the material under consideration produces little reduction in spring loading force. Materials considered most desirable for the ring spring were those with a high yield strength at elevated temperatures 650 to 750°F, and a low modulus of elasticity, $E$.

It is also desirable to keep the angle $\theta$ at a minimum value. The effect of $\theta$ on maximum spring reaction force is shown in Figure 13. However,
Figure 12. Ring Spring Reaction Force vs Spring Length

- **RING CROSS SECTION AREA**: 0.0307 sq.in.
- **RING BEVEL ANGLE**: 20 degrees
- **RING MEAN DIAMETER**: 5.25 in.
- **RING MATERIAL**: NITRIDED
- **ROD WEIGHT**: 100 lb
- **ROD FALL HEIGHT**: 48 in.

**COEFFICIENT OF FRICTION**
- **TANGENT OF ANGLE (20°)**
- **0**
reliable operation of the ring spring requires that tangent $\theta$ be greater than the coefficient of friction, to prevent binding of the spring in the compressed position. Figure 14 illustrates the energy dissipation characteristics of the spring as a function of the coefficient of the friction as the latter varies from zero to the value of tangent $\theta$. The difference in the areas under the loading and unloading curves is the energy dissipated. The coefficient of friction was considered to be the most critical parameter with regard to the practicability of the ring spring. Therefore, tests of many materials combinations were conducted.

**Materials Tests** - The aims of the materials tests were to select materials with good resistance to galling at expected operating temperature and with unit loadings calculated for the ring spring rubbing surfaces (5,000 to 10,000 psi), and to determine the maximum coefficient of friction for these materials combinations at expected operating temperatures.

The test samples consisted of two parts: a flat plate with a conical indentation, and a shaft tapered to fit the indentation. The plate was mounted inside a small furnace which was installed on a drill press table. The shaft sample was mounted in the drill press chuck and entered the furnace at the top as shown in Figure 15. The pressure between the plate and the shaft was varied by loading the vertical actuator of the press. The shaft sample was rotated manually by means of an extension bar attached to the drill chuck. The furnace was mounted and instrumented so that torque transmitted from the shaft sample to the plate sample by friction could be measured. In this way it was possible to determine the coefficient of friction between samples.

Of the samples tested, most exhibited high coefficients of friction and galling (destructive removal of material from one surface by the other) within 25 cycles. However, good results were obtained with both plate and shaft fabricated of nitrided 17-4PH stainless steel, and with both plate and shaft fabricated of nitrided Potomac M hot forging die steel. Both materials were selected for ring spring tests in prototype size. A spring fabricated of K-Monel and coated with a high temperature solid film lubricant was also tested.
Figure 13. Spring Reaction Force vs Bevel Angle

Figure 14. Ring Spring Reaction Force vs Displacement
Figure 15. Materials Test Furnace
Figure 16 is a sketch of the furnace used for tests of snubber springs. The spring is mounted in a fixture at the bottom of the furnace and is assembled under a preloaded condition to ensure correct placement and alignment of the rings. The control rod weight is simulated by a cylindrical slug of steel attached to the bottom of a guide shaft.

The guide shaft extends through a gas seal and guide bearing at the top of the furnace. A fixture is clamped on the guide shaft near the upper end to provide for mounting of an accelerometer and the wiper arm of a linear potentiometer. A signal from the potentiometer provides information on rod position and height of bounce after spring snubbing. The accelerometer measures acceleration of the rod as it is falling and while it is being decelerated by the spring. Rod position and acceleration vs time information are recorded by an oscillograph recorder.

For a life test of a safety rod shock absorber, approximately 500 to 1000 operations are necessary to prove reliability. For cyclic lifting of the simulated rod weight during such an extended test, a pneumatic piston and cylinder assembly was used. A spring-loaded grapple on the piston extension rod was used to pick up the simulated rod weight. Microswitches at the top and bottom of the grapple travel actuated solenoid air valves to change the direction of motion of the piston. Release of the simulated rod weight occurred when the grapple latch arm struck the crossbar at the top of its travel.

The first full-size ring spring to be tested was fabricated of K-Monel. K-Monel was selected because of its low modulus of elasticity even though it was not considered capable of operating "dry" (unlubricated) without galling. To prevent galling, the rubbing surfaces of the rings were coated with a high-temperature solid film lubricant (Electrofilm Company, Spec. 2006).

The K-Monel ring spring was subjected to two series of tests in the furnace. In the first test approximately 700 test drops on the spring were made with the 100-pound simulated control rod weight. Of these, approximately 300 drops were at indicated temperatures of 300 to 450°F, and 70 at an indicated 600°F. In the second test, 150 drops were achieved, of which 55 were at an indicated 600°F. The thermocouple used to read these temperatures was located in the center of the air space inside the ring spring, as shown in Figure 11. Both
Figure 16. Snubber Furnace Test Assembly
tests were terminated due to sticking of the spring in the compressed position. The failures were attributed to (1) insufficient clearance between the rings and the stainless guide sleeve which caused galling of some rings to the sleeve and overloading of a portion of the spring, and (2) improper heat distribution in the test furnace, resulting in localized heating of the rings to temperatures above the rating of the solid film lubricant.

A temperature profile was made of the ring spring in the furnace. Due to excessive heating of the lower portion of the furnace, local temperatures in the spring ranged up to 975°F. By redistribution of heaters and thermal insulation on the furnace, the spread of temperatures in the spring assembly was reduced to less than 50°F.

The third ring spring was designed with increased individual ring height, to eliminate the cocking or tilting of rings noted in earlier tests. The height of each ring was increased to 0.8 inch. Other pertinent information on the spring is listed below.

a) Material 17-4 PH stainless steel, heat treated to condition CH 1075
b) Lubricant "Everlube" 700
c) Free height of spring stack 13.1 inches
d) Height of each ring 0.8 inch
e) Ring diameters 5.602 inches OD, 5.252 inches ID
f) Ring thickness on edge 0.050 inch
g) Number of rings 13 inside, 12 outside, 2 end rings (1/2 height outside)
h) Angle of rubbing surfaces from vertical 14 degrees

The spring was tested in the snubber furnace in an ambient of air at 600°F. The 100-pound simulated rod weight was raised to a height of 4 feet by the automatic pneumatic cycling device and dropped on the spring at a rate of approximately one cycle per minute. The spring operated satisfactorily for 1053 cycles, or snubbing operations under these conditions. After approximately 550 operations the unloaded height of the spring stack gradually began to decrease, indicating
BELLEVILLE SPRING:
UP TO ø (32)
DOWN TO ø (30)
MATERIAL:
17-7 PH-CH 900

FLAT RING SPRING:
(30)
MATERIAL:
TYPE 304 SS

Figure 17. Belleville Spring Arrangement
sticking of the rings to each other. At 1050 cycles the spring height had decreased by 2-1/8 inches, and spring compression under load had decreased from the original 1-3/16 inches to 3/8 inch.

Examination of the ring spring after the test showed no evidence of cocking or tilting of rings. However, all but 3 of the 27 rings were stuck together due to failure of the lubricant. The lubricant is known to have a long lifetime at this temperature (unloaded); the failure was therefore attributed to wear rather than heat aging. Since the number of snubbing operations successfully obtained represents several years of safety rod operation in a reactor, the test is considered to be a demonstration of the adequacy of this type of shock absorber for "dry" (in a gas ambient) operation at OMR temperature conditions.

2. Belleville Spring

Calculations indicated that a shock absorber composed of stacked Belleville spring washers would be incapable of dissipating the required 50 percent of rod kinetic energy, i.e., would cause excessive rod bounce after snubbing. However, it was considered desirable to investigate experimentally the potentialities of the Belleville spring for energy dissipation. A spring element of 17-7PH stainless steel, age-hardened to condition CH975, was designed with the following dimensions:

a) Outside diameter 5.60 inches
b) Inside diameter 4.00 inches
c) Thickness 0.10 inch
d) Camber 0.15 inch

A spring stack height of 13 inches was selected for test. The washers were stacked with pairs in parallel to increase energy dissipation by rubbing between the adjacent Belleville washers. Between opposing pairs of spring washers, flat washers of a soft stainless steel (type 304) were inserted to increase friction losses. The arrangement is shown in Figure 17.

Tests of the spring resulted in considerably less rod bounce than was expected. At the beginning of the tests, the room temperature rod bounce averaged 25 to 30 percent. After 1000 operations at 600°F, rod bounce after
Figure 18. Eddy-Current Brake with Permanent Magnets
snubbing averaged 15 to 20 percent. Spring compression during impact was consistent in this test, averaging 2 to 2.5 inches. This indicates a spring constant which will produce rod snubbing loads of approximately 50 g's, or 5000 pounds for a 100-pound rod dropping 4 feet. The Belleville spring shock absorber operated satisfactorily for a total of 2000 cycles, after which it was disassembled for inspection of parts. No significant wear or galling was observed.

3. Eddy-Current Brake

A scheme using the eddy-current braking principle to reduce the kinetic energy of the falling rod before striking the spring snubber was investigated. Essential components consist only of permanent magnets and a copper sleeve. Motion of one past the other generates eddy currents in the sleeve that resist the motion. Two possible arrangements are shown in Figure 18. In arrangement No. 1, the magnets are attached to the control rod and fall through the sleeve as the rod drops. In arrangement No. 2, the copper sleeve is attached to the rod and falls through the ring magnets. The latter arrangement is more desirable since less weight is added to the control rod.

Analyses were made to determine the theoretical performance of the eddy-current brake. These analyses assumed a magnetic flux through the copper of 2000 gauss (considered to be a conservative figure). Analog computer studies indicated that if this flux were available, reductions in kinetic energy of the falling rod of up to 90 percent could be expected in a 24-inch long assembly. However, actual measurements with Alnico V magnets as shown in Figure 18(1) produced flux values not greater than 1000 gauss. Since the braking action is proportional to the square of the flux, this would indicate that only one quarter of the desired effect could be obtained. Subsequent analyses on the second arrangement pictured on Figure 18 indicated a possible substantial increase available in magnetic flux. The error in the original flux value assumed for eddy-current brake analyses was attributed to the difficulty in predicting leakage flux in a permanent magnet assembly and to the losses in magnet strength when
magnetized outside the assembly and subsequently assembled. The latter situation may possibly be remedied in the magnets with arrangement No. 2. These tests are continuing.

It was concluded that the eddy-current brake was not usable in the OMR unitized control rod due to insufficient magnetomotive force available in the Alnico V permanent magnets. However, it is noted that the required magnetomotive force could be obtained if space limitations allowed a greater active length of magnet, or if a permanent magnet could be used which possesses an energy product greater than Alnico V by a factor of two. The Carboloy Division of General Electric Company is presently developing magnet materials with energy products considerably in excess of this requirement, but they are not expected to become commercially available for at least two years.

4. Instrumentation Techniques - Sand Snubbing

Preparatory to actual tests of shock-absorbing devices in the furnace assembly, techniques for accurately measuring and recording position and acceleration of the rod while dropping had to be developed. A rod was suspended in a guide tube and held by means of an electrically-operated latch. A rectilinear potentiometer was mounted adjacent to the rod below the upper support table. The movable wiper for the potentiometer was attached to the side of the rod. Accelerometers were mounted on the upper end of the rod. Two types of accelerometers were tested: (a) Statham A5-200 (strain-gage type, frequency response, 0 to 600 cycles), and (b) Endevco 2213 (piezoelectric-crystal type, frequency response, 20 to 20,000 cycles).

Records of position and acceleration of the rod during drop tests were made using a cathode-ray oscillograph and a direct-reading oscillograph recorder. A container of sand was used to stop the rod at the end of its drop. Due to noise in the signal, considerable difficulty was encountered in producing good records of acceleration. This noise was attributed to excitation of the strain-gage accelerometer at frequencies above its natural frequency during snubbing, and to high frequency vibrations in the rod which were picked up by the crystal accelerometer. Filter circuits were used to remove the noise from the signal during a rod drop into the sand.
During the experiments to develop instrumentation techniques, measurements of rod deceleration characteristics, when the rod was dropped into sand, indicated the desirable characteristics of snubbing with particulate matter. On the basis of promising early data, a cursory investigation was made of variables such as rod end shape and the ratio of cross sectional areas of sand container and rod. It was found that the g-load was increased by reducing the diameter of the sand container and also by tapering the end of the rod to a point. Despite the encouraging results from the sand snubbing tests, use of such a shock absorber in the unitized OMR control rod was not considered feasible due to problems associated with containment of the sand in the snubber volume.

C. ELECTROMAGNETIC POSITION INDICATOR

Position indication schemes for the unitized magnetic jack control rod are limited and partially dictated by considerations of available space, operating temperatures, and the type of drive itself. Desirable features of a sensing device would be that it utilize the space already required for the guide tube of the magnetic jack rod extension, and that it have a minimum of moving or rubbing parts. A device which meets these requirements is an electromagnetic type utilizing one or more coils wrapped on the stainless-steel guide tube. However, during initial reactor operation, extreme accuracy is required of control rod position information. The electromagnetic type of transducer is known to be sensitive to temperature changes, i.e., the signal is affected by changes in the temperature of the stainless-steel coil form and the movable steel core.

Therefore, the following three types of electromagnetic sensing devices were tested for temperature sensitivity and the feasibility of temperature compensation: (1) a single long coil in which rod position is indicated by coil power losses; (2) two long coils wrapped over the length of the guide tube and connected as the primary and secondary coils of a transformer wherein rod position is indicated by secondary voltage; and (3) a single long coil connected as one side of an impedance bridge. A summary of experiments with these transducers and test results is given below.

1. Core Loss Measurements

Analysis of early test results showed good linearity between rod motion and coil power losses. Experiments were performed to determine the
A. POWER LOSS MEASUREMENTS

B. TRANSFORMER

C. IMPEDANCE BRIDGE

Figure 19. Electromagnetic Position Indicator Circuitry
temperature stability of such a scheme using both constant voltage and constant current with different core and coil combinations. The circuitry used is shown in Figure 19. Results of temperature drift tests are listed in Table II.

2. Transformer-Type Transducer

Two coils were wrapped closely together over the length of the guide tube and connected to act as a transformer. Mutual inductance between the coils, hence voltage induced in the secondary by current in the primary, is varied by motion of the steel rod through the primary and the secondary. Either constant current or constant voltage was maintained in the primary, while load resistance on the secondary was varied. The circuitry is shown in Figure 19. Results of temperature drift tests are listed in Table II.

3. Impedance Bridge

A single long coil was connected as one side of an impedance bridge, as shown in Figure 19. The unbalance voltage caused by changes in impedance of the coil is rectified, reduced by a voltage divider, and delivered to a millivolt recorder. A potentiometer is used to provide zero adjustment. Because of the coil inductance in the circuit, a slight phase difference voltage always exists. This is bucked out with a battery or constant-voltage diode circuit.

A number of tests were performed with the impedance bridge circuit, using coils of copper wire and Constantan wire. Most tests were made with coils 20 inches long wound on a stainless steel tube, 1.25 inches in diameter. Various movable cores were used, including a solid steel rod, a heavy-wall steel tube, and a heavy-wall steel tube slotted into four segments. Considerable improvement (reduction of temperature drift) was obtained by (a) use of Constantan wire rather than copper, (b) reduction of mass of steel core (changing from rod to tube), and (c) slotting of the steel tube to reduce eddy currents. Results of temperature drift tests are listed in Table II.

Analysis of the data obtained from the tests described above indicated an apparently basic temperature sensitivity of the electromagnetic type position indicator. Figure 20 shows the circuit representing an "ideal" iron core inductor and the equivalent circuit of an actual inductor. When the steel rod extension was moved into the coil, the effects measured by the readout circuitry included
TABLE II
TEMPERATURE DRIFT DATA - POSITION INDICATOR TESTS

<table>
<thead>
<tr>
<th>Type of Position Indicator</th>
<th>Coil Winding</th>
<th>Core Description</th>
<th>Coil Length (inches)</th>
<th>Core Movement (inches)</th>
<th>Circuit Parameter Held Constant</th>
<th>Load on Secondary (ohms)</th>
<th>Signal Drift (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer</td>
<td>AWG 22 Constantan</td>
<td>Solid steel rod, 1-inch dia.</td>
<td>20</td>
<td>16</td>
<td>Current</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Transformer</td>
<td>AWG 22 Constantan</td>
<td>Thick-wall tube, 1-inch OD, 3/8-inch wall</td>
<td>20</td>
<td>16</td>
<td>Current</td>
<td>None</td>
<td>29</td>
</tr>
<tr>
<td>Transformer</td>
<td>AWG 22 Constantan</td>
<td>Solid steel rod, 1-inch dia.</td>
<td>20</td>
<td>16</td>
<td>Voltage</td>
<td>None</td>
<td>25</td>
</tr>
<tr>
<td>Transformer</td>
<td>AWG 22 Constantan</td>
<td>Solid steel rod, 1-inch dia.</td>
<td>20</td>
<td>16</td>
<td>Voltage</td>
<td>None</td>
<td>21.4</td>
</tr>
<tr>
<td>Transformer</td>
<td>AWG 22 Constantan</td>
<td>Solid steel rod, 1-inch dia.</td>
<td>20</td>
<td>16</td>
<td>Voltage</td>
<td>10</td>
<td>17.7</td>
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<tr>
<td>Transformer</td>
<td>AWG 22 Constantan</td>
<td>Thick-wall tube, 1-inch OD, 3/8-inch wall</td>
<td>20</td>
<td>16</td>
<td>Voltage</td>
<td>None</td>
<td>14.9</td>
</tr>
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<td>Transformer</td>
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<td>Thick-wall tube, 1-inch OD, 3/8-inch wall</td>
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<td>16</td>
<td>Voltage</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Transformer</td>
<td>AWG 22 Constantan</td>
<td>Thick-wall tube, 1-inch OD, 3/8-inch wall</td>
<td>20</td>
<td>16</td>
<td>Current</td>
<td>-</td>
<td>~10</td>
</tr>
<tr>
<td>Wattmeter</td>
<td>AWG 22 Constantan, 10 layers in parallel</td>
<td>Solid steel rod, 1-inch dia.</td>
<td>20</td>
<td>16</td>
<td>Current</td>
<td>-</td>
<td>12.5</td>
</tr>
<tr>
<td>Wattmeter</td>
<td>AWG 22 Constantan, 10 layers in parallel</td>
<td>Solid steel rod, 1-inch dia.</td>
<td>20</td>
<td>16</td>
<td>Voltage</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Wattmeter</td>
<td>AWG 22 Constantan, 5 parallel layers in series with 5 parallel layers</td>
<td>Thick-wall tube, 1-inch OD, 3/8-inch wall</td>
<td>20</td>
<td>16</td>
<td>Voltage</td>
<td>-</td>
<td>9.1</td>
</tr>
<tr>
<td>Impedance Bridge</td>
<td>AWG 20 Copper, 1 layer</td>
<td>Bundle of 7 1/2-inch dia. steel rods</td>
<td>20</td>
<td>20</td>
<td>-</td>
<td>-</td>
<td>38</td>
</tr>
<tr>
<td>---------------------------</td>
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<td>Impedance Bridge</td>
<td>AWG 20 Copper, 1 layer</td>
<td>Bundle of 7 1/2-inch dia. steel rods</td>
<td>20</td>
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<td>Solid steel rod, 1-inch dia.</td>
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<td>16</td>
<td>-</td>
<td>-</td>
<td>19</td>
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<tr>
<td>Impedance Bridge</td>
<td>AWG 16 Constantan, 4 layers</td>
<td>Slotted thick-wall tube, 1-inch OD, 3/8-inch wall</td>
<td>20</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>18.3</td>
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<tr>
<td>Impedance Bridge</td>
<td>AWG 16 Constantan, 5 parallel layers in series with 5 parallel layers</td>
<td>Thin-wall tube, 1-inch OD, 3/8-inch wall</td>
<td>20</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>15.8</td>
</tr>
<tr>
<td>Impedance Bridge</td>
<td>AWG 22 Constantan, 5 parallel layers in series with 5 parallel layers</td>
<td>Slotted thick-wall tube, 1-inch OD, 3/8-inch wall</td>
<td>20</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>14.7</td>
</tr>
<tr>
<td>Impedance Bridge</td>
<td>AWG 20 Copper, 4 series layers in parallel with 4 series layers</td>
<td>Slotted thick-wall tube, 1-inch OD, 3/8-inch wall</td>
<td>20</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>9.5</td>
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<td>Impedance Bridge</td>
<td>AWG 16 Constantan</td>
<td>Slotted thick-wall tube, 1-inch OD, 3/8-inch wall</td>
<td>20</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>3.1</td>
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<tr>
<td>Impedance Bridge</td>
<td>AWG 16 Constantan</td>
<td>Slotted thick-wall tube, 1-inch OD, 3/8-inch wall</td>
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<td>16</td>
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<td>16</td>
<td>-</td>
<td>-</td>
<td>1.8</td>
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<td>AWG 16 Constantan</td>
<td>Slotted thick-wall tube, 1-inch OD, 3/8-inch wall</td>
<td>20</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
</tr>
</tbody>
</table>

* Signal temperature drift for temperature change of 300°F, given in percent of full-scale signal.

*NOTE: Circuit gain manually corrected to be proportional to temperature.*

*NOTE: Temperature compensated with tungsten thermistor.*
changes in both inductance, $L$, and equivalent core-loss resistance, $R_c$. Changes in temperature of the device also caused variations in signal by affecting $L$ through changes in magnetic properties of the steel, and $R_c$ and $R_w$ through changes in resistivity in coil wire and stainless guide tube.

![Diagram of inductors](image)

**Figure 20. Circuitry for Ideal and Actual Inductors**

Variations in resistivity of the coil winding and stainless guide tube, $R_c$ and $R_w$, were independent of rod position, hence they affected only the null balance. This is termed "zero shift." The effect on signal due to changes in temperature of the movable steel rod was proportional to the length of the rod inserted in the coil. This may be considered as a change in the sensitivity of the transducer.

Tests were performed using the impedance bridge type of transducer to separate and determine the magnitude of zero shift and sensitivity change with temperature. A variable gain amplifier was inserted in the transducer output circuit between the rectifier and recorder. The temperature of the coil and
movable rod was monitored with thermocouples. As the temperature of the transducer changed during heating in the test furnace, the gain of the output circuit was varied manually to maintain constant signal at the recorder (rod in fully-inserted position). Sensitivity changes vs temperature was found to be roughly linear. Results of typical tests are listed in Table II.

Based on the results of these experiments, a circuit arrangement to provide automatic temperature compensation was devised. This circuit is shown in Figure 21. Temperature compensation was produced by a voltage-divider consisting of a thermistor \( R_T \) and output resistor \( R_o \). The thermistor used was a tungsten wire space-wound on a ceramic mandrel and mounted in close proximity to the transducer coil. As the resistance of the thermistor varied with temperature, the voltage-divider ratio, hence output circuit gain, was changed to maintain an essentially constant signal. This scheme was found to be quite effective in reducing the effect of temperature on signal, as indicated by data listed in Table II.

4. Temperature-Compensated Impedance Bridge

In tests of the temperature-compensated transducer, it was found that overcompensation was obtained during rapid temperature changes. This is due to the fact that the temperature of the movable steel rod lags behind the temperature of the coil and thermistor. Equalization and proper compensation occurs in approximately 30 minutes. During reactor temperature coefficient tests, when maximum position indication accuracy is required, it is expected that establishment of steady-state conditions for this length of time will be possible. Figure 22 is a graph of signal vs rod motion through the 20-inch coil.

5. Calibrating Coils

It is necessary to obtain a signal other than that from the long coil position indicator, to indicate when the rod is fully withdrawn or inserted. Also, during operation of the control rod, check points at intermediate positions along the long coil, which are known to be temperature-insensitive, are desirable. Such check points are useful in detecting possible electrical malfunctions or temperature effects in the long coil transducer.

To perform the required functions, a differential transformer type device was used. The long coil transducer was used as the primary of the differential transformer. For a particular check point, two small coils were wound on a
Figure 21. Circuitry for Impedance Bridge Position Indicator with Temperature-Compensating Thermistor

Figure 22. Signal vs Motion of Long Coil Position Indicator
single coil form. The coils were connected as the secondaries of the differential transformer, in series bucking. Signal output is the algebraic sum of the voltages generated by the secondary coils. When no steel has been inserted in either, or when the same amount of steel is present in both, the signal is low. However, when the end of the steel drive rod passes into one coil (before reaching the other coil) the signal reaches a maximum. The height of this signal peak may vary with temperature, but its location with respect to the small coils will be unchanged. Thus, the calibrating coils are useful as a temperature-independent check on the long coil. They can also be used as "up" and "down" indicators by amplifying their output to a large enough value to light small lamps.

IV. CONCLUSIONS

A unitized control-safety rod has been designed for the 45.5-thermal-mega-watt Organic Moderated Reactor. This type of control element is designed to be installed inside the reactor tank and to operate entirely immersed in the organic coolant. Hence, all components must be capable of operating in an ambient temperature of 550°F.

Tests have been performed on components for the unitized rod, including position indicators, shock absorbers, and magnetic jack electromagnet coils. The results of these tests have indicated that components capable of operation at this temperature are feasible. A temperature-compensated electromagnetic rod position indicator was shown to be capable of the required accuracy. Electromagnets capable of operating at temperatures up to 1000°F are feasible; however, due to water and other contaminants in the organic coolant, it was found necessary to "can" the magnetic jack coils. A significant decrease in lift coil pull-in time was found possible through use of resistance and capacitance in the coil circuit. Both ring spring and Belleville spring shock absorbers were found to perform satisfactorily at temperatures up to 600°F in air.