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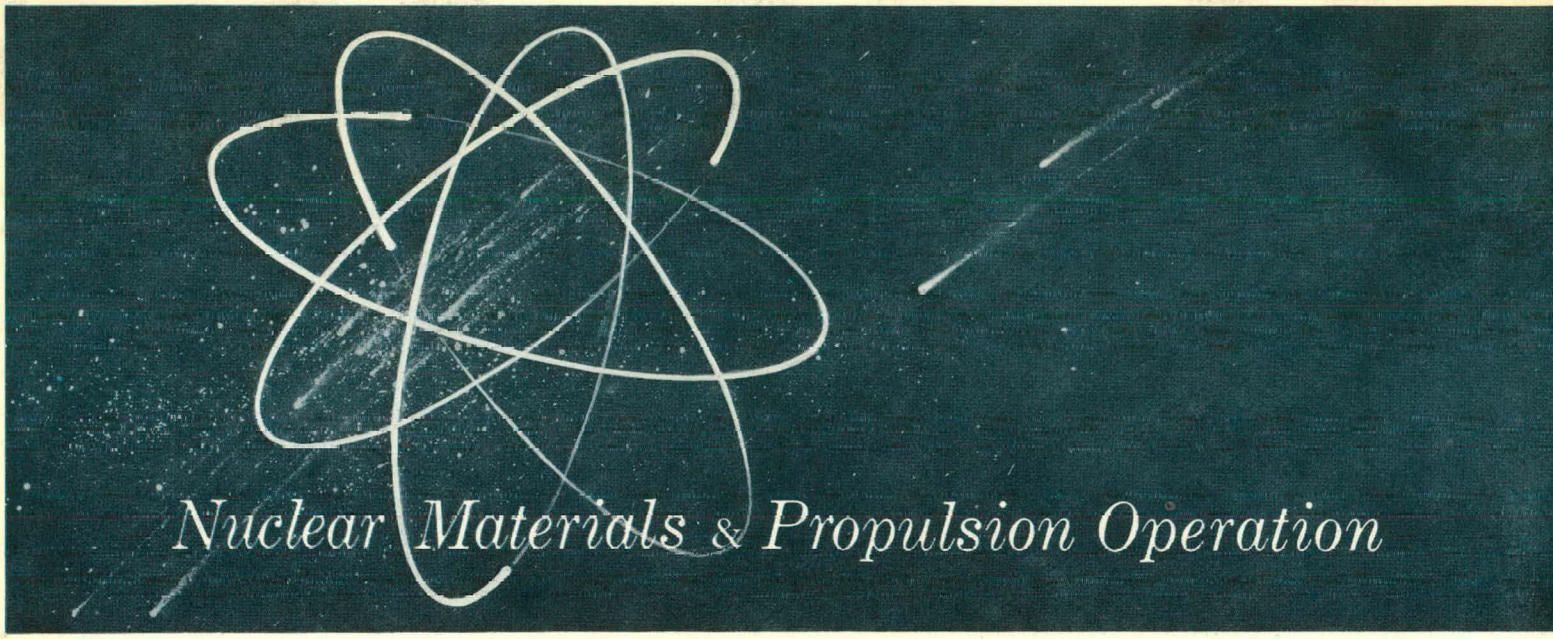

THIRD ANNUAL REPORT- HIGH-TEMPERATURE MATERIALS AND REACTOR COMPONENT DEVELOPMENT PROGRAMS

Volume III- Instrumentation and Controls

February 28, 1964

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United States Atomic Energy Commission Contract No. AT(40-1)-2847

NUCLEAR MATERIALS and PROPULSION OPERATION
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PREFACE

This report, GEMP-270C, is one of three volumes comprising the third annual report on the High-Temperature Materials and Reactor Component Development Programs being conducted by the General Electric Nuclear Materials and Propulsion Operation under Contract No. AT(40-1)-2847 of the Atomic Energy Commission.

Volumes I (GEMP-270A) and II (GEMP-270B) report the progress made from January 1, 1963 through January 31, 1964 on the unclassified and classified portions, respectively, of the materials program, and Volume III (GEMP-270C) reports the progress on that part of the contract covering instrumentation and controls. Some of these programs were terminated at the end of Fiscal Year 1963, others are continuations of Fiscal Year 1963 programs, and still others were initiated in Fiscal Year 1964. The status of each program is indicated in the more detailed breakdown of each volume given below.

This report also replaces the thirty-second bimonthly report on Ceramics and Chemistry for the period from November 15, 1963 to January 15, 1964, and the thirty-third report on Metallurgy covering the period from December 15, 1963 to February 15, 1964 except the 15 days in February. The next Ceramics and Chemistry bimonthly report, the thirty-fourth, will cover the period from February 1, 1964 to March 15, 1964. The thirty-fifth report, on Metallurgy, will cover the period from February 1, 1964 to April 15, 1964.

GEMP-270A

1. High-Temperature Reactor Materials Fabrication Research (continuation)
2. Effects of Radiation on High-Temperature Alloys (continuation)
3. Radiation Effects in BeO (continuation)
4. Fission Gas Diffusion in Unfueled Ceramic Materials (initated FY-64)
5. Fission Product Transport Processes in Refractory-Metal Fuel Systems (initiated FY-64)
6. Internal Conversion Ceramic Fuel Element Research (initiated FY-64)

GEMP-270B

1. Fuels
   - 1.1 High-Temperature Studies of Substoichiometric Urania and Urania Solid Solutions (initiated FY-64)
   - 1.2 $UO_{2.9}$ - $3Y_2O_3$ Fuel Material (terminated FY-63)
   - 1.3 High-Temperature Carbides and Borides Research (initiated FY-64)
   - 1.4 Coated Fuel Particle Development Evaluation (continuation)
2. Fuel Elements
   - 2.1 Refractory Metal Fuel Element Materials Research (continuation)
   - 2.2 Oxidation-Resistant Fuel Element Materials Research (continuation)
   - 2.3 Graphite Fuel Element Materials Research (continuation)
3. Stabilized Ceramic Fuel Elements
   - 3.1 Burnup Capabilities of Y_2O_3-Stabilized UO_2 and Stabilized Fuel - BeO Matrix Material (initiated FY-64)
   - 3.2 Coatings for Ceramic Fuel Elements (terminated FY-63)

3.3 Stabilization of UO_2 in Ceramic Fuel Elements (terminated FY-63)
3.4 Fission Product Migration in Solids (terminated FY-63)

4. Other High-Temperature Nuclear Materials Research
   4.1 Reactor Controls, Reflector, and Shield Materials Research (continuation)
   4.2 Direct Conversion High-Temperature Materials Research (continuation)
   4.3 High-Flux Reactor Materials Gaseous Fuels Research (initiated FY-64)

GEMP-270C

1. Circulating-Ball Reactivity Control (terminated FY-63)
2. Static Switching (terminated FY-63)
3. Capacitance Temperature Sensor (continuation)
4. High-Temperature Extension of Conventional Nuclear Sensors (continuation)
5. Development of Nuclear Sensors (continuation)

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FIGURES

INTRODUCTION AND SUMMARY

This report, GEMP-270C, is one of three volumes of the third annual progress report on GE-NMPO high-temperature materials and reactor component development programs during Calendar Year 1963 under Contract No. AT(40-1)-2847. This volume covers five reactor instrumentation and controls programs: 1.1, circulating-ball reactivity control with capability of operating around sharp bends; 1.2, static switching utilizing solid-state devices; 1.3, capacitance temperature sensor based on the change in dielectric constant of alumina or beryllia versus temperature change; 1.4, high-temperature extension of conventional nuclear sensors; 1.5, development of nuclear sensors for monitoring and controlling high-temperature, high-performance reactors.

Significant results achieved on these programs are as follows:

A shim - scram actuator was designed incorporating an electromagnetic drive for shim and scram, a shim speed limiting device, and a force feed-back position indicator.

A three-channel trip circuit and a two-out-of-three logic circuit using controlled switches in place of transistors was designed, built, and tested.

A capacitance-type temperature sensor was operated in an inert atmosphere at temperatures up to 2083°C (3782°F).

Models of a gridded and a compensated a-c ionization chamber were tested in both thermal neutron and gamma environments. The compensated a-c ionization chamber demonstrated better than 98 percent gamma compensation at a thermal-neutron flux of 5×10^{-11} nv and 1 megawatt reactor power.

1. CIRCULATING-BALL REACTIVITY CONTROL (57101)

The objective of this program was to develop methods of nuclear reactor control with the capability of operating around sharp bends that may exist between the drive head and the control element.

This program, terminated June 30, 1963, was reported in detail in past progress reports.* A topical report on the program will soon be issued.

1.1 SUMMARY AND CONCLUSIONS

Work during this program centered on two similar concepts of reactor control, both capable of operating around sharp bends. One design employed a string of balls that were circulated in a closed loop by a mechanical drive. The other design was based on a rod composed of small spherical-ended segments joined by a flexible cable and driven by a linear electromagnetic drive. Although the circulating-ball design was successfully demonstrated, the problem of ball jamming was never completely solved and could have resulted in unreliable reactor control. The segmented-rod design was successfully demonstrated as a shim - scram-type actuator; no characteristics that might be detrimental to further development were revealed during the work on this type of control.

1.2 RECOMMENDATIONS

No further work is warranted on the circulating-ball type of control.

Because the electromagnetic drive portion of the segmented-rod design demonstrated excellent potential, it should be investigated further. The electromagnetic drive might prove to be superior to the magnetic-jack-type actuator now in widespread use. Besides a large reduction in the number of moving parts, it would also provide an additional scram capability not present in the magnetic-jack design.

*"Reactor Instrumentation and Control Progress Report No. 70 through 78," GE-NMPO, GEMP-70 through GEMP-78, January 19, 1962 through July 31, 1963.

2. STATIC SWITCHING

(57102)

The objective of this program was to develop static switching circuits utilizing solid state devices in place of mechanical relays or electron tubes in order to achieve increased speed of operation, increased reliability, and reduced size and weight. An application for these circuits is in nuclear reactor fast scram systems where it is important to have minimum time lag between a condition in the reactor that requires scram and the actual scramming of the reactor.

The work on this program was terminated June 30, 1963, and is covered in detail in past progress reports* and in a topical report that will be issued soon.

2.1 SUMMARY AND CONCLUSIONS

The unitunnel diode-transistor trip circuit coupled with a controlled rectifier latching circuit, that was developed under this program, has the following advantages in comparison with existing trip circuits.

1. Fast response. The response of the trip circuit is less than 600 microseconds. The response of the latching circuit is a function of the power supply frequency and the load.
2. Very few parts. The trip circuit requires only 11 parts, including six resistors. The latching circuit requires 20 parts.
3. Stable and accurate trip point. The trip point is established by the unitunnel diode and requires no external voltage or current reference source.
4. Low trip point setting. The trip point can be set as low as 40 microamperes.
5. Small size and light weight. Each trip circuit can be contained in a volume element 2 inches long, 1 inch wide and 1 inch high, and would weigh less than 4 ounces.

In addition to this circuitry, a trip circuit using unitunnel diodes and a controlled switch was investigated. This circuitry proved to have extremely fast response but was easily triggered by random noise pulses. A controlled rectifier circuit was designed to control the linear induction motor used in Task 57101.

2.2 RECOMMENDATIONS

It is recommended that the unitunnel diode-transistor trip circuit and the associated controlled rectifier latching circuit be further developed for a specific reactor control.

*"Reactor Instrumentation and Control Progress Report No. 70 through 78," GE-NMPO, GEMP-70 through GEMP-78, January 19, 1962 through July 31, 1963.

3. CAPACITANCE TEMPERATURE SENSOR

(57104)

The objective of this program is to develop a probe-type temperature sensor that will be more stable under the influences of high temperature and contaminating environments than present probe sensors. The sensor will depend upon a change of dielectric constant of alumina, beryllia, or other ceramic materials with respect to temperature.

Two general types of capacitance temperature sensors are presently under development in this program. One type would be used in an oxidizing atmosphere and the other used in a vacuum or an inert gas atmosphere.

With some limitations, alumina, beryllia, and thoria appear to be the most promising dielectric materials in the capacitance temperature sensors used in either oxidizing or non-oxidizing atmospheres. The present limit for operation in an oxidizing atmosphere was established as 1649°C (3000°F) with the limiting factor being the melting point of the platinum electrodes. The present upper temperature limit for operation in a non-oxidizing atmosphere has not been established, but from test results this appears to be in excess of 2083°C (3782°F).

3.1 HIGH-TEMPERATURE TESTS IN NON-OXIDIZING ATMOSPHERES

Prior to Calendar Year 1963 all testing was accomplished in an oxidizing atmosphere at temperatures below 1649°C. During Calendar Year 1963, several tests were run above 1649°C in an inert atmosphere and with refractory metals as the electrodes. The first test in this series was the probe shown in Figure 3.1 which employed alumina as the dielectric and molybdenum as the electrodes. The sensor exhibited good response but extremely poor repeatability. Although the alumina apparently melted on the second run, a catastrophic failure of the sensor did not result; only a gradual drift downward occurred in the frequency. This test was conducted in hydrogen. The results of the two runs are shown in Figure 3.2.

The second and third tests in this series were conducted in argon with a probe constructed with molybdenum electrodes and a beryllia dielectric. The probes differed in mechanical construction in that the probe in test No. 2 resembled the alumina probe of test No. 1, and the probe in test No. 3 was electrically shielded. Although test No. 2 exhibited good sensitivity to 2260°C (4100°F), repeatability was poor, probably caused by the somewhat loose mechanical design. A better mechanical design enabled the third test to demonstrate good repeatability, but the probe lost sensing ability above 1649°C. To improve sensing above this temperature, the readout circuitry was reviewed, and the change in electrical resistance of beryllia with temperature was studied. One of the components in the readout circuitry was a 51-picofarad capacitor in series with the probe capacitor. A post-test bench check of the readout circuitry disclosed that, when low resistance values were applied across the sensor cable, the series capacitor was shorted to ground. This resulted in allowing the series capacitor to determine oscillator frequency instead of the sensor capacitance. As shown in Figure 3.3, measurement of the electrical resistance of the beryllium in the

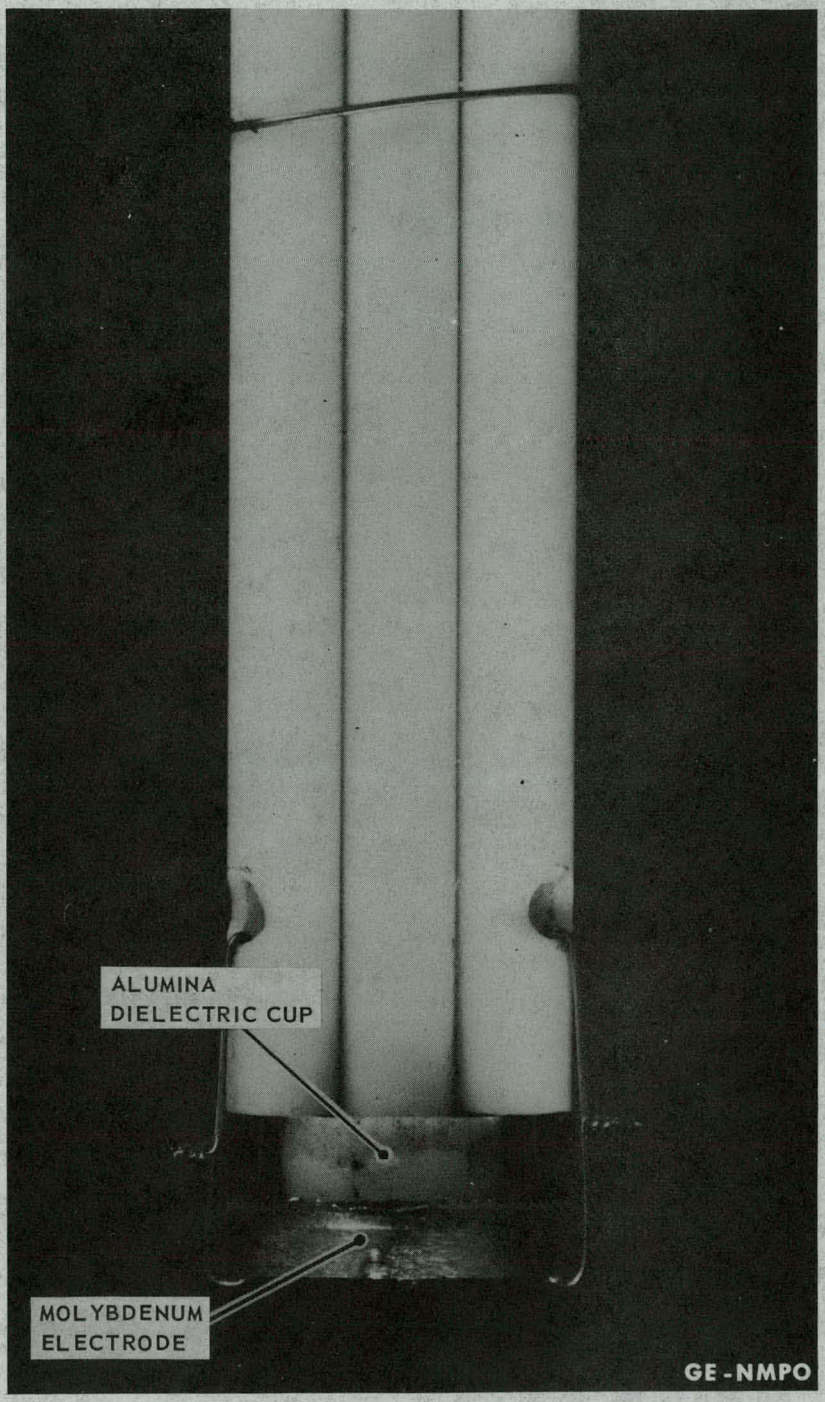

Fig. 3.1 – Molybdenum-alumina test specimen prior to testing to the melting point of alumina (Neg. P62-8-15)

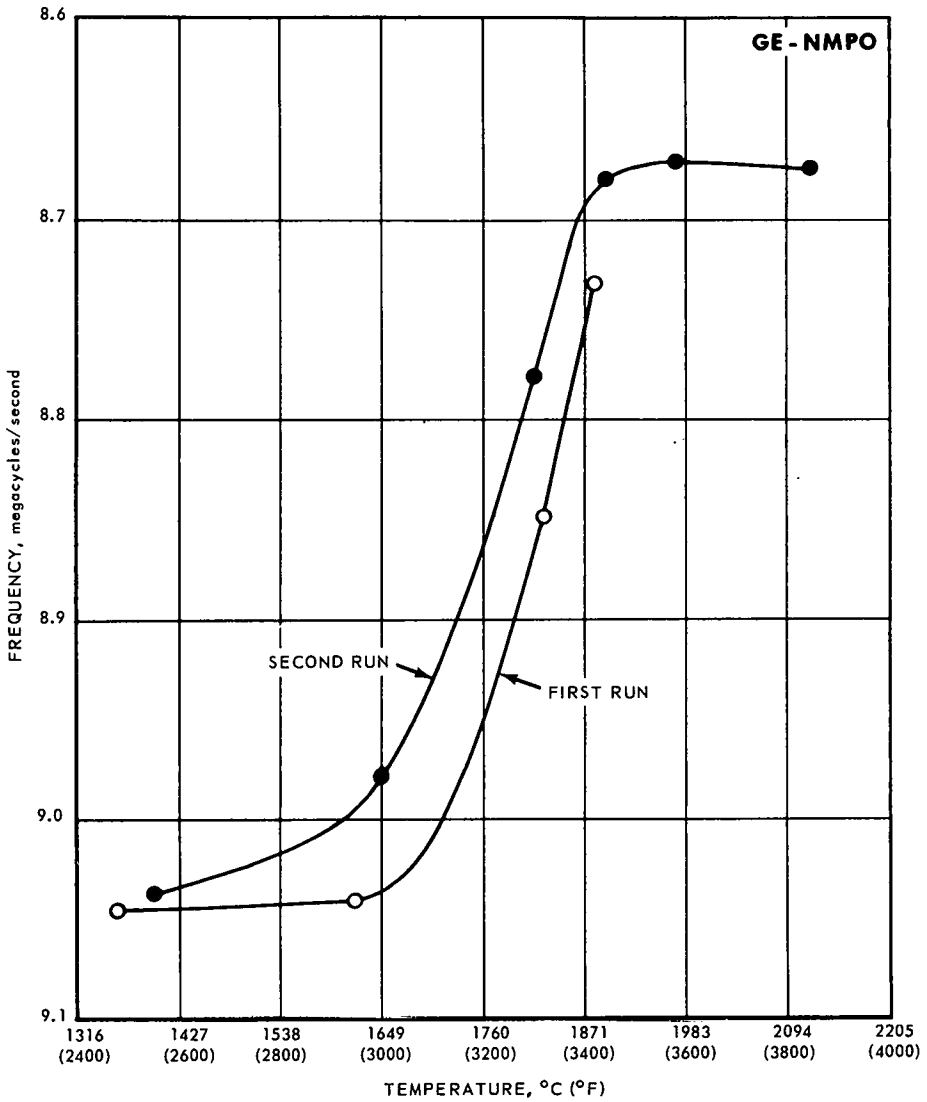

Fig. 3.2 – Response of an alumina sensor at maximum temperature

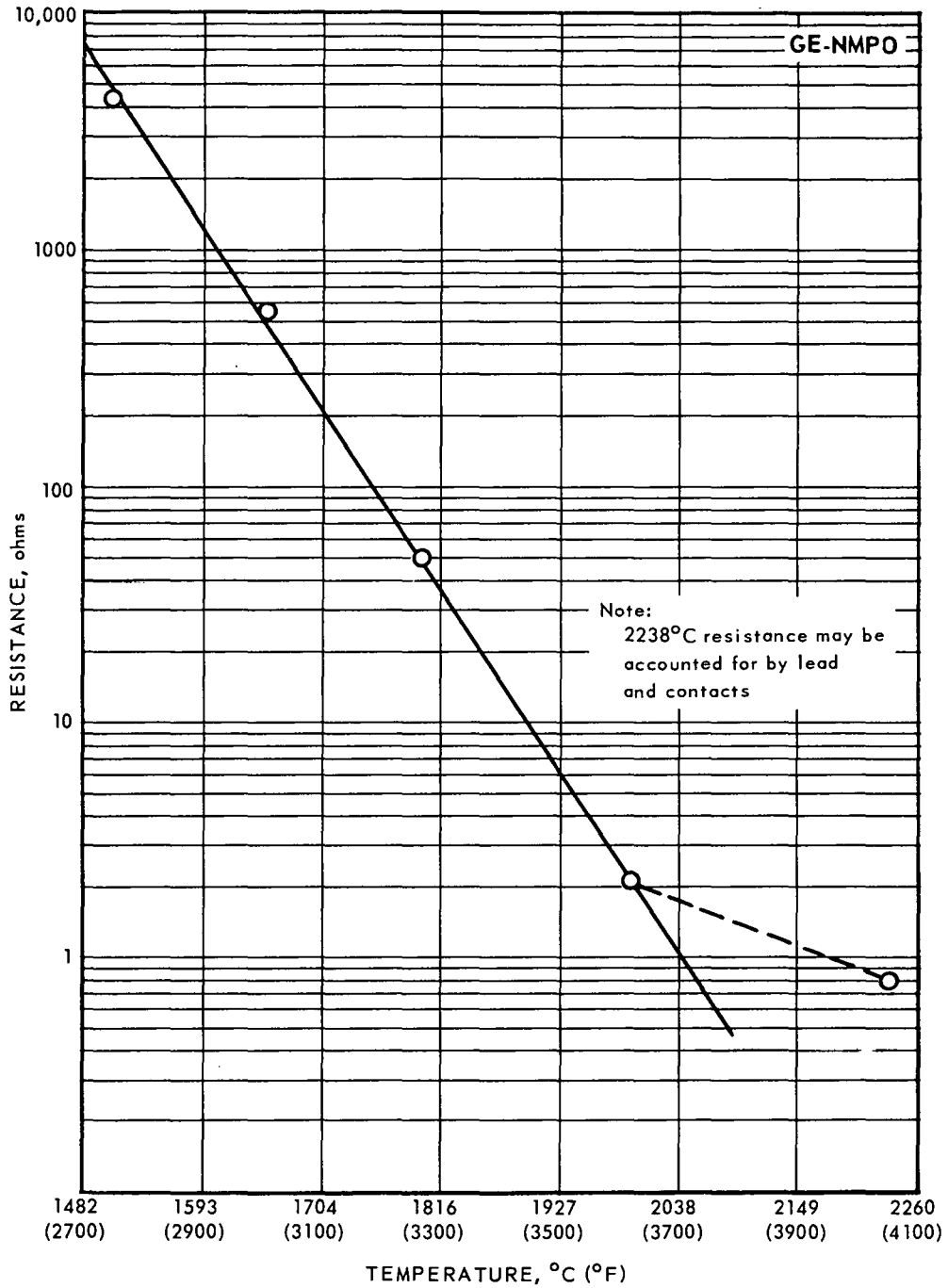

Fig. 3.3 – Resistance change in shielded BeO-Mo probe (tested in argon)

sensor revealed that a very low resistance could exist across the cable when the sensor was at high temperature. This appeared to account for the failure of the sensor at 1649°C since the resistance of the sensor had dropped from 10,000 to less than 1000 ohms.

3.2 SENSOR AND CIRCUITRY RE-DESIGN

The new requirements of higher electrical resistance of the sensor at temperature and/or removal of the capacitor in series with the sensor required re-design of the sensor and the readout circuitry. Removal of the series capacitor required that the oscillator tolerate a very low shunt resistance (temperature effect on the dielectric material) or that somehow the sensor maintain a high electrical resistance (500 to 1000 ohms) at the maximum operating temperature.

The popular room temperature concept of a condenser is a pair, or series of pairs, of plates with dielectric separators between the plates or electrodes. The sensors tested to date were of this general geometry. However, this concept was changed considerably to provide the required higher electrical resistance. Figure 3.4 is a preliminary test model of a new design. Basically, the electrodes were moved apart to increase the electrical resistance at temperature. Figure 3.5 is a plot of the resistance versus temperature of the test model. As shown, the resistance is still above 100 ohms at 2000°C (3632°F). The same test sensor was operated as a capacitance sensor to 1993°C (3619°F) with excellent response. This rather unorthodox type of capacitance geometry could be suitable for future sensor development. A more sophisticated model of this geometry was constructed and will soon be tested. The new probe will be evacuated in anticipation of other atmospheres, which may become conductive, such as hydrogen or argon.

The re-design of the readout circuitry to eliminate the series capacitor required additional investigation that eventually led back to the sensor dielectric material. Up to this point in the overall sensor development program, capacitance and resistance measurements of the sensor were accomplished with a commercial-type precision impedance-bridge instrument. The investigation disclosed that measurements with this instrument could be in error by several decades if the capacitor being measured did not maintain a

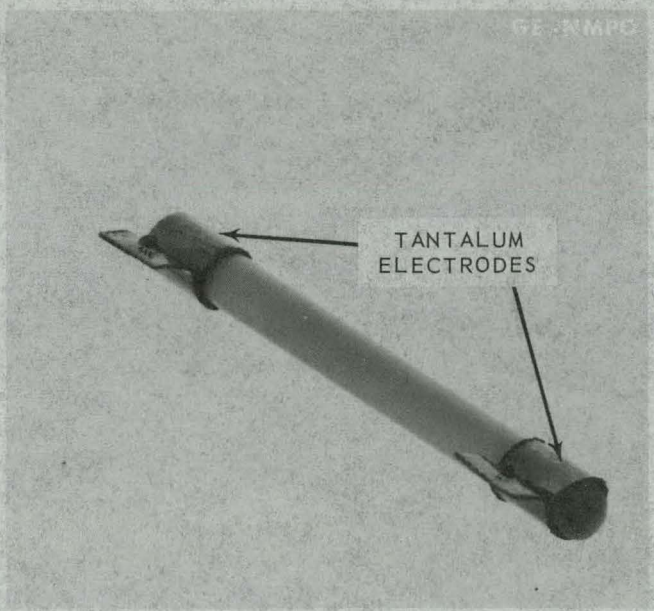

Fig. 3.4 – BeO specimen with tantalum electrodes (Neg. P63-9-3)

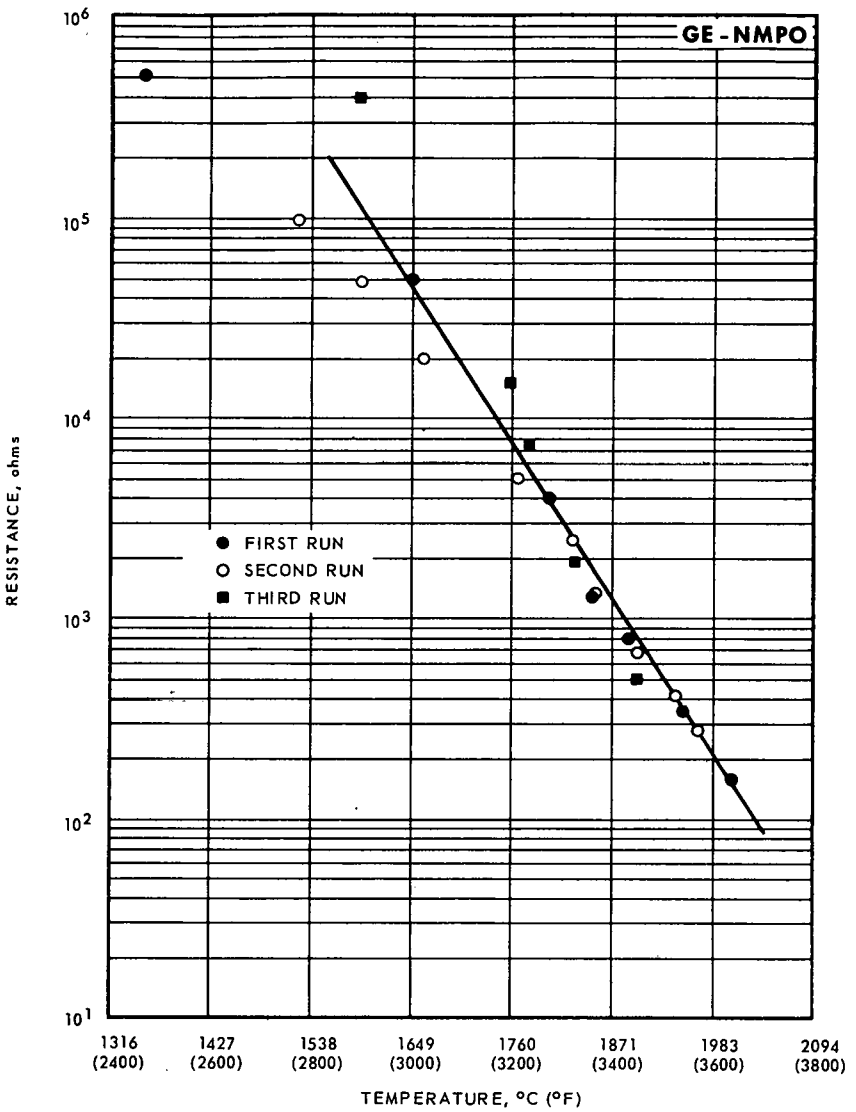

Fig. 3.5 – Resistance of beryllia-tantalum specimen

high resistance or did not behave as a capacitive element. In an attempt to improve these measurements, the bridge circuit shown in Figure 3.6 was constructued and used to measure the resistive and capacitive components of sensor impedance. Small capacitive values could be determined at resistances as low as 500 ohms. The capacitive changes formerly observed in the sensor were smaller by several decades when measured with this bridge than the values measured with the commercial impedance bridge. Based on this information, the capacitor that was in series with the sensor was removed. The transistorized oscillator circuit, shown in Figure 3.7, was constructed and operated with a probe up to 2083°C. Somewhere between 2083° and 2121°C (3850°F) the probe resistance dropped enough to stop oscillation of the readout circuitry. The dual approach of increasing probe resistance and removing the series capacitor increased the upper operating limit of the probe from 1993°C to 2083°C in an inert atmosphere. It is quite conceivable that, when operating in a vacuum, the upper limit is quite close to 2205°C (4000°F).

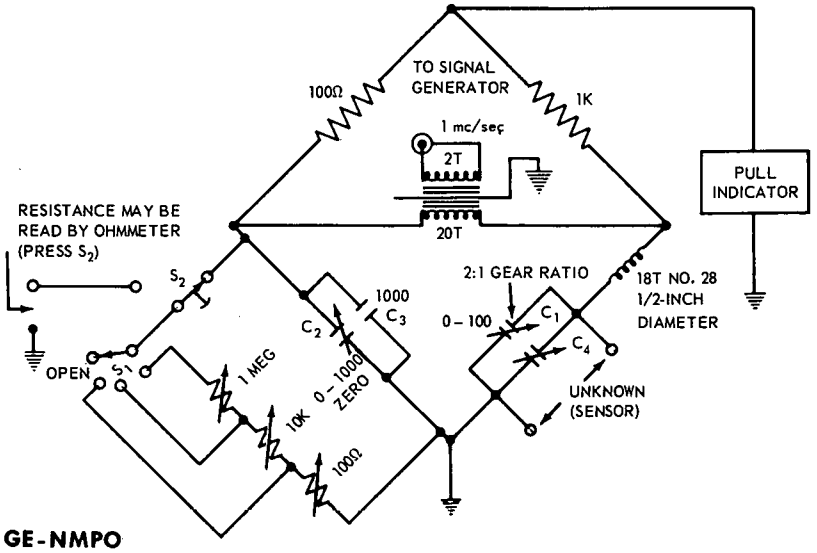

Fig. 3.6 – Present bridge arrangement for resistance and capacitance resolution

3.3 SUMMARY AND CONCLUSIONS

Beryllia and thoria appear to have good potential for use as the dielectric material for sensing temperatures above 1983°C (3600°F). The low electrical resistivity exhibited by these materials at high temperatures may be compensated for by changing the geometry and increasing the tolerance of the electronic circuitry to low resistance.

3.4 PLANS AND RECOMMENDATIONS

Beryllia, thoria, and possibly yttria will be tested in the configurations calculated to develop the most favorable resistance-to-capacitance ratio. Effort will be extended to establish the upper operating limit for a capacitance-type temperature sensor in non-oxidizing atmospheres.

The sensor for use in oxidizing atmospheres will be further refined by possible substitution of single crystal sapphire for the alumina.

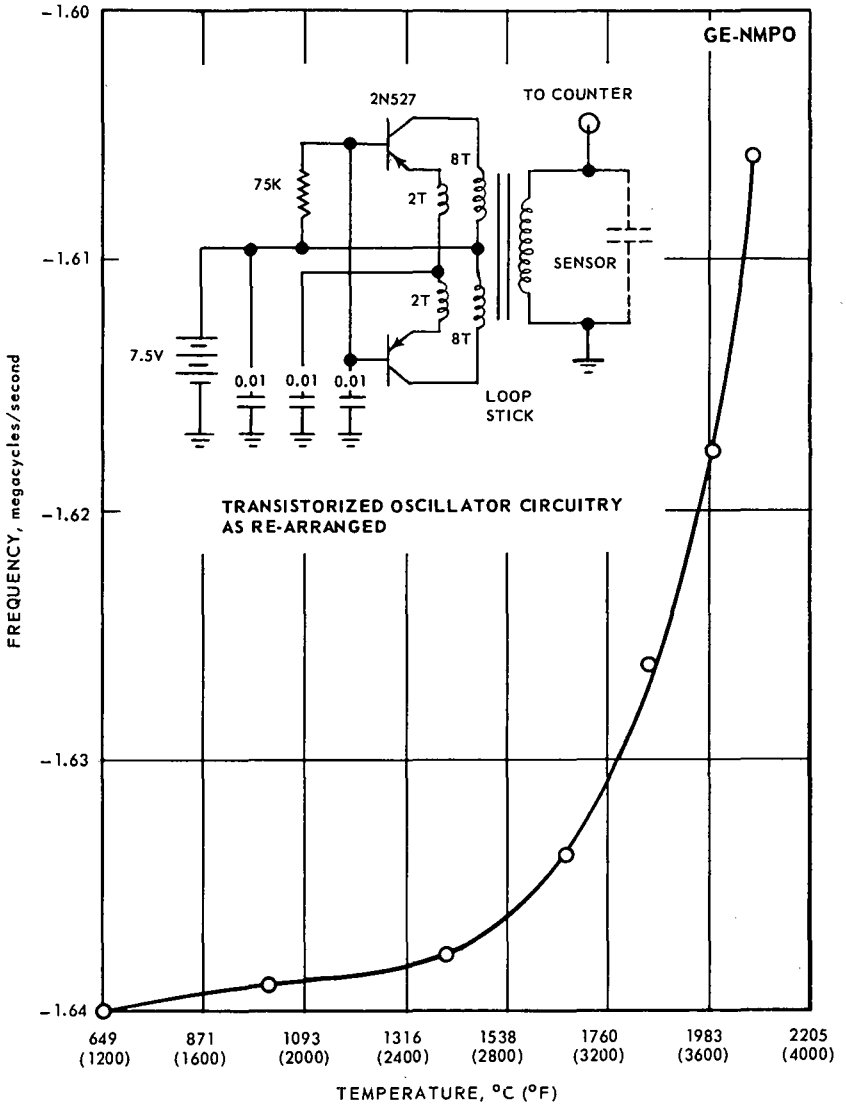

Fig. 3.7– Frequency response of re-arranged beryllia transistor oscillator

4. HIGH-TEMPERATURE EXTENSION OF CONVENTIONAL NUCLEAR SENSORS

(57106)

The objective of this program is the extension of conventional nuclear sensors for operation to higher temperatures. The objective temperatures are 816°C (1500°F) for fission counters and 538°C (1000°F) for d-c ionization chambers.

4. 1 FISSION COUNTERS

Design and Materials

The basic design of the experimental 816°C fission counter is shown in Figure 4. 1. Concentric cylinders were used for the construction of the anode and cathode structures. The anode was fabricated as an integral part of the vacuum seal which is used to separate the counter from the coaxial extension lead. The vacuum seal was constructed by furnace-brazing nickel-metal members to the metallized high-purity alumina insulator. The brazing was carried out in a hydrogen atmosphere using oxygen-free high-conductivity copper as the braze material. The cathode was fabricated from either nickel or stainless steel; it has an outside diameter of 1. 27 centimeters and a length of 4. 5 centimeters. The neutron sensitive material, U^{235}, was applied only to the internal surface of the cathode to a thickness of 1 mg/cm^2, yielding a total coated area of 10 cm^2. The low-capacitance extension coaxial lead was constructed to be noise-free. The overall length of the counter, lead extension, and adapter containing a coaxial connector was 91. 4 centimeters.

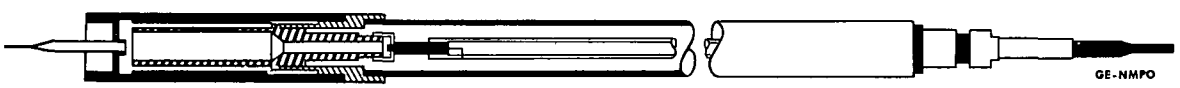

Fig. 4.1 – Design of 816°C fission counter

Fabrication and Testing

The fission counter assemblies were fabricated exclusively by inert-gas shielded arc-welding methods after all parts were carefully cleaned and dried. The welded counter assemblies were evacuated and outgassed at a temperature of 835°C (1535°F) and a pressure of approximately 10^{-6} mm of Hg for several hours. After the assemblies were cooled to room temperature, the counter and extension lead were individually filled with dry argon gas to a pressure of 1 atmosphere.

The fission counters were mounted in the source tank and electrically heated while monitoring the output of a Po-Be neutron source. Prior to temperature testing, each counter was tested for a minimum of 24 hours at room temperature to establish a basis of comparison. Integral bias data, signal-to-noise ratio, saturation characteristics, voltage breakdown, and fission-induced pulse characteristics were the parameters of basic

interest. Ten counters were tested at 816°C. Seven of the ten counters operated adequately at this temperature indicating that satisfactory fission counter operation to a temperature of 816°C is feasible. These seven counters withstood the testing temperature for times ranging from 225 to 514 hours. Two of the counters failed after 5 and 46 hours, respectively. The tenth counter was extremely noisy throughout the total of 312 hours at 816°C when complete failure was observed.

Figure 4.2 is a representative integral bias curve comparing fission counter operation at room temperature and at 816°C. The figure indicates that the inherent counter sensitivity and slope of the counting-rate plateau do not change over the range of testing temperatures. However, the length of the counting-rate plateau is shortened as a result of a decrease in amplitude of the fission-induced pulses as the temperature is increased. The significance of the counting-rate plateau is that a minimum loss of counter sensitivity is incurred per unit change of electronic bias setting over the length of the plateau. This is important in biasing out random noise, but is of even greater importance for biasing out gamma ray pulse pile-up effects. The decrease in pulse amplitude and the subsequent shortening of the plateau length was most pronounced as the temperature was increased above approximately 675°C (1247°F).

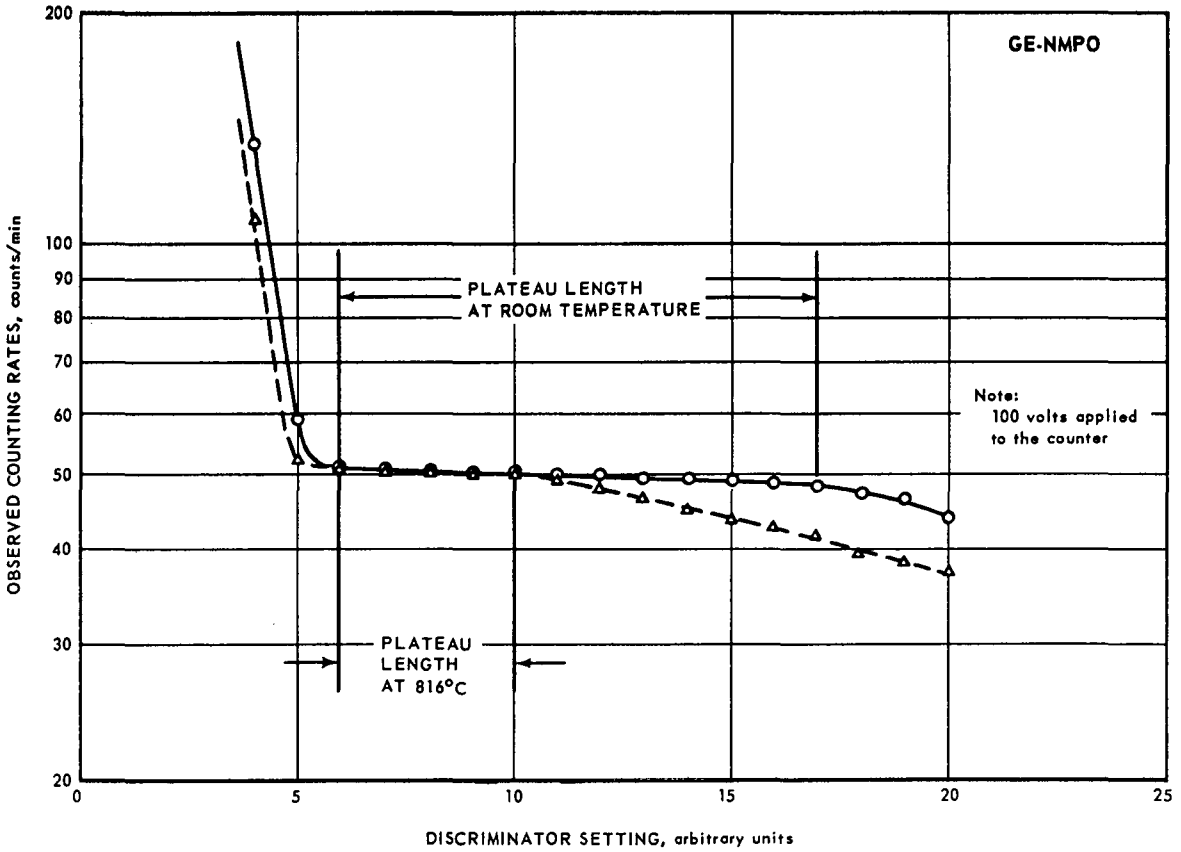

Fig. 4.2 – Integral bias data comparing fission counter operation at room temperature and at 816°C

Component Testing

Six counter assemblies* without fissionable material applied to the cathode were tested to investigate their long-life capability at 816°C. The results varied; time at the testing temperature of 816°C before failure occurred ranged from 195 to 626 hours. These six

*"Reactor Instrumentation and Control Progress Report No. 77," GE-NMPO, GEMP-77, May 31, 1963, pp. 31–32.

assemblies and the ten fission counters which failed as a result of the temperature testing were disassembled and examined. With the exception of one counter assembly, the cause of failure was located at the furnace-braze joint between the welding flange and the metallized alumina insulator. The nickel plating applied over the Mo-Mn metallized alumina surface was separated from the metallizing, thereby destroying the integrity of the vacuum seal.

Nine vacuum seals* of the design shown in Figure 4.3 were tested and determined to be highly resistant to thermal shock and temperature soaking. Five of these seals were temperature cycled in air to 816°C at least nine times each without failure. One seal maintained vacuum integrity after being thermal-cycled to 816°C fifteen times. The other three seals were still vacuum-tight after testing for 350 hours at 816°C and six thermal cycles to 816°C.

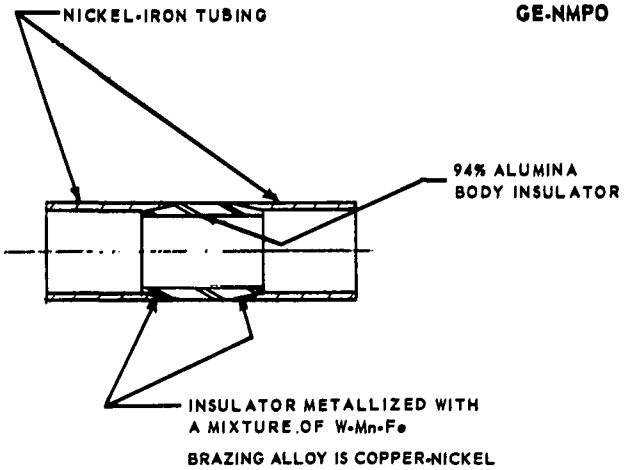

Fig. 4.3 – Vacuum seal assembly tested to 816°C

The superior performance of this type of vacuum seal is due to the design and fabrication techniques used by the vendor. Complementary tapers on the metal parts and the mating metallized insulator surfaces produce an optimum fit-up of parts. The binding process utilized during brazing limits the expansion of the metal sleeves and insures intimate contact between the metal sleeves, the copper brazing material, and the metallized insulator. The metal sleeves are prestressed by the binding process utilized during the brazing cycle. Prestressing of the metal sleeves alters the normal expansion differences during subsequent heating cycles and temperature soakings. There is an apparent safety margin of approximately 275°C (527°F), the difference between counter operating temperature and prestressing temperature. However, the high purity (94%) of the alumina insulator of the vacuum seal is still the limiting factor from the standpoint of deriving the maximum fission-induced pulse output from the counters. Therefore, improved counter operation is dependent upon fabricating the vacuum seals with insulators of the highest purity. Long-life capability at 816°C should be enhanced by this type of vacuum seal, and reliable operation of vacuum seals of this type for 500 to 1000 hours at 816°C appears to be practical.

* "Reactor Instrumentation and Control Progress Report No. 78," GE-NMPO, GEMP-78, July 31, 1963, pp. 34–35.

4.2 D-C IONIZATION CHAMBERS

Design and Materials

Uncompensated, neutron-sensitive, d-c ionization chambers are used to provide neutron flux measurements in the power operating range of nuclear reactors. The power operating range usually extends downward two decades from the full-power rating of the reactor. Figure 4.4 illustrates the design of an uncompensated d-c ionization chamber which was built and tested to a temperature of 538°C. The high-voltage and collector electrodes were constructed of stainless steel concentric cylinders coated with 1 mg/cm^2 of B^{10}. An electrode separation of 0.076 centimeter allows the chamber to be saturated with a maximum of 300 volts for a 1-milliampere neutron-induced output current. Leakage currents flowing in the high-voltage insulator are intercepted by the guard ring system and consequently are not a part of the signal current. The guard ring is also utilized to electrically define the collecting volume and to provide an electrostatic and personnel safety shield. Stainless steel, nickel, and high-purity alumina were the basic materials used to construct the chambers.

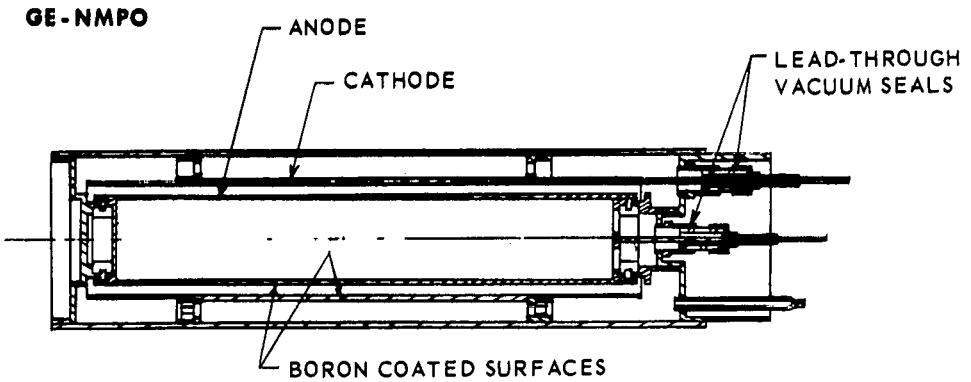

Fig. 4.4 – Uncompensated d-c ionization chamber for operation to 538°C

Fabrication and Testing

Inert-gas shielded arc welding was used exclusively to fabricate the assemblies after all parts were carefully cleaned and dried. The welded chambers were evacuated and outgassed at a pressure of approximately 10^{-6} mm of Hg and a temperature of 649°C (1200°F) for several hours. After cooling to room temperature, the chambers were filled with dry nitrogen gas to a pressure of 1 atmosphere.

One chamber of the type shown in Figure 4.4 was tested to a temperature of 538°C for 838 hours. Testing was not on a continuous basis because the temperature was reduced to room temperature every 75 hours. Heating rates applied to the chamber were maintained at approximately 250°C (482°F) per hour throughout the testing. The temperature was reduced to room temperature in approximately 5 hours by shutting off the furnace. The maximum temperature-induced leakage current of 1.9×10^{-7} ampere at 538°C indicates that approximately three decades of linear neutron-induced current can be realized. The test was discontinued after 838 hours as a result of a failure in a cathode support-structure plug weld.

Two other chambers of the same type were tested to 538°C for 750 and 375 hours, respectively, without evidence of failure. Maximum leakage currents for the two chambers

were observed to be 2.5×10^{-7} and 2.1×10^{-7} ampere. The data, therefore, indicate that adequate reactor-power-range neutron sensing is feasible using this type of uncompensated d-c ionization chamber. Improvement of the design would be greatly enhanced if higher purity insulating components were available.

Component Testing

The construction of d-c ionization chambers for higher temperature applications is dependent upon the availability of vacuum seals that must exhibit a long-life capability and must be highly resistant to thermal shock. The dielectric used in the seals must contribute minimum temperature-induced leakage currents and must be capable of withstanding the required applied potentials without electrical breakdown.

Three types of vacuum seals for possible ionization chamber applications were tested to a temperature of 538°C. Vacuum seals insulated with sapphire exhibited the lowest temperature-induced leakage currents. Long-life capability at temperature has not been adequately demonstrated. The evaluation of this parameter has been hampered because the body flange of the seal is not adequate for welding. However, the seals have not failed in approximately 300 hours of testing.

Vacuum seals insulated with 94-percent alumina have been vastly superior from the standpoint of long life at temperature and thermal shock. Seals of this design (Figure 4.3) were tested to 816°C for possible application to fission counters. They have not failed after 350 hours at 816°C and six thermal-shock cycles from 816°C to room temperature. However, leakage currents developed at 538°C by seals of this design have not been as satisfactory as obtained with the sapphire seals.

Vacuum seals insulated with Lucalox,* fabricated by the same vendor and to the same design as the 94-percent alumina seals (Figure 4.3), have been received but testing is not complete. However, the initial investigation indicates that the temperature-induced leakage current for Lucalox-insulated vacuum seals is greater than for the sapphire-insulated ones. Figure 4.5 is a plot of leakage currents developed as a function of temperature by the three different seal designs.

Solid-dielectric coaxial lead extensions were also investigated for use with d-c ionization chambers at higher temperatures. Figure 4.6 is a representative plot of developed leakage currents and corresponding resistances of an MgO-insulated coaxial cable tested to 649°C (1200°F) with 300 volts applied. Cables of this type have been repeatedly cycled to 649°C and have been maintained for several hundred hours at this temperature without detrimental effects. The sheath of the cable is stainless steel swaged to a diameter of 0.635 centimeter, and the conductor is nickel tubing with a diameter of 0.159 centimeter.

4.3 SUMMARY AND CONCLUSIONS

Fission-counter operation to a temperature of 816°C was demonstrated to be feasible, but operation at this temperature was not entirely satisfactory. Insulators of the highest purity are necessary to achieve the maximum amplitude for the fission-induced pulses. Reliable operation of vacuum seals for 500 to 1000 hours at 816°C appears to be practical based on the evaluation of an improved vacuum seal design. Adequate reactor power range neutron sensing to a temperature of 538°C is feasible using uncompensated d-c ionization chambers. A significant reduction of temperature-induced leakage currents is possible if insulators of the highest purity are utilized. Longer operating life at temperature for the ionization chambers can be anticipated as a result of improvements in vacuum seal technology.

*Registered trademark of the General Electric Company.

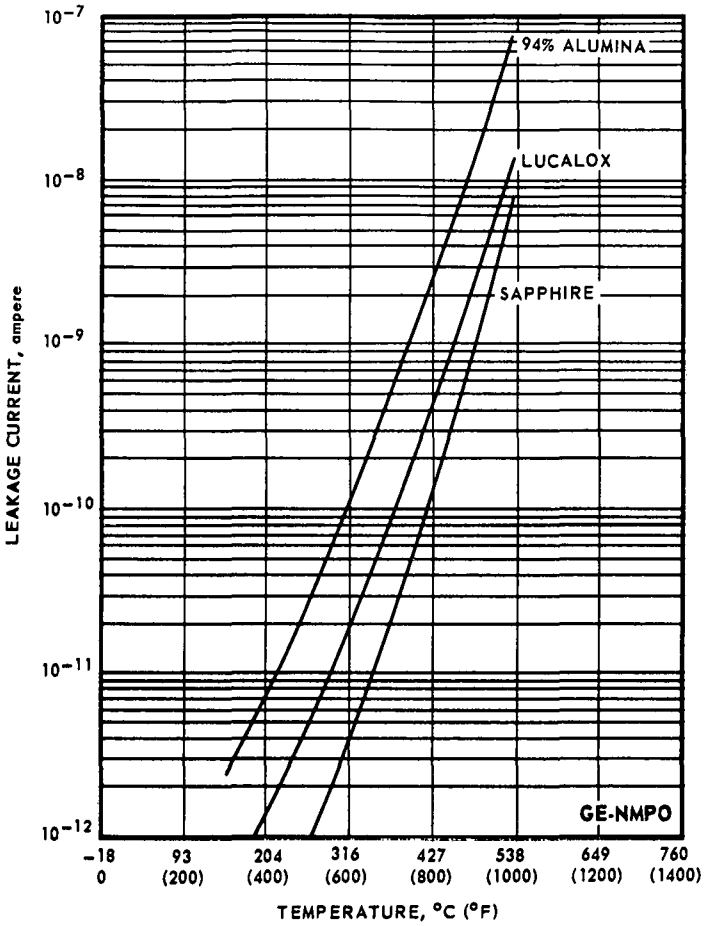

Fig. 4.5 – Temperature-induced leakage currents for the indicated insulating materials with 100 volts d-c applied

4. 4 PLANS AND RECOMMENDATIONS

The evaluation testing of the improved vacuum seal design utilizing Lucalox insulators will be completed. The results of this testing will be applied to the fission counters and d-c ionization chambers for operation to the proposed temperatures. Testing emphasis will be to obtain the pertinent resistance and leakage current data and to demonstrate long-life capability of the vacuum seal design. The investigation of other materials and detector configurations will also be continued.

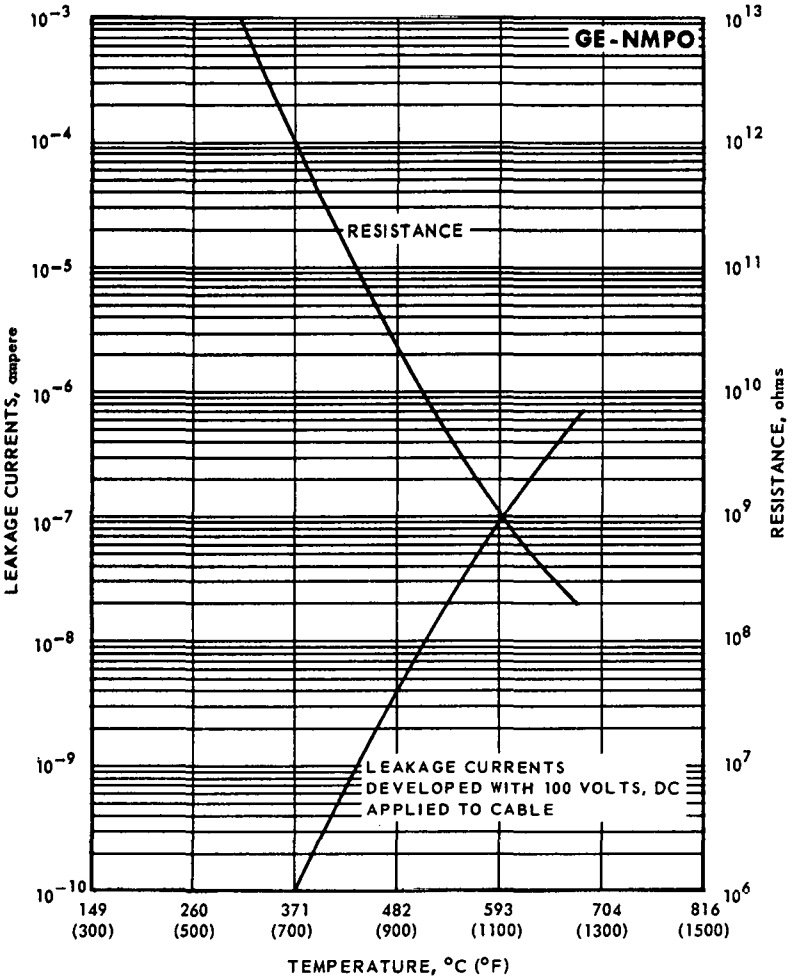

Fig. 4.6 – MgO coaxial cable temperature test data

5. DEVELOPMENT OF NUCLEAR SENSORS

(57107)

The objective of this program is to develop advanced nuclear sensors for general use in the nuclear industry for monitoring and controlling high-temperature, high-performance reactors.

During Calendar Year 1963 emphasis was placed on the development of a-c ionization chambers and charged-fragment detectors.

5.1 A-C IONIZATION CHAMBERS

A-C ionization chambers display an alternating-current signal which is a function of thermal neutron flux and can be analyzed with regard to amplitude, phase, and frequency characteristics. Rugged, reliable a-c instrumentation can be used with these ionization chambers. Some units discriminate against the d-c leakage currents which tend to increase as a function of temperature. The following paragraphs discuss the different types of chambers and the testing and evaluation of each type.

Grid Chambers

One method of producing an a-c output from an ionization chamber is to modulate the ion current enroute to the chamber collector by means of a double grid. The grid circuit is biased and driven with a sinusoidal voltage which produces a signal in the collector circuit which is twice that of the driving frequency. This signal is then easily separated from any d-c leakage currents.

In the first gridded chambers,* constructed by winding the grids on an insulating form placed around the collector, proper grid separation and tension at 538°C was difficult to maintain. Subsequently, a more satisfactory design was achieved by making cylindrical, self-supporting grids.†

Gridded chambers were operated with frequencies up to 15,000 cps. Complete electronic systems were built to operate at fixed frequencies of 120, 500, and 10,000 cps. A time response of less than 1 millisecond was obtained with a gridded chamber and a 10,000-cps electronic system.‡ While a system balance was easier to obtain with the low frequencies, the need for a faster time response made the higher frequencies necessary.

Two cylindrical gridded chambers were built and tested at the Bulk Shielding Facility at ORNL. These chambers are shown in Figure 5.1. A signal current of about 10^{-9} ampere could be detected and the linear range of the chambers was from about 1.7×10^{8} to 1.7×10^{11} nv.§ These chambers were designed to operate with about 500 volts applied, and a

*"Reactor Instrumentation and Control Progress Report No. 76," GE-NMPO, GEMP-76, April 29, 1963, p. 39.

†"Reactor Instrumentation and Control Progress Report No. 77," GE-NMPO, GEMP-77, May 31, 1963, p. 36.

‡Ibid., p. 39.

§"Reactor Instrumentation and Control Progress Report No. 79," GE-NMPO, GEMP-79, September 30, 1963, p. 19.

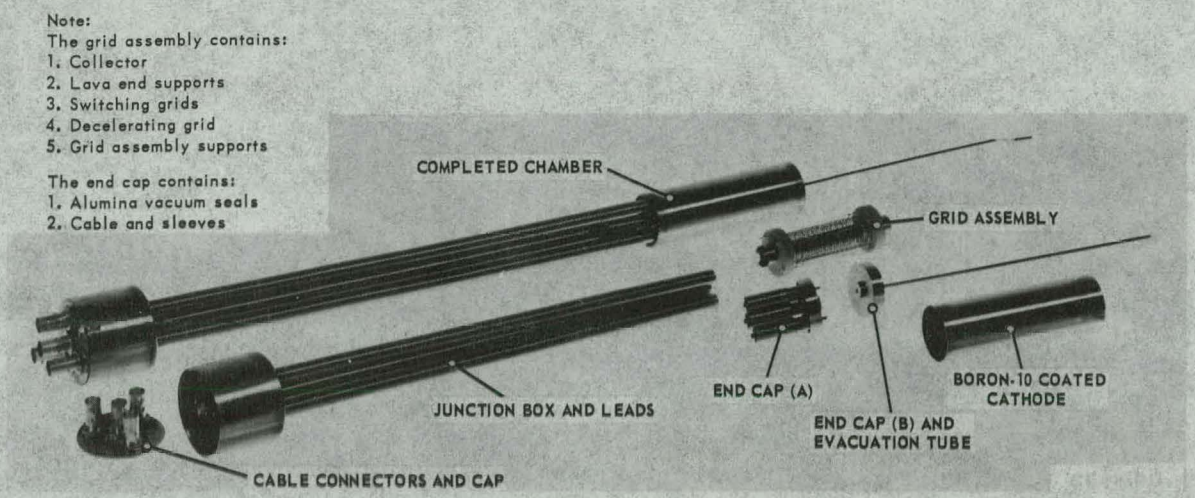

Fig. 5.1 – Cylindrical gridded chambers (Neg. P63-6-17)

switching voltage of about 100 volts peak-to-peak across the grids. Increased voltages should extend the thermal neutron range of this device.

A cylindrical-chamber grid assembly was also tested at 538°C to determine if any temperature-induced imbalance would be present. The change in system balance as a function of temperature was found to be insignificant.

Split-Collector Chambers

Split-collector a-c ionization chambers produce an a-c output signal by switching the ion current between two collector circuits. The collectors are intermeshed but insulated from each other as shown in Figure 5.2. These chambers are controlled by a modulated driving voltage which produces a signal of the envelope frequency. The split-collector elements for low-temperature chambers were easy to fabricate, since conventional printed circuit materials and techniques could be used. The performance of the split-collector chamber at lower temperatures was demonstrated early in the program.* However, none of the high-temperature units fabricated to date was completely satisfactory. It was necessary to use ceramic materials as insulators at 538°C and difficulty was encountered in maintaining at least 1 megohm resistance between the collectors. The close tolerance between collector conductors (0.025 cm) accentuated surface resistance problems.

The use of a new type of ceramic such as Lucalox and a different technique of surface cleaning might alleviate the resistance problem, making fabrication of a dependable high-temperature unit feasible.

Compensated A-C Ionization Chambers

Compensation is most easily accomplished by using ionization chambers with two sensitive elements in a bridge network; one element sensitive only to gamma radiation, the other sensitive to both gamma radiation and thermal neutrons. The bridge network tends to cancel out the gamma-current component from the total collector current. In a compensated a-c ionization chamber, the d-c power supplies in the bridge network are replaced by a center-tapped transformer. The result is an a-c signal which is a function of thermal neutron flux. In the chamber, the signal current has the same frequency and phase

*"Reactor Instrumentation and Control Progress Report No. 73," GE-NMPO, GEMP-73, July 31, 1962.

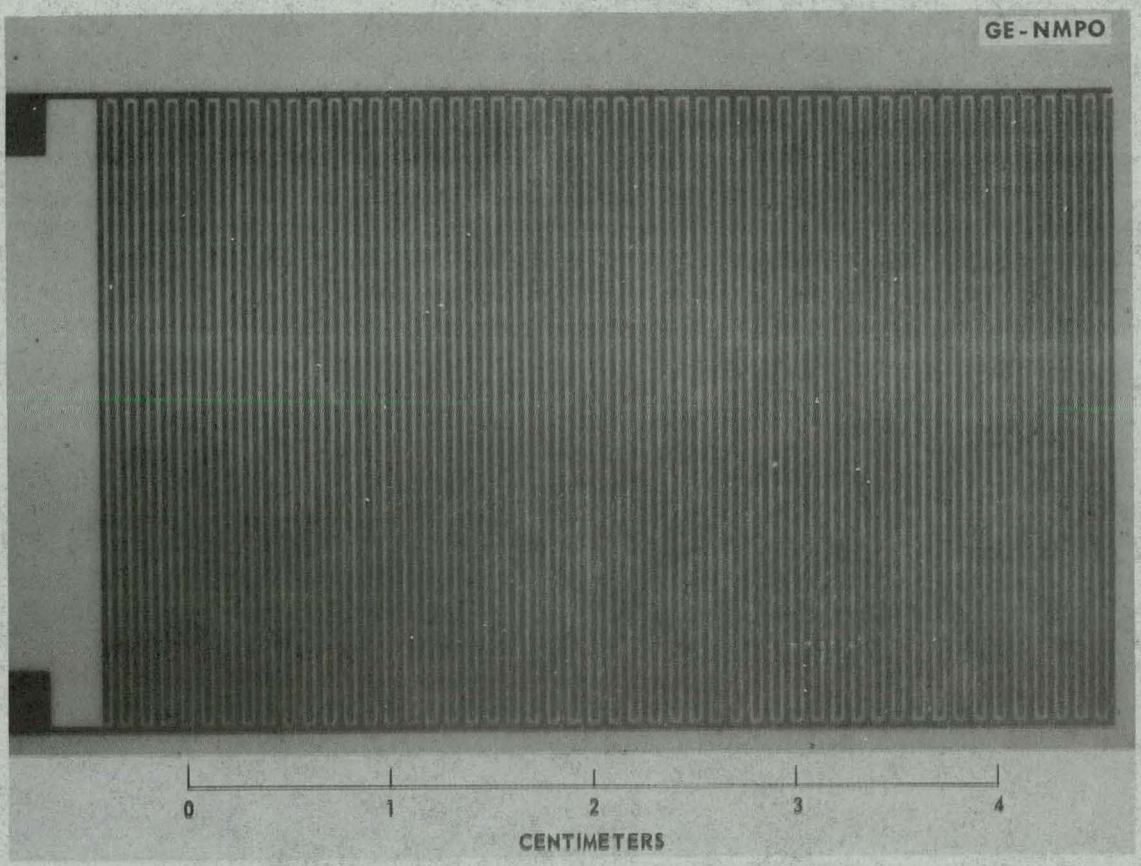

Fig. 5.2 – Split-collector printed circuit (Neg. P63-5-11)

as the driving voltage since the driving voltage is used to keep the chamber saturated. Care is therefore taken to minimize any leakage paths in the design of the chamber.

Two existing chambers were modified for low-temperature a-c operation, and a new chamber designed specifically for a-c use at higher temperature was built. While many of the design considerations parallel those applying to d-c chambers, others are unique. For example, the a-c chamber must be well balanced with regard to capacitive reactance from each of the cathodes to the collectors and to ground; also, the driving voltage must be kept as low as possible to minimize balance and voltage-breakdown problems. All of the chambers studied contained six sensitive elements, three of which respond only to gamma radiation; the other three respond to both gamma and neutron radiation. The two types of elements are mounted alternately around the circumference of two supporting discs. Figure 5.3 is a photograph of the sensitive elements of the high-temperature chamber. The center section is mounted inside a stainless steel cylinder which contains the vacuum seals.

The two modified compensated ionization chambers were operated in the a-c mode at the Bulk Shielding Facility at ORNL.* Figure 5.4 shows the thermal neutron response and testing range of one of these chambers. At maximum reactor power (1 megawatt) the thermal neutron flux was about 5×10^{11} nv and a gamma compensation better than 98 percent was demonstrated. While most of the tests were conducted at a frequency of 500 cps, frequencies up to 3000 cps were used successfully.†

*"Reactor Instrumentation and Control Progress Report No. 80," GE-NMPO, GEMP-80, November 30, 1963, p. 17.

†Ibid., p. 19.

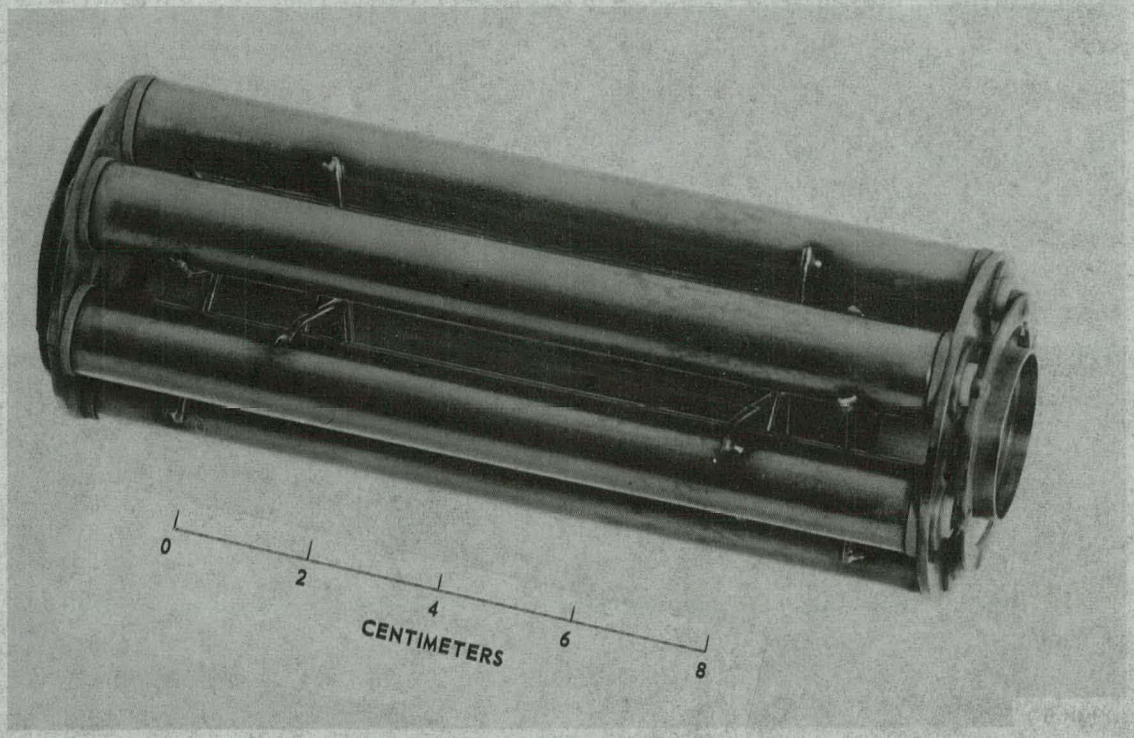

Fig. 5.3 – Sensitive elements of a compensated a-c ionization chamber
(Neg. P63-12-21B)

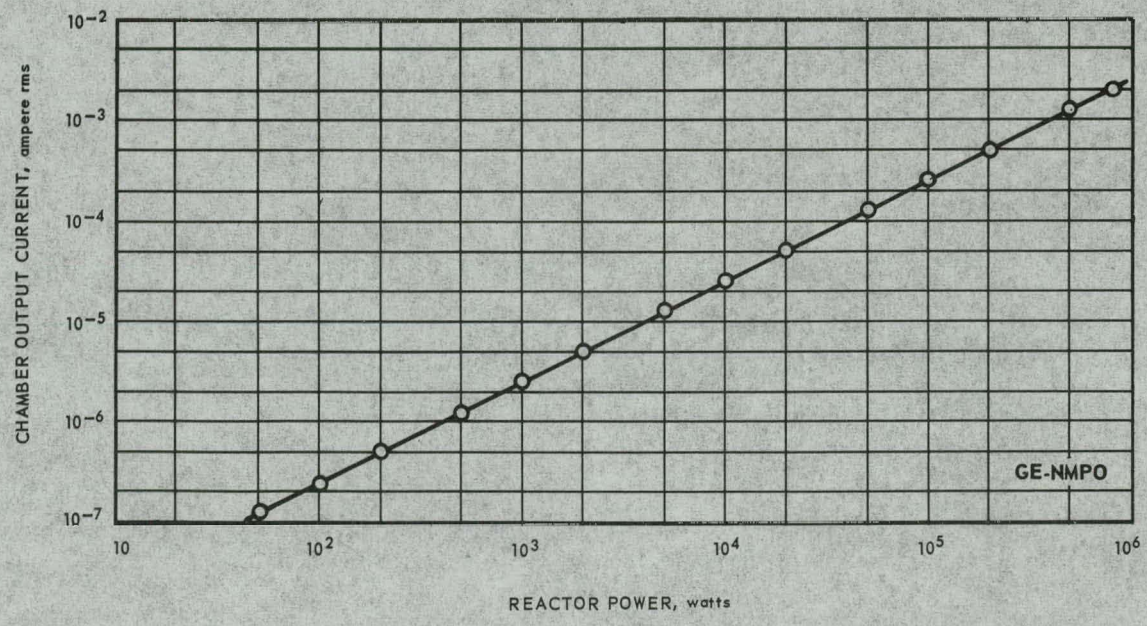

Fig. 5.4 – ORNL-BSF test of close-spaced compensated ionization chamber

If a power line frequency is used, the electronic driver unit becomes little more than a transformer and a balancing control. As mentioned above, no d-c power supply is needed. A chamber operating on 400 cps has been used with such a simple driver and a transistorized preamplifier. These elements are part of a 400-cps regulating-rod servosystem which is now being evaluated.

5.2 CHARGED-FRAGMENT NEUTRON DETECTORS

An unpowered charged-fragment neutron detector consists of an emitter electrode coated with a neutron-sensitive material and insulated from a collector electrode in a vacuum. A B^{10}-coated emitter bombarded with thermal neutrons will eject positively charged alpha particles and lithium recoil nuclei into the sensing volume. Originally,* it was assumed that the alpha particles would traverse the gap between electrodes and impinge upon the collector electrode. However, the positively charged alpha particles and lithium recoil nuclei, on passing through the B^{10}-coated surface, produce low-energy secondary electrons in such vast abundance that the net effect produces a negative charge on the collector.

Charged-fragment neutron detectors of the design shown in Figure 5.5 were constructed and tested under X-rays, gamma rays, and thermal neutron flux. These detectors were constructed of nickel and stainless steel metallic members and had aluminum oxide insulators. The detectors were 1.27 centimeters in diameter and 5.08 centimeters long. The neutron-sensitive material was coated only to the internal surface of the emitter electrode. The B^{10} coatings were applied to a thickness of 0.8 mg/cm^2 and the U^{235} coatings to a thickness of 0.5 mg/cm^2. The collector surfaces in both types were nickel, and the separation between electrodes was 0.050 centimeter. The coaxial extension lead welded to the detector was fabricated by swaging the stainless steel sheath over the MgO insulation and nickel conductor tubing. The lead was sealed by welding a nickel-to-aluminum oxide-insulated vacuum seal at the end farthest from the detector. The diameter of the extension lead was 0.635 centimeter, and the overall length of the detector and lead was 122 centimeters. The detector and lead were evacuated and outgassed at a pressure of approximately 10^{-6} mm of Hg and at a temperature of 538°C for 24 hours prior to being sealed.

Thermal-neutron flux testing of the charged-fragment neutron detectors was conducted at the BSF and ORR facilities in Oak Ridge. Figure 5.6 demonstrates the response of B^{10}-coated charged-fragment detectors† over a range of thermal-neutron flux of approximately 3×10^7 to 6×10^{11} nv. This thermal-neutron flux range corresponds to a BSF reactor power range of 50 watts to 1 megawatt. The data indicate a linear response to thermal neutrons of at least two decades for the B^{10}-coated detectors. An average sensitivity to thermal neutrons for the B^{10}-coated detectors was determined to be 1.1×10^{-20} amp/nv-cm^2. The polarity of the output current was negative with respect to

◊ Fig. 5.5 – Charged-fragment neutron detector design

*"Reactor Instrumentation and Control Progress Report No. 72," GE-NMPO, GEMP-72, May 31, 1962, pp. 41–42.

†"Reactor Instrumentation and Control Progress Report No. 79," GE-NMPO, GEMP-79, September 30, 1963, pp. 20–22.

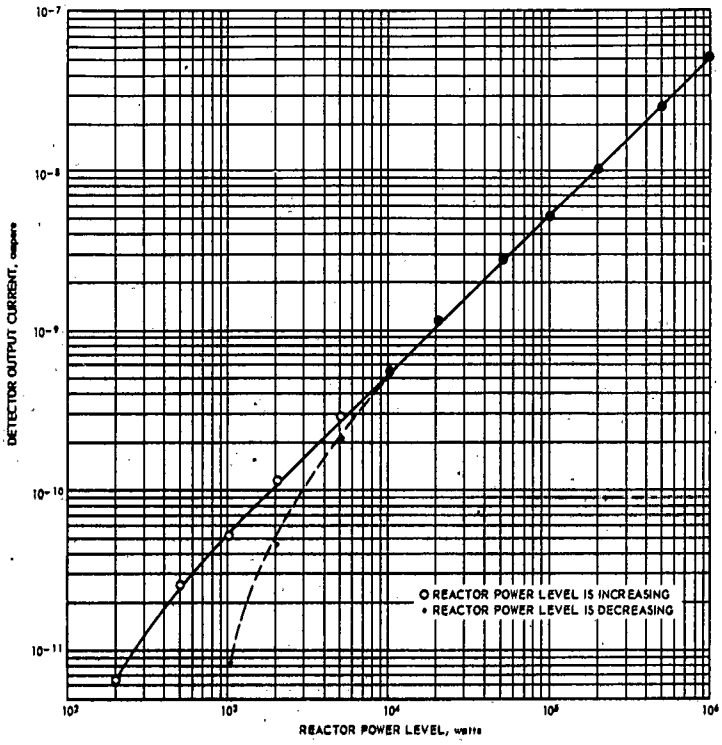

Fig. 5.6 – Neutron-induced output current of a B^{10}-coated charged-fragment neutron detector as a function of reactor power level

thermal neutrons, and positive with respect to gamma radiation. This is demonstrated in Figure 5.6 where the curve bends downward as reactor power is decreased below 10,000 watts and gamma radiation becomes predominant. In a predominantly gamma radiation background, the Ni^{58} surface of the collector electrode, having a greater mass number than the B^{10}-coated electrode, is the principal source of emitted secondary electrons.

Figure 5.7 demonstrates the response of U^{235}-coated charged-fragment detectors* over a range of thermal-neutron flux of approximately 4×10^8 to 8×10^{12} nv. This thermal-neutron flux range corresponds to a BSF reactor power range of 50 watts to 1 megawatt. The data indicate a linear response for the U^{235}-coated detectors of at least two decades. An average sensitivity to thermal neutrons for the U^{235} detectors was determined to be 6×10^{-20} amp/nv-cm^2. The polarity of the output current was negative with respect to both thermal neutrons and gamma radiation. The U^{235}-coated emitter electrode in this case has a greater mass number than the Ni^{58} surface of the collector electrode. This was demonstrated in Figure 5.7 where the curve bends upward as reactor power is decreased below 1000 watts and gamma radiation becomes predominant.

An investigation of long-term stability of charged-fragment neutron detector output current at a steady-state thermal-neutron flux was conducted at the ORR Facility in Oak Ridge. Three B^{10}-coated detectors† were tested for 66 hours in a thermal-neutron flux of approximately 3×10^{13} nv. The results were not conclusive because the detectors were not rigidly supported with respect to the reactor core. One of the detectors did exhibit a reasonably stable output current for approximately 37 hours. However, for the

*"Reactor Instrumentation and Control Progress Report No. 80," GE-NMPO, GEMP-80, November 30, 1963, pp. 21–22.

†Ibid., pp. 23–24.

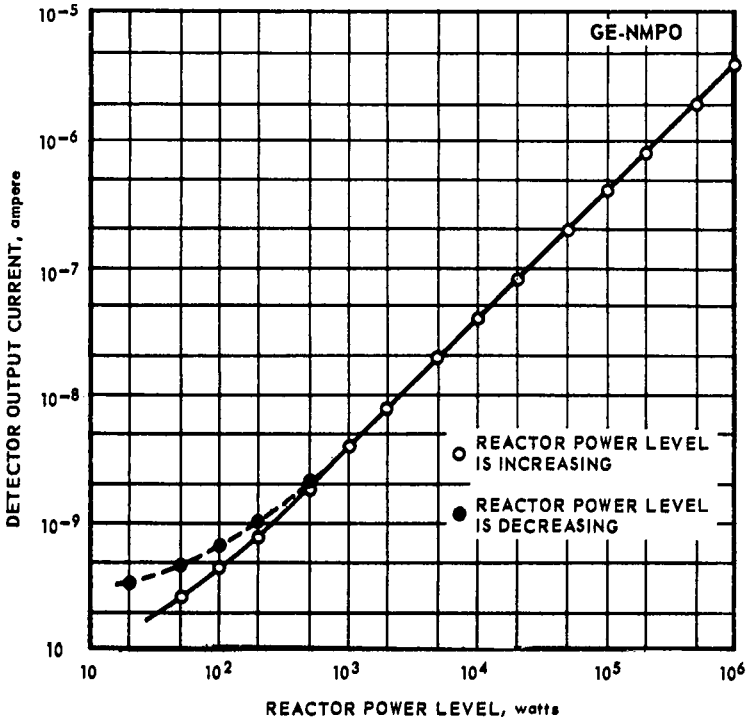

Fig. 5.7 – Neutron-induced output current of a U^{235}-coated charged-fragment neutron detector as a function of reactor power level

first 7 hours of the testing, the output current from this same detector was observed to decrease by a factor of two. The output of the other two detectors was stable for only about 8 hours, beginning at the eleventh hour of testing.

Four U^{235}-coated charged-fragment detectors were also tested at the ORR Facility to investigate the problem of long-term stability. These four detectors were supported by a rather rigid irradiation device; hence, relative motion with respect to the reactor core was minimal. After 5 hours of testing in a thermal-neutron flux of approximately 3×10^{13} nv, it was apparent that stable operation would not be achieved. A potential of 1.5 volts of direct current was applied to the detectors with the result that adequately stable output currents were observed for a period of 18 hours. An investigation was then conducted to determine the overall effect of applying a potential to the detectors. Figure 5.8 shows the result of this investigation and demonstrates how a phenomenon such as small stray potentials could affect output-current stability of the detectors. The data also indicate that with an applied potential of 1.5 volts, the magnitude of output current for three of the detectors was increased by approximately 1 decade. The saturation characteristics and the vast increase of output current as a function of applied voltage indicate that gas is probably present in the fourth detector. The reason for the lower sensitivity and unfavorable saturation characteristics of the third detector is not readily apparent. Detector Nos. 1 and 2 appear adequately saturated with as little as 5 volts potential applied. It is evident that a small potential applied to the detectors is sufficient to overcome the energy of the vast majority of the low-energy secondary electrons. Thus, any small potential generated in the detector circuit will influence the less energetic secondary electrons emitted, and stability of output current will be affected.

The U^{235}-coated charged-fragment neutron detectors were irradiated in the cobalt-60 well at a peak gamma dose rate of 8.93×10^5 r/hr. The sensitivity to gamma radiation

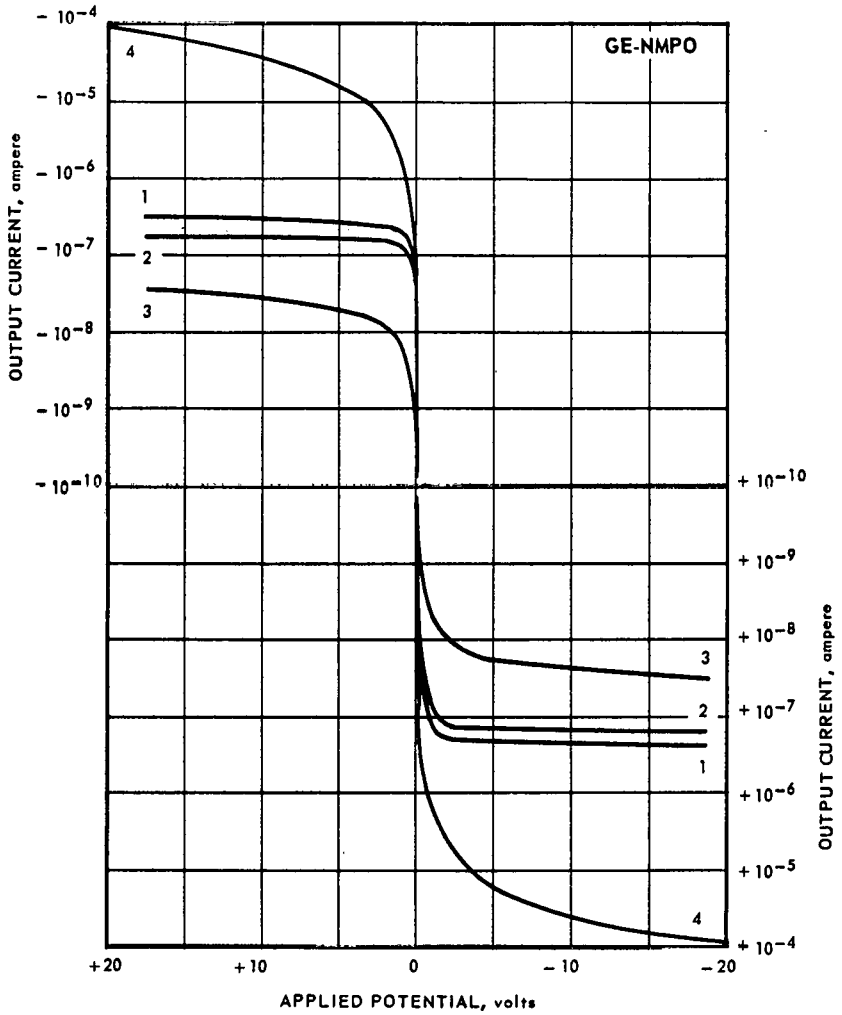

Fig. 5.8—Charged-fragment neutron detector output-currents as a function of applied potential

was determined to be approximately 2.5×10^{-16} amp/r-hr. Gamma dose rate profiles taken in the well facility compared favorably with data previously obtained with a standard carbon-wall ionization chamber. The four detectors were irradiated at the peak gamma dose rate for 100 hours; they demonstrated an excellent stability of output currents during this period. The secondary electrons produced in the detector by cobalt-60 irradiation have sufficient energy and would not be greatly influenced by small stray potentials.

5.3 SUMMARY AND CONCLUSIONS

Three basic types of a-c ionization chambers were worked on during Calendar Year 1963. Associated electronic systems have been built to test and operate these chambers at various frequencies. Models of the gridded and compensated a-c ionization chambers were tested in both thermal neutron and gamma environments. High-temperature models of the various types of chambers were studied and some temperature performance testing was conducted.

A-c ionization chambers are compared and evaluated in terms of dependability, ease of construction, performance, and applicability to specific needs. The characteristics of electronic systems are also important to evaluation of the chambers.

At the present time, the compensated a-c ionization chamber seems to be the most promising type because of its relatively simple and rugged construction. The associated

electronic system is also very inexpensive and dependable. Gamma compensation is obtained at the same time that the driving signal is cancelled out. This type of chamber is also more applicable to fail-safe circuits in reactor shutdown systems.

Unpowered charged-fragment neutron detectors using B^{10} or U^{235} as the emitter coating were demonstrated to respond linearly to changes of thermal-neutron flux. However, neither type of detector exhibited a stable output current when irradiated for long periods of time in a thermal-neutron flux. Potentials, developed within the detecting circuit, possibly due to contact potentials, are suspected to be the cause of detector output-current instability as a function of time.

5.4 PLANS AND RECOMMENDATIONS

Most of the emphasis should be placed on the compensated a-c ionization chamber in an attempt to determine the possible sensitive range, degree of compensation, and types of applications for this device. The chamber will be operated in the a-c mode at 538°C to determine the effect of temperature upon system balance, compensation, and noise output. No more general testing of the gridded and split-collector chambers is planned; however, specific problems concerning vacuum seals, high-temperature cables, and instrumentation applicable to the various types of chambers will be pursued.

Emphasis will be placed on identifying the mechanism of stray potential within the charged-fragment neutron detecting circuit. Methods of increasing this stray potential to a suitable level will be sought. Other neutron-sensitive coatings such as cadmium will be considered as a possible source of higher-energy emitted secondary electrons.

APPENDIX

REPORTS ISSUED DURING CALENDAR YEAR 1963

PROGRESS REPORTS

GEMP-177A
Second Annual Report - High-Temperature Materials and Reactor Component Development Programs, Volume I - Materials, February 28, 1963.

GEMP-177B
Second Annual Report - High-Temperature Materials and Reactor Component Development Programs, Volume II - Materials, February 28, 1963.

GEMP-177C
Second Annual Report - High-Temperature Materials and Reactor Component Development Programs, Volume III - Reactor Component Development, February 28, 1963.

METALLURGY

GEMP-19A and B
High-Temperature Materials Program Progress Report No. 19, January 25, 1963.

GEMP-21A and B
High-Temperature Materials Program Progress Report No. 21, April 23, 1963.

GEMP-23A and B
High-Temperature Materials Program Progress Report No. 23, May 31, 1963.

GEMP-25A and B
High-Temperature Materials Program Progress Report No. 25, July 31, 1963.

GEMP-27A and B
High-Temperature Materials Program Progress Report No. 27, September 30, 1963.

GEMP-29A and B
High-Temperature Materials Program Progress Report No. 29, November 30, 1963.

CERAMICS

GEMP-22A and B
High-Temperature Materials Program Progress Report No. 22, April 30, 1963.

GEMP-24A and B
High-Temperature Materials Program Progress Report No. 24, June 28, 1963.

GEMP-26A and B
High-Temperature Materials Program Progress Report No. 26, August 16, 1963.

GEMP-28A and B
High-Temperature Materials Program Progress Report No. 28, November 11, 1963.

GEMP-30A and B
High-Temperature Materials Program Progress Report No. 30, December 31, 1963.

INSTRUMENTATION AND CONTROLS

GEMP-76
Reactor Instrumentation and Control Progress Report No. 76, April 29, 1963.

GEMP-77
Reactor Instrumentation and Control Progress Report No. 77, May 31, 1963.

GEMP-78
Reactor Instrumentation and Control Progress Report No. 78, July 31, 1963.

GEMP-79
Reactor Instrumentation and Control Progress Report No. 79, September 30, 1963.

GEMP-80
Reactor Instrumentation and Control Progress Report No. 80, November 30, 1963.

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C. S. Wukusick, "Oxidation Behavior of Intermetallic Compounds in the Nb-Ti-Al System," GE-NMPO, GEMP-218, July 1963.

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D. G. Besco and J. R. Beeler, Jr., "Computer Programs Describing Collision Cascades in Binary Materials, I: Square Planar Lattice," GE-NMPO, GEMP-192, February 1963.

E. C. Duderstadt and J. F. White, "The Sintering of BeO to Variable Densities and Grain Sizes," GE-NMPO, GEMP-219, September 1963.

J. R. Beeler, Jr., "High-Speed Computer Experiment Techniques: Many-Particle Systems," GE-NMPO, GEMP-252, December 1963.

D. G. Besco and J. R. Beeler, Jr., "Computer Programs Describing Collision Cascades in Binary Materials, III: Body-Centered Cubic and Face-Centered Cubic Structures," GE-NMPO, GEMP-243, August 1963.

D. G. Besco and J. R. Beeler, Jr., "Computer Programs Describing Collision Cascades in Binary Materials, II: Wurtzite Structure," GE-NMPO, GEMP-200, February 1963.

J. A. Delaney, "Pseudo Infinite Lattices in a Digital Computer," GE-NMPO, GEMP-193, February 1963.

J. C. Blake, H. J. Kurtz, and R. L. Sundin, "Problems Associated with High Temperature Fasteners," GE-NMPO, GEMP-186, April 15, 1963.

INVENTION DISCLOSURES

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E. A. Aitken, S. F. Bartram, and E. F. Juenke, "Crystal Chemistry of the Rhombohedral $MO_3 \cdot 3R_2O_3$ Compounds," Basic Science Division, American Ceramic Society Meeting, Washington, D. C., October 8, 1963, GE-NMPO, TM 63-10-2. Submitted to Inorganic Chemistry.

R. E. Fryxell and B. A. Chandler, "Creep, Strength, Expansion, and Elastic Moduli of Sintered BeO as a Function of Grain Size, Porosity, and Grain Orientation," American Ceramic Society Meeting, Pittsburgh, Pennsylvania, April 30, 1963, GE-NMPO, TM 63-5-4. Submitted to J. Nuc. Matls.

C.S. Wukusick and J. F. Collins, "Properties of Fe-Cr-Al Type Alloys Containing Additions of Yttrium," ASTM Subcommittee on Resistance Heating Materials Meeting, Atlantic City, N.J., January 25, 1963, GE-NMPO, TM 63-7-63. Submitted to ASTM Materials Research and Standards.

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E. A. Aitken, "Fuel Oxides," American Nuclear Society Meeting, Cincinnati, Ohio, April 1963, GE-NMPO, TM 63-4-13.

C. G. Collins, "Radiation Effects in BeO," International Conference on Beryllium Oxide, Sidney, Australia, October 1963, GE-NMPO, TM 63-10-12.

B. A. Chandler and J. B. McConnelee, "Thermal Stress Evaluation of Ceramic Fuel Elements," GE-NMPO, TM 63-4-2. Submitted to J. Nuc. Matls.

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