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DEVELOPMENT AND EVALUATION OF MAGNETIC AND ELECTRICAL MATERIALS CAPABLE OF OPERATING IN THE 800° TO 1600° F TEMPERATURE RANGE

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Prepared by
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16. Abstract

This report summarizes results of a research program on electrical materials for advanced space electric power systems. The areas investigated included improved high-temperature magnetic materials, high-temperature capacitor materials, ceramic-to-metal bore-seal technology, and simulated-space environmental testing of electric-power system components.

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SECTION I

INTRODUCTION

This is the final report on NASA Contract NAS3-6465 summarizing the program results and technical developments on magnetic, capacitor, electrical conductor, electrical insulation and bore seal materials suitable for application to advanced space electric power systems. The contract consisted of three programs as follows:

- Program I - Magnetic Materials for High-Temperature Operation.
- Program II - High-Temperature Capacitor Feasibility.
- Program III - Bore Seal Development and Combined Materials Investigations Under a Space Simulated Environment.

Program I was directed toward the improvement and further development of magnetic materials suitable for application in the rotor of a generator or motor in advanced space electric power systems.

Program II was carried out to determine the feasibility of building a lightweight compact capacitor suitable for operation up to 1100°F in vacuum with low electrical losses. One type of application for such a device is in static power conditioning apparatus for space applications.

Program III extended the bore seal development work initiated under Contract NAS3-4162 (ref. 1)*. The ultimate objective of this program was to design and fabricate a four-inch diameter ceramic to columbium-1% zirconium bore seal capsule for life testing in the 1100° to 1400°F temperature range. Materials compatibility was determined by life-test evaluation of constructed test models in which the various magnetic, electrical and insulation materials were applied to the designs as they would be in actual space electric power components.

Detailed reporting of the work accomplished on these programs is given in three Topical Reports entitled "High Temperature Magnetic Materials (WAED 67.34E)" (ref. 2), "High Temperature Capacitor (WAED 67.24E)" (ref. 3), and "Bore Seal Development and Simulated Space Evaluation of High-Temperature Electrical Materials and Components (WAED 67.46E)" (ref. 4). Seven Quarterly

* References are identified at the end of this report.

Reports (refs. 5, 6, 7, 8, 9, 10, and 11) were also written to report progress as the programs were carried out.

Sections II, III, and IV summarize the technical results on magnetic materials (Program I), capacitor materials (Program II), and bore seal and materials compatibility test models (Program III). Each section contains a technical discussion and conclusions and recommendations for that program.

SECTION II

PROGRAM I - HIGH TEMPERATURE MAGNETIC MATERIALS

A. SUMMARY OF TECHNICAL RESULTS

The objective of this program was to investigate methods of improving the magnetic and mechanical properties of materials suitable for application in the rotor of a generator or motor in advanced space electric power systems. Particular emphasis was placed on improving material strength at high temperature while retaining useful magnetic properties.

The investigation was centered in four areas, as follows:

1. Precipitation hardened magnetic materials for application in the 1000° to 1200°F temperature range.

2. Investigation for raising the alpha-to-gamma transformation temperature in cobalt-iron alloys.

3. Dispersion strengthened magnetic materials for application in the 1200° to 1600°F temperature range.

4. Creep testing of Nivco alloy.

Two precipitation hardened magnetic alloys were developed through the laboratory stage for application in rotating electrical apparatus operating in the 1000° to 1200°F temperature range. One experimental martensitic type alloy and one cobalt-base alloy surpassed the magnetic and mechanical properties of similar alloys commercially available, particularly for the 1000° to 1200°F temperature range. The greatest improvement exhibited over presently available alloys was in thermal stability. The reversion to austenite (non-magnetic) in the experimental martensitic alloys began about 150°F higher than in 15 percent nickel maraging steel. The precipitation hardened cobalt-base alloy exhibited excellent creep properties to 1200°F. Under similar test conditions, the creep strain of this alloy was one-third that of commercially available Nivco alloy.

Attempts to increase the alpha-to-gamma transformation temperature in the cobalt-iron system alloys did not produce useful results. In most cases, the addition elements depressed the transformation temperature.

Two dispersion strengthened magnetic alloys were developed as candidates for application in the 1200° to 1600°F temperature range in rotating electrical apparatus, one each in the cobalt base system and in the iron-27 percent cobalt system. The cobalt base alloy demonstrated the capability of being able to sustain 10,000 psi stress for 10,000 hours with less than 0.4 percent creep strain at a temperature within the 1200° to 1600°F range. Also, in this range the coercive force was always less than 12 oersteds, while saturation magnetization was greater than 12 kilogauss, except at 1600°F. The iron-27 percent cobalt dispersion strengthened alloy developed 25 percent higher values of saturation magnetization at 1200° to 1600°F than the cobalt base alloy, and at least 50 percent higher values at room temperature to 1600°F than the Nivco alloy.

Ten-thousand-hour creep data were determined for Nivco alloy, which is a commercially available high temperature magnetic alloy. At stresses above 37,500 psi, Nivco alloy exhibited a rapid increase in creep rate at temperatures above 1100°F.

In determining the applicability of the new alloys identified, a comparison between existing alloys is of interest. Figure 1 compares the 10,000-hour creep properties of three experimental alloys from Larson-Miller extrapolations with two commercially available alloys which are H-11 (5Cr-1Mo-1V-Fe) and Nivco alloy (Co-23Ni-1.7Ti-0.4Al-0.2Zr). For the same stress, the experimental precipitation hardened (PH) martensitic alloy 1-A-S-2 (Fe-12Ni-30Co-1W-3Ta-0.4Al-0.4Ti) has higher temperature capabilities than the H-11 and is a logical replacement. The same is true of the precipitation hardened cobalt-base alloy 1-B-S-1 (Co-5Fe-15Ni-1.2Al-5.0Ta-0.2Zr) which has greatly improved creep resistance over that exhibited by Nivco alloy.

The dispersion strengthened (DS) alloys of either cobalt-iron or cobalt are shown as an area on the curve, and their preliminary data suggests that they are candidates above 1200°F where precipitation hardened cobalt-base rotor material becomes marginal in long-term stability.

A comparison of the magnetic induction of the various magnetic materials is shown in figure 2. It shows that a magnetic induction improvement is available in both of the new precipitation hardened alloys (1-A-S-2 and 1-B-S-1) over that found in H-11 and Nivco alloy. It also indicates the magnetic induction possible in alloys strengthened by dispersion-strengthened mechanisms. These alloys exhibit very good magnetic properties because the non-magnetic strengthening phase is minimized. They are limited to higher temperature (> 1200°F) because their rate of increasing strength with decreasing temperature is lower than the precipitation hardened alloys, which are stronger at the lower temperatures.

In applying these materials to a wide variety of high-temperature designs, a number of tradeoffs are followed which necessitate

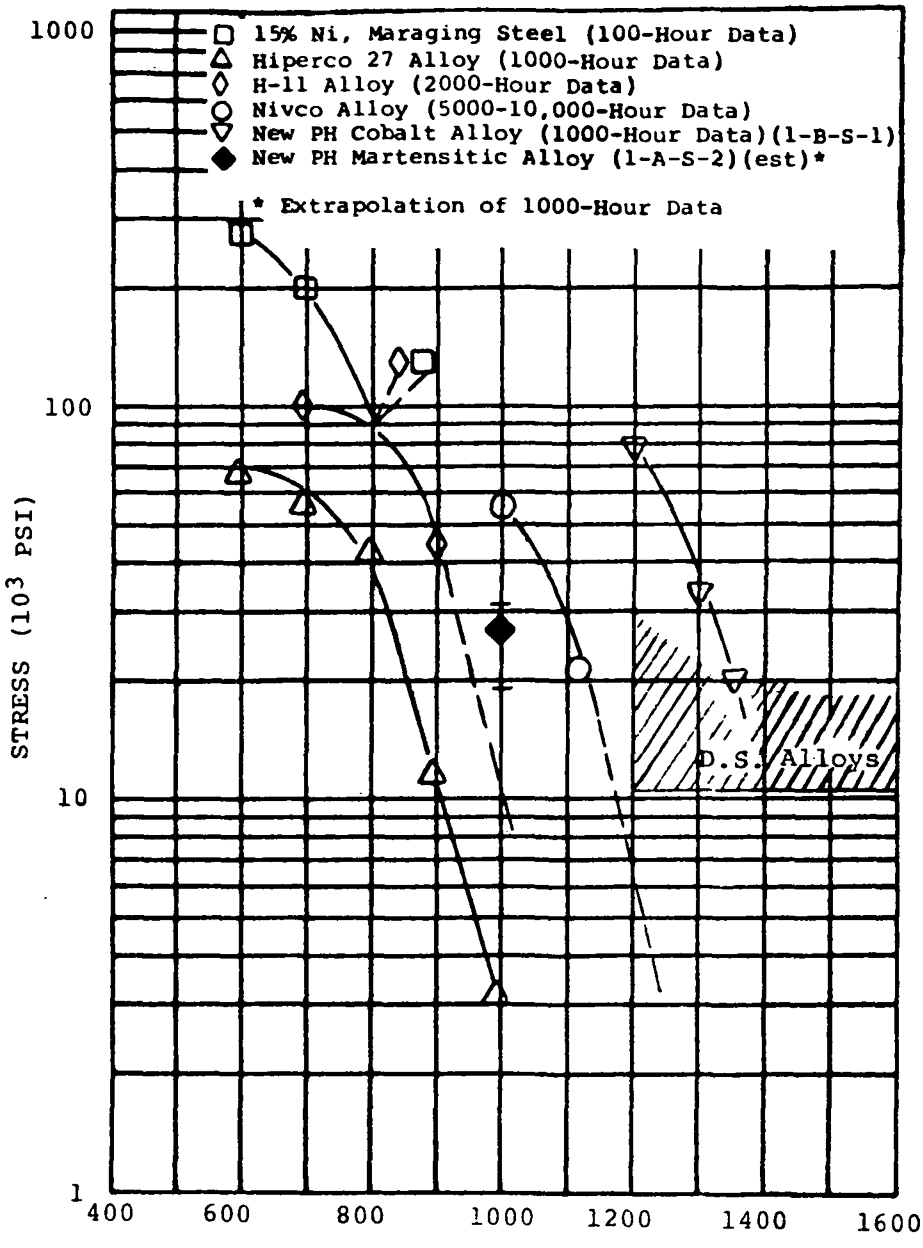

FIGURE 1. Stress to Produce 0.4 Percent Creep Strain in 10,000 Hours Based Upon Extrapolations Using the Larson-Miller Parameter. Comparison is Made Between Alloys Developed on This Program and Commercially Available Alloys.

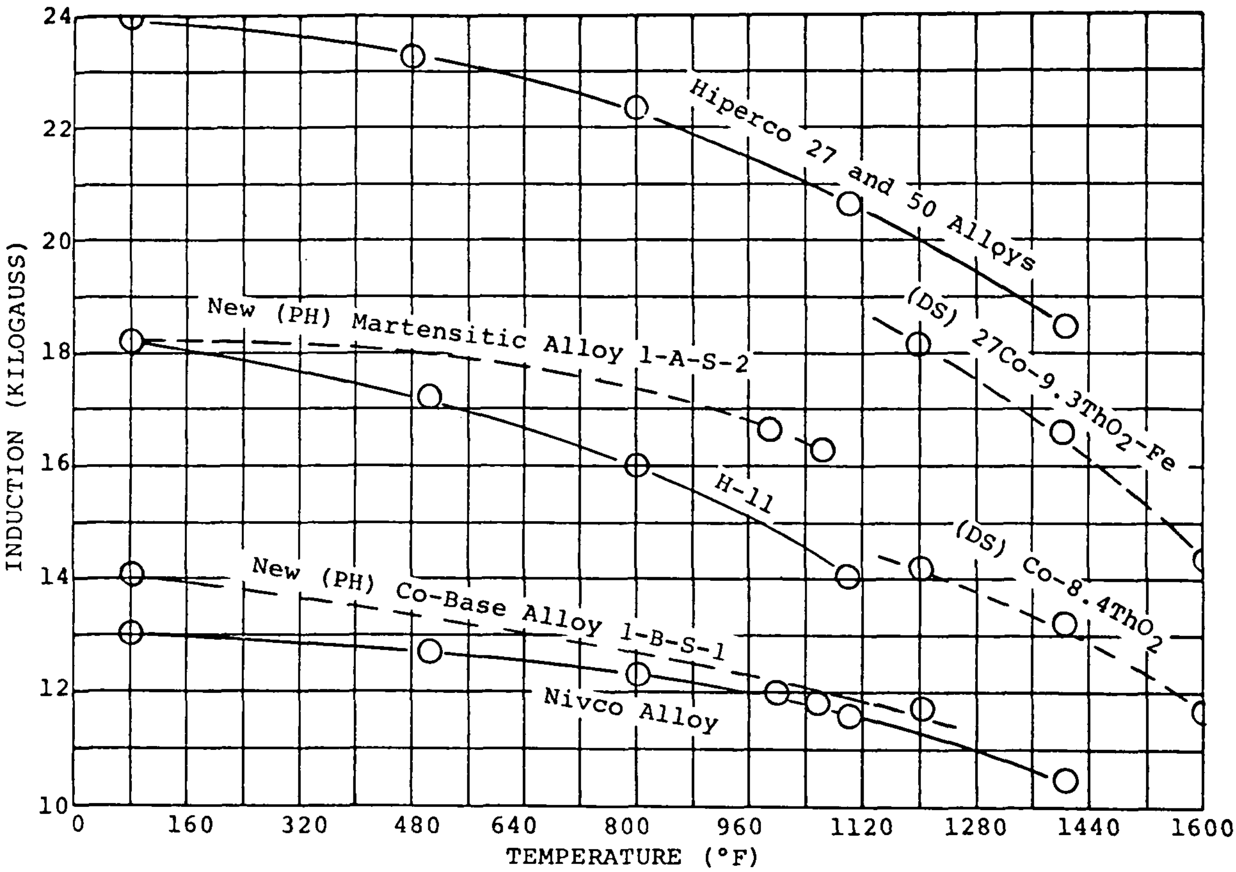

FIGURE 2. Magnetic Induction Versus Temperature at a Magnetization of 250 to 300 Oersteds for High Temperature Magnetic Alloys Developed on this Program Compared to Existing Alloys.

quite complicated geometric programing using a computer. This was beyond the scope of this program, but an attempt has been made to identify application temperatures for various materials based upon a design guideline for high-temperature inductor alternators where creep resistance and magnetic induction, in that order, set the weight of a generator. Electric motors or lower-stressed magnetic applications may alter this guideline. Table I presents the suggested magnetic material for various temperatures and includes the present commercial material suitable for this range. The advantage of the newer replacement alloy is summarized in a remarks column. Specific data and descriptions of the materials and tests described above may be found in the High Temperature Magnetic Materials Topical Report (WAED 67.34E) (ref. 2).

TABLE I. Application Temperatures for Potential High Temperature Rotor Magnetic Materials

Temperature Range (°F)	Existing Commercial Material	Possible Replacement[a]	Remarks
800 to 1000	H-11 (Fe-5Cr-1Mo-1V)	1-A-S-2 (Fe-12Ni-30Co-1W-3Ta-0.4Al-0.4Ti)	Precipitation hardened alloy with improved electrical overload capability, higher creep resistance, better stability.
1000 to 1200	Nivco Alloy (Co-23Ni-1.7Ti-0.4Al-0.2Zr)	1-B-S-1 (Co-5Fe-15Ni-1.25Al-5Ta-0.2Zr)	Precipitation hardened alloy with greatly improved creep resistance, better stability.
1200 to 1350	None	DS 27Co-9.3ThO2-Fe[b]	Dispersion strengthened alloy which provides a high-temperature, stable material not now available.
1350 to 1600	None	DS 8.4ThO2-Co[b]	Dispersion strengthened alloy which provides a high-temperature, stable material not now available.

(a) Tests on these materials were carried out on relatively small laboratory specimens. Considerable effort would be required to produce them in the shapes and sizes required for actual applications.

(b) Materials tested showed yield strength to be approximately the same as its ultimate and creep strength.

B. CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

a. Two precipitation-hardened magnetic alloys were developed through the laboratory stage for application in rotating electrical apparatus operating in the 800° to 1200°F temperature range. Both offer improved stability, magnetic induction and creep resistance over H-11 and Nivco alloy which are the best commercial magnetic rotor materials now available.

b. The feasibility of achieving satisfactory soft-magnetic properties in the 1200° to 1600°F temperature range in creep-resistant, dispersion-strengthened cobalt-base and iron+27% cobalt-base materials was established on small diameter extruded and secondary worked rod. To achieve the desired creep resistance, additional powder-making refinements are needed to fully exploit the dispersion-strengthened alloys as rotor materials.

c. Ten-thousand-hour vacuum creep data were provided on the Nivco alloy which is a commercially available high-temperature magnetic alloy.

2. Recommendations

a. A development program should be carried out to scale up the size of newly-developed precipitation-hardened magnetic alloy forgings to a size suitable for application to inductor alternator rotors.

b. Effort should be continued on the development of dispersion-strengthened iron+27% cobalt-base magnetic materials, particularly on the powder making method to provide a finer and more uniform thoria dispersion, for application in the 1200° to 1600°F operating range.

SECTION III

PROGRAM II - HIGH TEMPERATURE CAPACITOR FEASIBILITY

A. SUMMARY OF TECHNICAL RESULTS

The overall objective of this program was to demonstrate methods of fabricating single-wafer capacitors from a group of candidate dielectric materials. The most promising material was then selected for a more detailed study by fabricating it into a multilayered capacitor having a greater total capacitance than that of the single wafer capacitor. The program was concluded with a 1120-hour life test at 1100°F in vacuum using the multilayered capacitor.

Four candidate high-purity dielectric materials were fabricated into thin wafer test capacitors, and their electrical properties were measured in vacuum at temperatures up to 1100°F. The materials tested were: pyrolytic boron nitride (Boralloy), single crystal Al_2O_3 (Linde Sapphire), hot-pressed BeO (Atomics International), and polycrystalline Al_2O_3 (Lucalox).

An evaluation of the test data showed that pyrolytic boron nitride (PBN) had superior electrical properties over the temperature range, and could be fabricated into very thin ($<$ 0.001-inch thick), capacitor wafers.

A "figure of merit" (M) rating system was devised to compare the four candidate materials in terms of capacitance at room temperature, volume of dielectric between the electrodes, dissipation factor at 1100°F and 1 kc/sec, and capacitance change from room temperature to 1100°F. Figure 3 shows the relative figure of merit ratings using pyrolytic boron nitride as the reference material. It also defines the figure of merit formula. Pyrolytic boron nitride was a logical first choice for a high temperature (to 1100°F) capacitor dielectric material by a factor of at least 100.

Electrodes were applied to capacitor wafers by a sputtering process, using 80% platinum 20% rhodium alloy or noble metals as the sputtering target. Triode sputtering methods were used, wherein a separate hot-filament electron source was used for gas ionization at pressures as low as 5×10^{-4} torr, and separate ion targets were supplied to provide the source material for deposition. Figure 4 shows the three element sputtering assembly and associated fixtures.

A five layer capacitor assembly was constructed using PBN as the dielectric material and platinum for electrodes. Electrode contacts were arranged so that the capacitance of each wafer was in

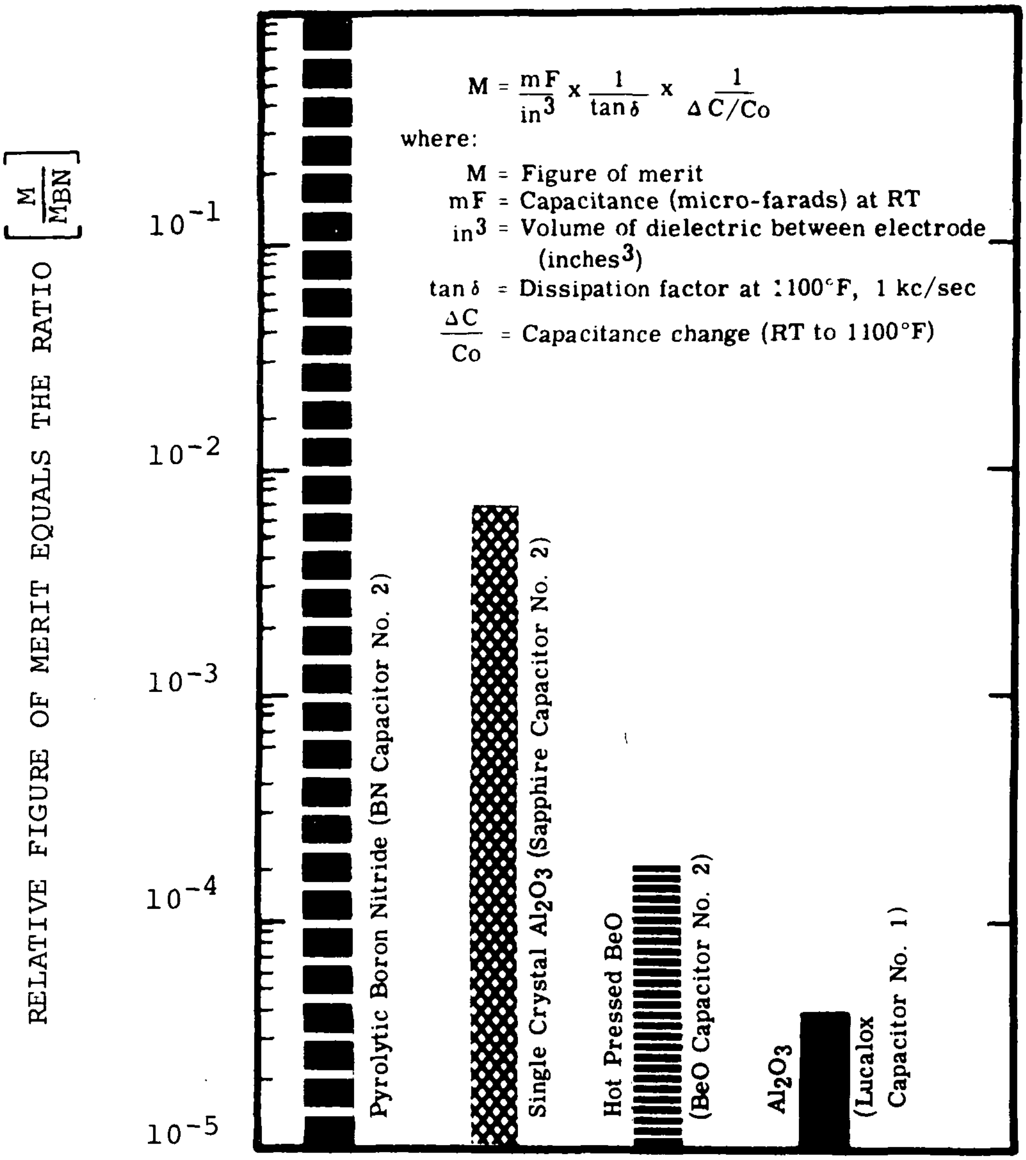

FIGURE 3. Figure of Merit (M) for Four Different Dielectric Materials Expressed as the Relative Ratio $\left[\frac{M}{M_{BN}}\right]$ (M is calculated for 1 kc/sec Electrical Data)

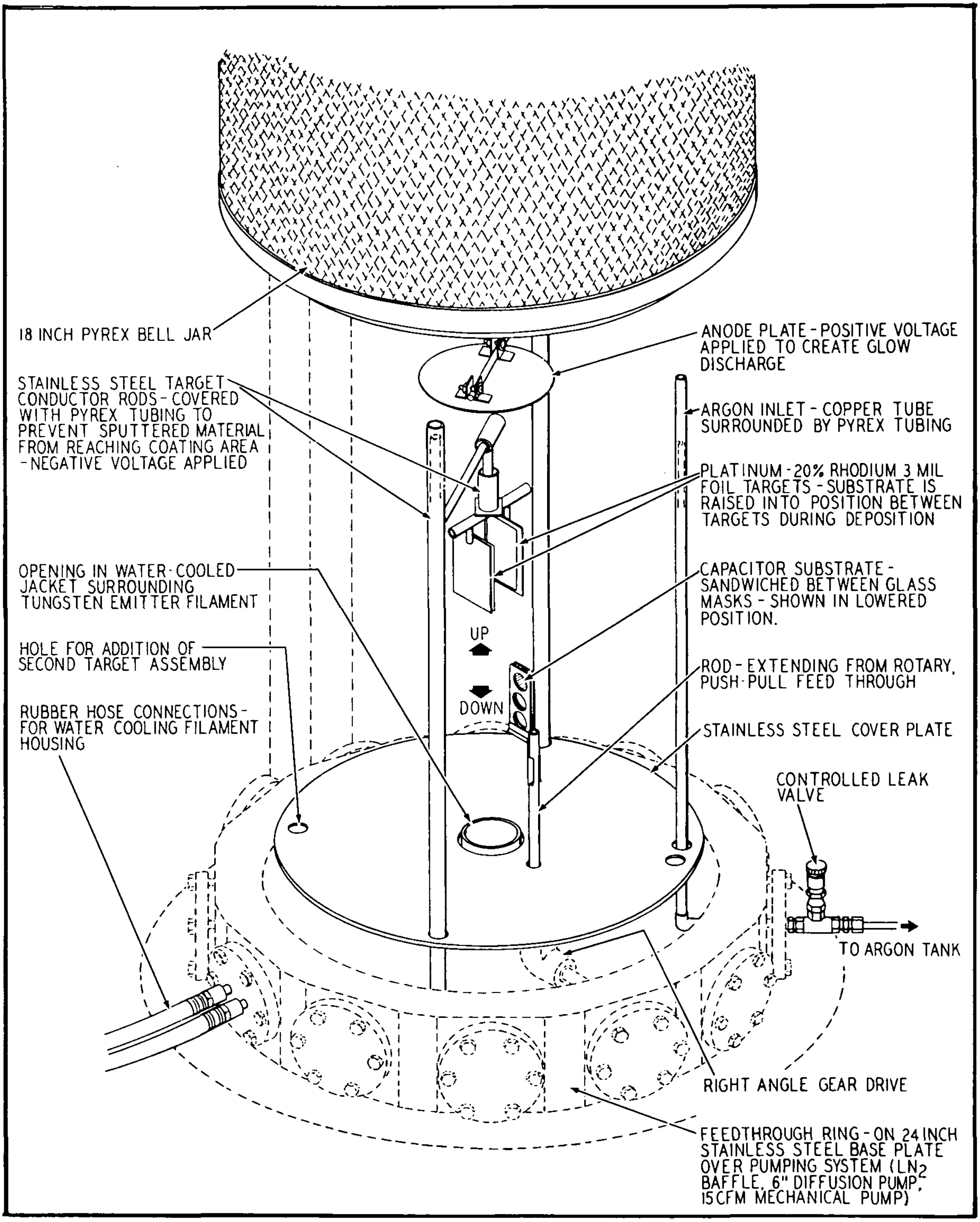

FIGURE 4. Three Element Sputtering Assembly and Associated Fixturings

parallel. Thus the five-wafer stack had a capacitance equal to five times the capacitance of each wafer. Figure 5 shows the wafers with tabs extending from opposite edges. The bottom figure shows the parallel interconnection arrangement. Electrodes were sputtered on both sides of the wafer at the same time. Wafer thickness ranged from 0.85 mil to 1.03 mil.

The five-stack capacitor assembly was placed on life test at 1100°F in a chamber evacuated to the 10^{-8} torr range. Testing was carried out with 500 Vdc applied for the first 259 hours, 750 Vdc for the next 218 hours, and 1000 Vdc for the final 643 hours. Figure 6 shows the capacitance history at 10 kc/sec during the course of the test.

The decrease in capacitance during the life test (1120 hours) amounted to approximately 4 percent. Successful completion of the life test indicates that pyrolytic boron nitride is a suitable dielectric material for high-temperature capacitor applications. Specific data and descriptions of the materials and test procedures discussed above may be found in the High Temperature Capacitor Topical Report (WAED 67.24E) (ref. 3).

B. CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

a. Pyrolytic boron nitride (Boralloy) can be machined into very thin (0.0004 to 0.001-inch) and flexible, pinhole-free wafers and sheets from thick blocks of starting material.

b. A method of interconnecting sputtered thin-film electrodes (platinum, rhodium and platinum-rhodium alloys) deposited on individual PBN wafers has been shown to be a practical and efficient design concept that closely approximates the calculated maximum capacitance that can be achieved in a given volume.

c. Successful completion of a 1120-hour life test (PBN multilayer capacitor) at 1100°F in vacuum under continuous d-c voltages from 500 to 1000 Vdc/mil has demonstrated overall design and performance feasibility.

2. Recommendations

Future effort should include the development of methods for producing high quality 1/4 to 1-mil thick "as deposited" capacitor films, and methods of increasing electrode adherence and structural stability. These improvements can then be used to fabricate larger, hermetically-sealed capacitor units that could be tested under simulated service conditions for 5000 to 10,000 hours.

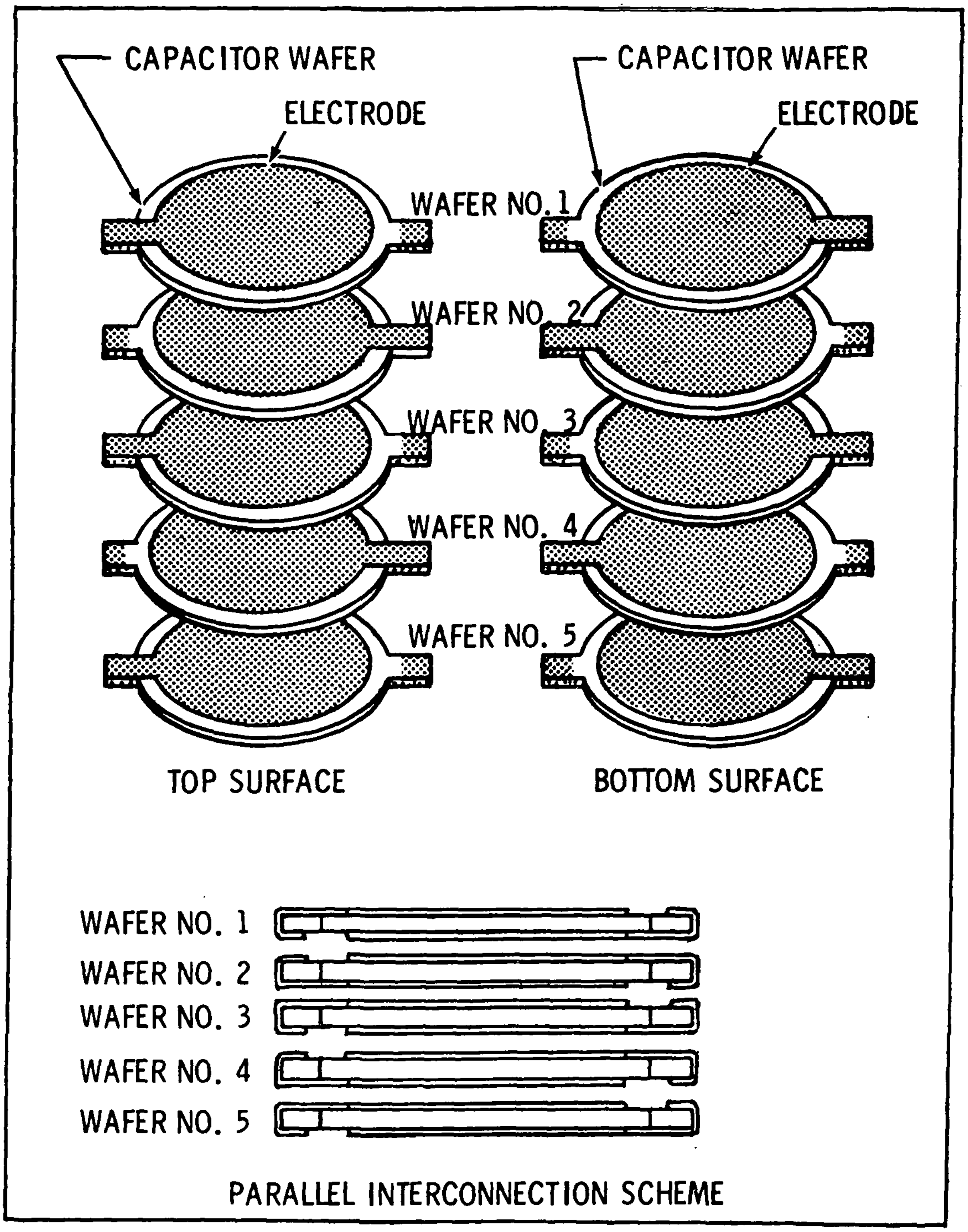

FIGURE 5. A Five Layer Stacked Capacitor Showing Tabbed Wafers and Electrode Geometries and Electrode Orientation Necessary for Parallel Electrical Interconnection

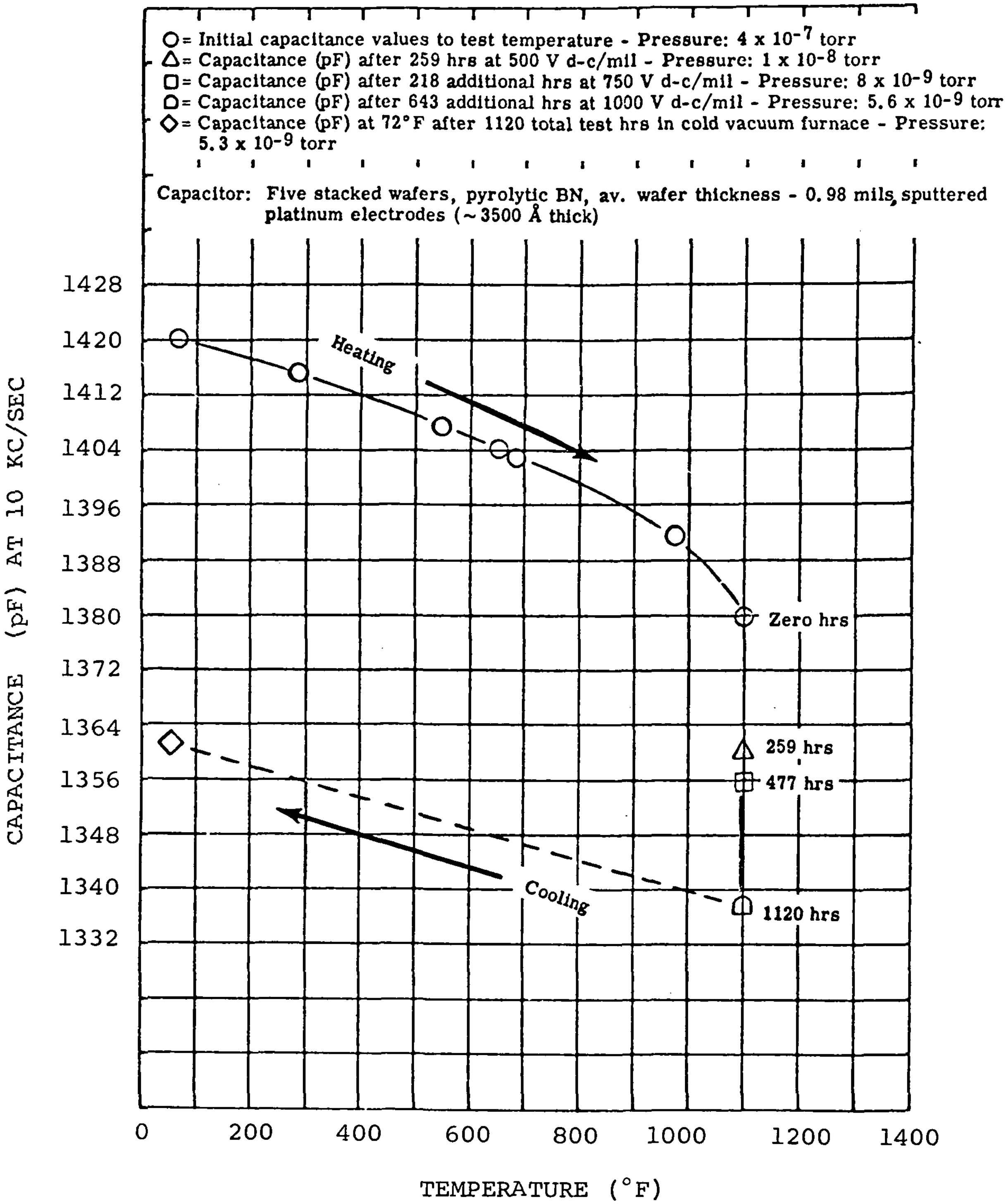

FIGURE 6. Capacitance Versus Temperature and Time at Increased DC Energizing Voltages (Constant Temperature; 1100°F) in Vacuum for a Five Wafer Multilayer Pyrolytic Boron Nitride Capacitor

SECTION IV

PROGRAM III - BORE SEAL DEVELOPMENT AND COMBINED MATERIALS INVESTIGATION

A. SUMMARY OF TECHNICAL RESULTS

The ultimate objectives of the Bore Seal Development portion of program III were to fabricate a 4-inch-diameter model bore seal and to test it in potassium and vacuum environment in the 1100° to 1400°F temperature range for 5000 hours. Two-thousand-hour alkali-metal exposure tests were conducted on small ceramic-to-metal seal specimens fabricated from high-purity beryllia ceramic and a columbium-1% zirconium metal member using several active-metal braze alloys. In addition, mechanical, vibration, and thermal shock tests were made on intermediate size ceramic-to-metal seal specimens.

The function of a bore seal in advanced space electric power alternators is to protect the more vulnerable stator windings from the corrosive effects of an alkali-metal coolant. The candidate materials for the elevated temperature alkali-metal resistant bore seal application on this program were tested and screened in work conducted on the NASA sponsored program NAS3-4162. The results from that program were reported in the Bore Seal Topical Report NASA CR-54093 (ref. 1). Materials and ceramic-to-metal sealing techniques were selected for extended (2000-hour) testing in alkali metal on this program. Tests and evaluation were made before and after exposure to alkali-metal vapor and liquid at 1600°F for periods to 2000 hours. Table II shows the primary materials tested.

TABLE II. Bore Seal Materials Evaluated

Ceramic	Metal Members	Active Metal Brazing Alloys
99.8% Beryllia (<100 ppm Si)	Columbium-1% Zirconium	68Ti-28V-4Be
99.8% Beryllia (<50 ppm Si)		46Zr-46Ti-4Be-4V
99.9% yttria		60Zr-25V-15Cb

The best brazed ceramic-to-metal systems were subjected to elevated temperature flexural strength tests, and to thermal shock and vibration tests; all on small test configurations.

A four-inch-diameter model bore seal capsule was successfully fabricated utilizing a molybdenum-metallized, 99.8% beryllia ceramic tube, columbium-1% zirconium metal member and an active-metal brazing alloy composed of 60 weight percent zirconium, 25 weight percent vanadium and 15 weight percent columbium.

Figure 7 shows a summary of test results on the effect of elevated temperature potassium, lithium, and vacuum exposure on the flexural strength of modulus-of-rupture assemblies brazed with two of the better brazing alloys. Room temperature flexural strength is plotted at several exposure times for several lots of beryllia ceramic. Modulus-of-rupture ceramic-to-metal assemblies brazed with two of the brazing alloys are also included.

The results indicate only a slight effect of alkali-metal (potassium or lithium) exposure on the flexural strength of 99.8% beryllia ceramic after test periods to 2000 hours at 1600°F. The control test on similar specimens exposed to vacuum for the same length of time and at the same temperature, indicate no effect on flexural strength.

However, there was degradation in brazed assembly strength in alkali-metal exposed assemblies, the degradation by lithium being much more severe than by potassium. The test results show the superiority of the 60Zr-25V-15Cb brazing alloy over the 56Zr-38V-16Ti brazing alloy.

The elevated temperature flexural strength of modulus-of-rupture assemblies brazed with the 60Zr-25V-15Cb brazing alloy was determined in the as-brazed condition. There was no significant change in the flexural strength of the ceramic-to-metal seal at temperatures to 1600°F. All tested specimens fractured in the ceramic.

A four-inch-diameter model bore seal capsule was constructed for use in the combined materials environmental test described later in this section. The model bore seal capsule was fabricated from a four-inch-diameter, four-inch-long 99.8% beryllia tube and hemispherical metal end members (columbium-1% zirconium). After metallizing the ceramic parts with molybdenum, the members were joined using 60Zr-25V-15Cb active metal brazing alloy. The bore seal capsule (figure 8) was loaded with potassium, electron-beam welded, and placed in the cavity of the stator for thermal-vacuum endurance testing. This bore seal capsule remained potassium leak tight after 5000 hours at 1300°F.

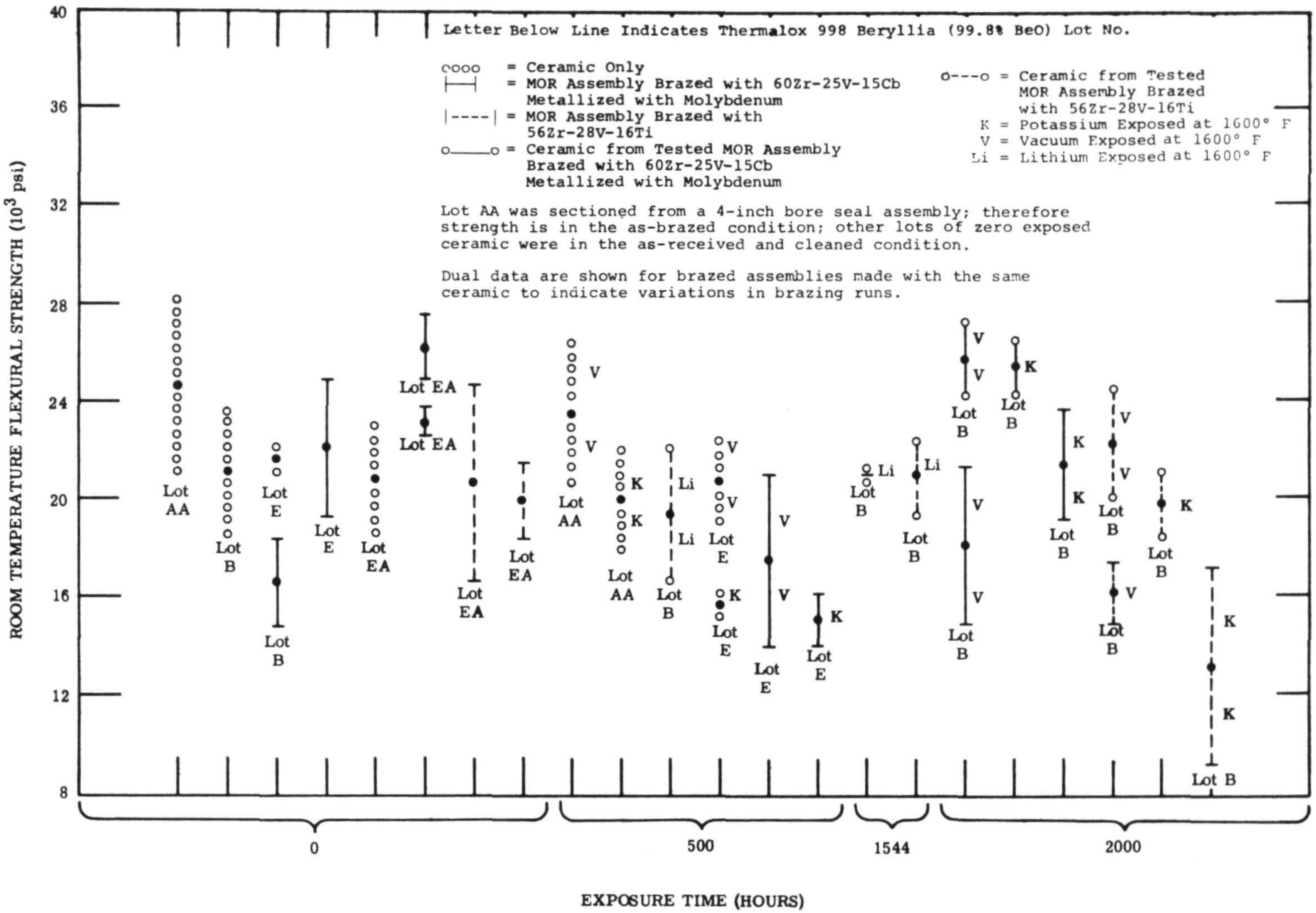

FIGURE 7. Overall Summary of Room Temperature Flexural Strength of 99.8% Beryllia (Thermalox 998) Bars and Brazed Modulus-of-Rupture Assemblies as Prepared and for Various Exposure Conditions

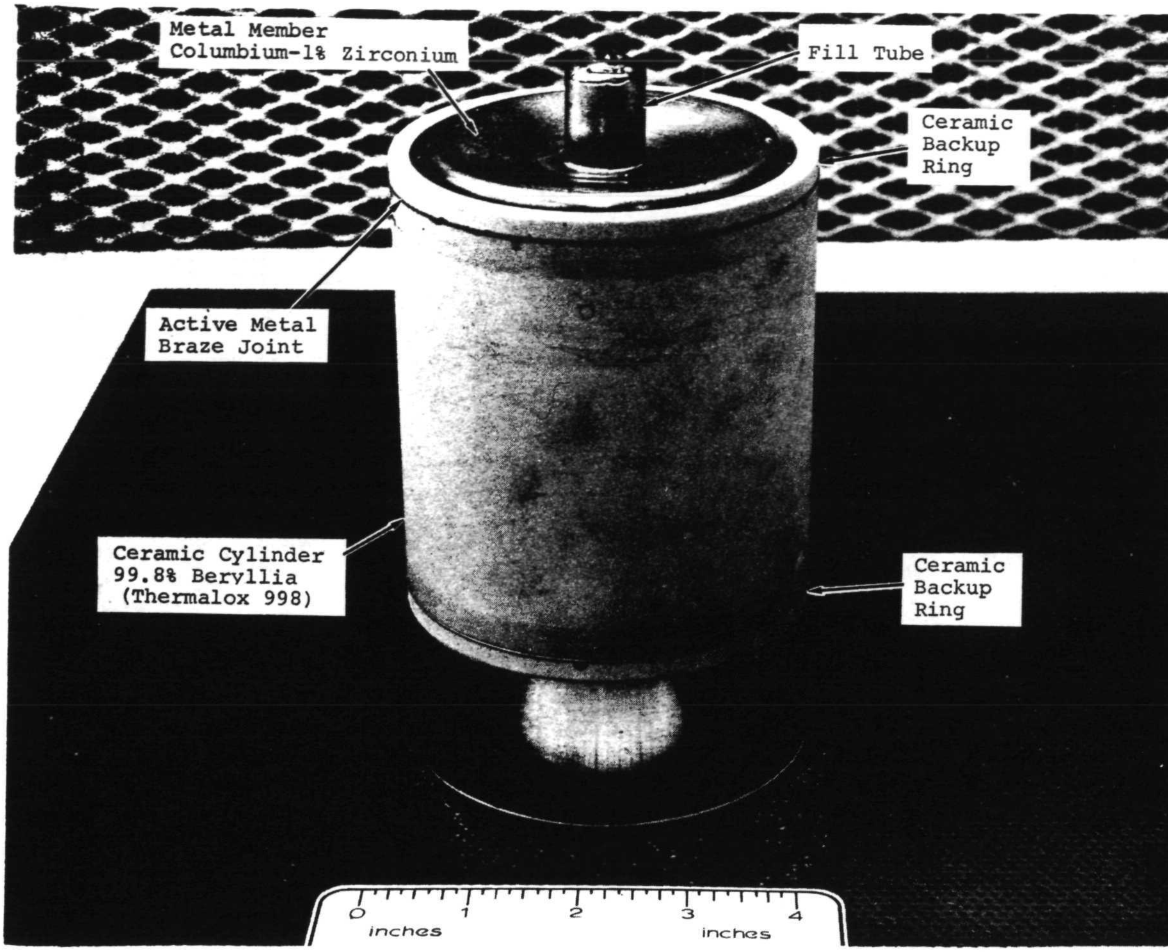

FIGURE 8. Assembled 4-Inch-Diameter Bore Seal Capsule

Detailed descriptions of the materials, processing techniques, and test procedures discussed above may be found in the Bore Seal Development and Simulated Space Evaluation of High Temperature Electrical Materials and Components Topical Report WAED 67.46E (ref. 4).

Material compatibility tests were carried out at two test temperatures, 1100°F and 1300°F, using sets of models consisting of a stator, transformer and two solenoids for each test temperature. All materials except flexible boron nitride fiber sheet insulation were selected based on the findings of the materials study accomplished on Contract NAS3-4162.

1. Magnetic Materials

Hiperco 27 alloy in two forms was utilized as the magnetic material for the three test model designs. The stator frame and stack retaining ring and the solenoid housing and plunger (armature) were machined from forged Hiperco 27 alloy billets. The laminations used in the stator and transformer stacks were punched from Hiperco 27 alloy sheet 0.008-inch thick.

2. Conductor Materials

A clad, silver core wire was selected as the conductor wire for the test program. A nickel cladding (20% of cross-section area) was used for testing at 1100°F and an Inconel cladding (28% of cross-section area) for 1300°F tests. Wire was obtained in three sizes for each clad material. Stator conductors were made rectangular in cross-section(0.091-inch by 0.144-inch including cladding), to obtain the maximum wire density in the stator slots. Transformer primary windings and solenoid windings were made from 0.032-inch diameter (No. 20 AWG) wire, including cladding. Transformer secondary windings were formed from 0.144-inch diameter (No. 7 AWG) wire, including cladding.

3. Insulation Materials

Insulation materials used were divided into four categories: (a) rigid, (b) flexible, (c) interlaminar and, (d) conductor.

a. Rigid

Alumina (Al_2O_3) with a minimum purity of 99% was used for all rigid insulation applications.

Stator slot insulation was provided by U shaped channels (slot liners) as insulation between conductors and stack, and strip spacers for insulation between conductors in the same slot. Alumina wedges were used to hold the slot leads in place.

The transformer windings were formed on alumina spools having a rectangular cross-section with rounded corners. Alumina end plates were attached to the spools to provide insulation between windings and laminations.

The solenoid windings were formed on alumina spools with alumina end plates to provide insulation between the conductor and ground. An alumina rod and bushing served as bearing surfaces for the solenoid plunger.

Hollow alumina tubes were used as thermocouple insulators in all test models, to insure that thermocouple sheaths could not become grounded to any part of the assemblies.

Zirconium-silicate alumina-orthophosphate potting compound (W-839) was used to hold stator slot insulation in place and as strips on the solenoid winding OD to hold winding turns in place for the 1100°F models. A cement made from chopped boron nitride fibers was used for the 1300°F temperature models.

b. Flexible

Flexible insulation was used in the transformers only as insulation between winding layers. Burnil CM-2, a synthetic fluorophlogopite mica paper, was used in the 1100°F test model. Insulation performance begins to degrade at higher temperatures, so this material was replaced with a boron nitride (BN) fiber flexible sheet insulation in the 1300°F test model. The flexible BN insulation was developed on a Westinghouse independent research program.

c. Plasma-arc sprayed Al_2O_3, Interlaminar Insulation

High-purity (99.998%) Al_2O_3 (Linde A) was plasma-arc sprayed on lamination surfaces to serve as interlaminar insulation, and on all metallic surfaces where cold-welding in vacuum was to be avoided.

d. Conductor Insulation

Conductor insulation was Anadur "E" glass (1100°F) and "S" glass (1300°F), which is a glass serving overcoated with a ceramic oxide loaded silicone wire enamel.

When manufacture of the first set of models was complete, the assemblies were installed in thermal-vacuum chambers for a 5000-hour endurance test under high-vacuum conditions, with a hot spot temperature of 1100°F. The hot spot temperature was maintained in part by supplying current to each model (Joule heating) and in part by a heating element in each test chamber. The stator windings were energized with 400 cps power at 290 volts per phase, while the transformer primary windings were energized with 600 volts ac at 400 cps. The energized solenoids were powered with approximately 15 volts dc. The stator was tested in one chamber and the transformer and two solenoids were tested in a second chamber. While the first 5000-hour test was in progress, a second set of models was constructed for test at a 1300°F hot-spot temperature.

Figure 9 is a cutaway view of the stator design without the bore seal capsule. Figure 10 is a cutaway view of a thermal-vacuum chamber with the stator test model installed. A second

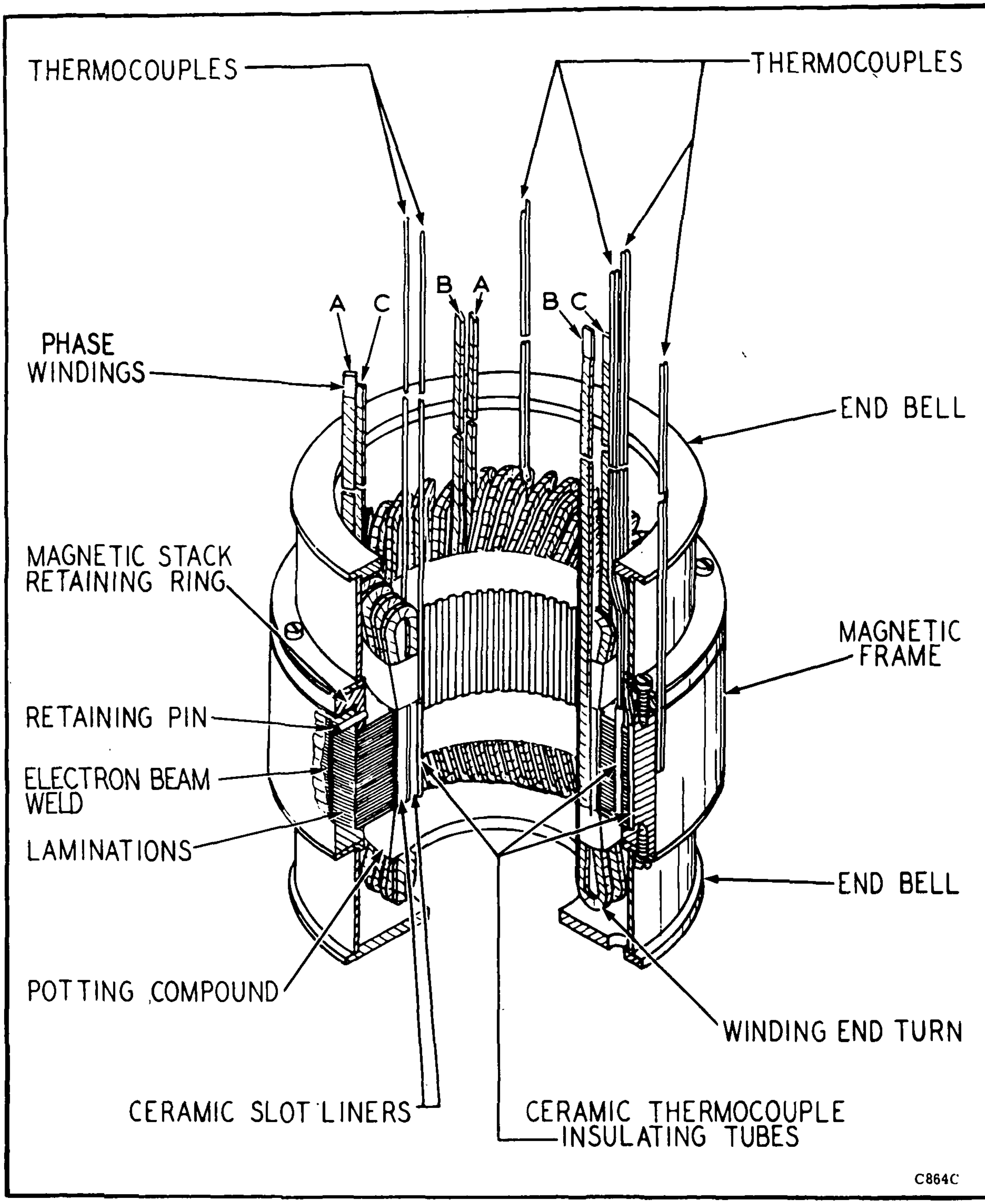

FIGURE 9. Cutaway View of Test Stator Without a Bore Seal

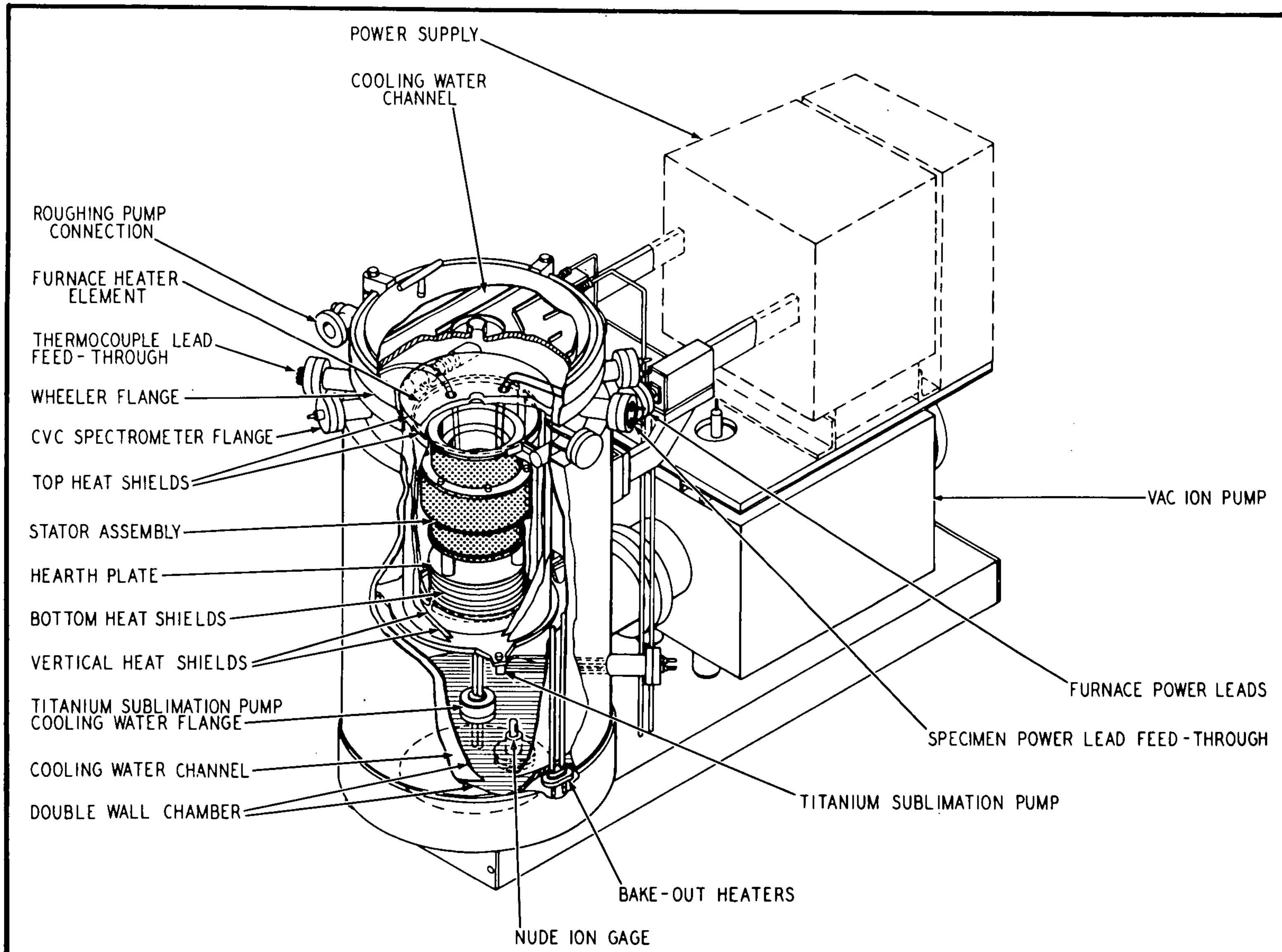

FIGURE 10. Cutaway View of Vacuum Furnace Showing the Stator Test Specimen Installed

identical chamber was used to test the solenoids and transformers. Figures 11, 12, 13, and table III are plots and a tabulation of the 1100° and 1300°F test temperature stator electrical performance. The data trends were also typical of those obtained on the transformers and solenoids. Conductor resistances were constant at temperature throughout the tests, indicating that no aging was occurring. Insulation system performance was fairly constant in the 1100°F models, but tended to improve with time in the 1300°F models. The continuously energized solenoids (1100° and 1300°F) did not show any apparent indication of ion migration in the insulation system as a result of the application of a constant dc voltage.

The transformers performed in a satisfactory manner electrically at the start of each test, but the loss of mechanical support that occurred when the Anadur insulation was cured (Anadur shrinkage) caused turn-to-turn shorting in both primary windings in less than 300 hours of testing. A 600-volt ac potential was applied to each winding in each model for the remainder of the aging test, to investigate the effects of voltage stress on the insulation systems. After failure, the insulation system performance maintained a constant level.

Specific data and descriptions of the materials and test procedures discussed above may be found in the Bore Seal Development and Simulated Space Evaluation of High-Temperature Electrical Materials and Components Topical Report (WAED 67.46E) (ref. 4).

B. CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

a. A four-inch-diameter 99.8% beryllia cylinder and Cb-1%Zr end bells were formed into a bore seal capsule using a 60Zr-25V-15Cb brazing alloy for the ceramic-to-metal joints. The capsule remained potassium leak-tight after 5000 hours at 1300°F in a thermal-vacuum chamber.

b. The magnetic, conducting and insulating materials used in both stators were compatible electrically and mechanically at the two test temperatures.

c. Modified design techniques and/or new insulation or foil conductor materials will be required to develop high-temperature multilayer transformer windings. Present inorganic insulations undergo shrinkage after curing, which allows mechanical motion between turns and the eventual abrasion and shorting of adjacent turns.

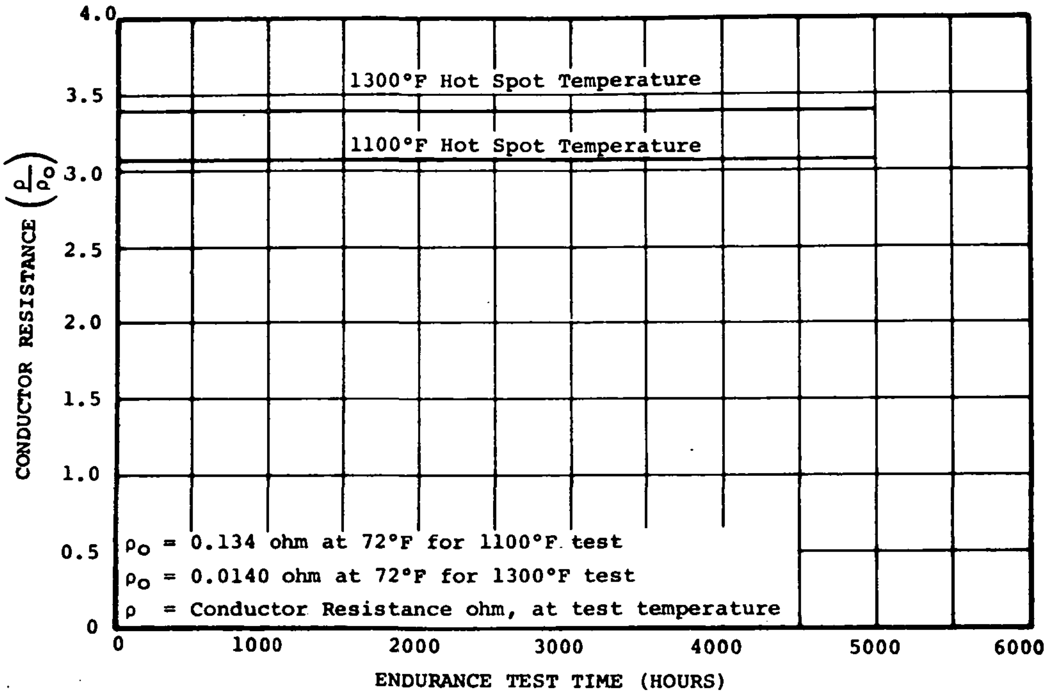

FIGURE 11. Stator Conductor Resistance vs. Endurance Test Time at 1100° and 1300°F Conductor Hot-Spot Temperatures

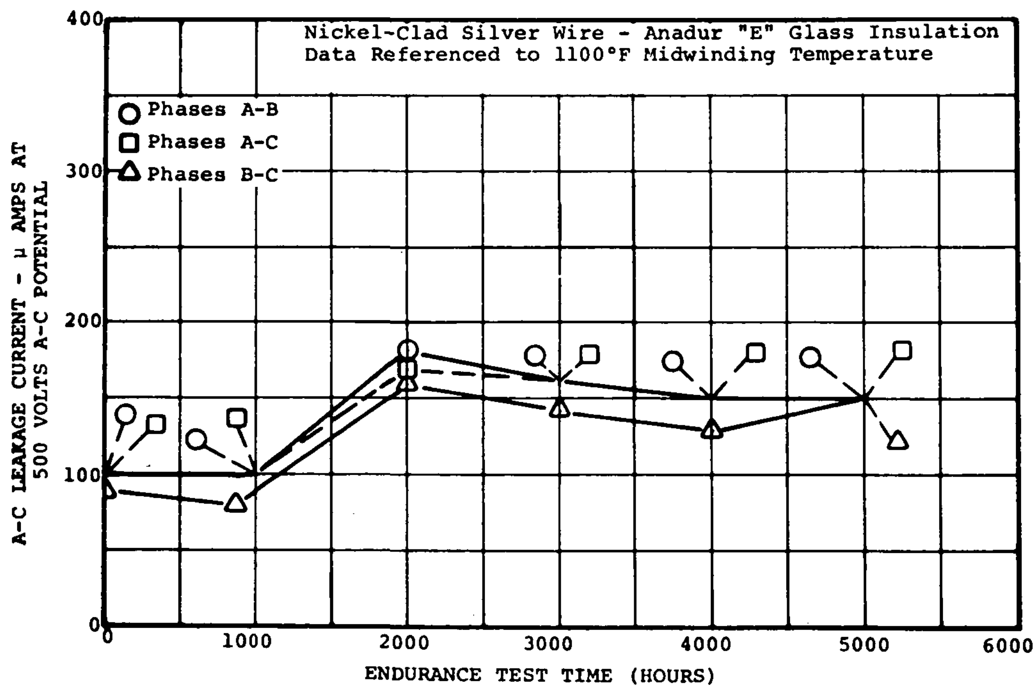

FIGURE 12. Stator Insulation System Performance, Phase-to-Phase vs. Endurance Test Time - 1100°F Model

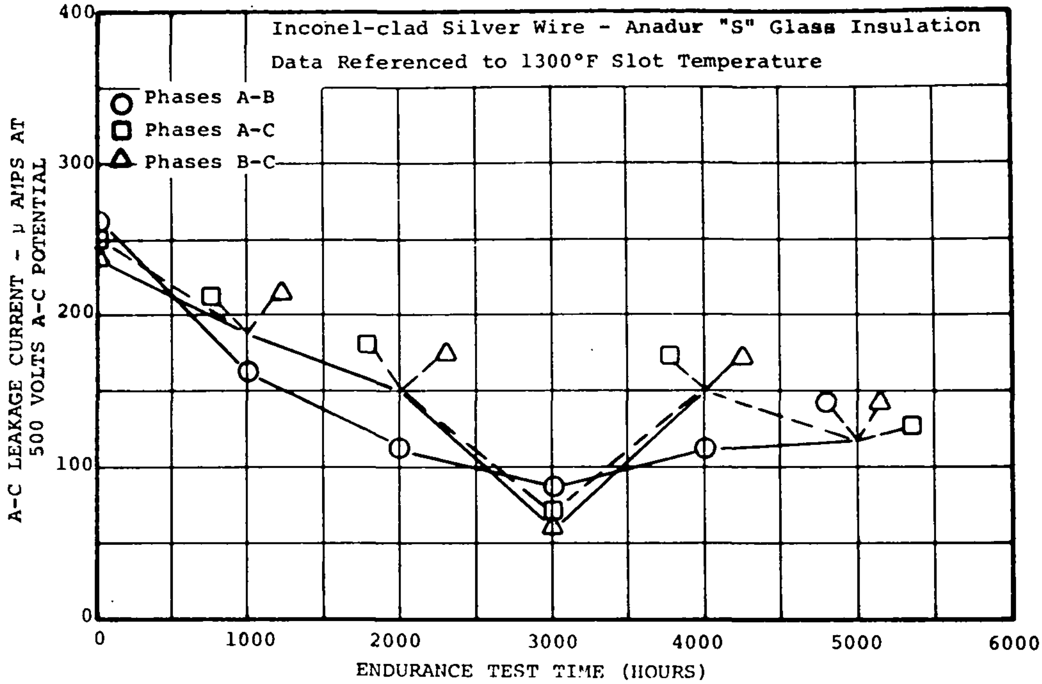

FIGURE 13. Stator Insulation System Performance, Phase-to-Phase, vs. Endurance Test Time - 1300°F Model

TABLE III. Insulation Performance of 1100° and 1300°F Stators (Slot Hot-Spot Temperatures) in a Vacuum in the 10^{-9} Torr Range

Endurance Test Time (hours)		0	2500	5000
Average Insulation Resistance (ohms) With 500-volts dc Applied:				
Phase to Phase	1100°F	6.8×10^6	6.8×10^6	6.8×10^6
	1300°F	1.5×10^6	4.3×10^6	5.5×10^6
Phase to Ground	1100°F	3.2×10^6	3.2×10^6	3.2×10^6
	1300°F	1.0×10^6	2.2×10^6	2.8×10^6
Stator conductors were rectangular nickel-clad (20% of cross-sectional area) and Inconel-clad (28% of cross-sectional area) silver wire (0.091-inch by 0.144-inch) with Anadur "E" and "S" glass insulation. Slot insulation consisted of 0.022-inch thick 99% alumina slot liners and 0.047-inch thick 99% alumina strips between phases.				

d. Maintaining an essentially constant dc electrical stress on the energized solenoids at temperature for 5000 hours did not cause any change in the insulation system operating characteristics at either test temperature.

2. Recommendations

a. A form of active metal brazing alloy (foil) having low interstitial content should be obtained and applied to small test specimens. These specimens should then be subjected to long term tests (2000 to 5000 hours) in alkali metal to determine strength and vacuum integrity as compared to the currently used powder form of alloy.

b. Larger diameter beryllia bore seal ceramic and bore seals (8 inches or larger), representative of a large alternator for space power systems, should be fabricated. The uniformity of composition and density and vacuum integrity of these ceramic cylinders should be determined. Ceramic-to-metal seals should be produced and the effect of brazing cycle on internal stresses in the braze joint of large assemblies should be determined.

c. Conductor and insulation system performance in the 1300°F hot-spot temperature stator warrants continuing the aging test at temperature in vacuum for an additional 5000 hours, to obtain a total of 10,000 hours in a simulated space environment.

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