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RESEARCH AND DEVELOPMENT PROGRAM ON MAGNETIC, ELECTRICAL CONDUCTOR, ELECTRICAL INSULATION, AND BORE SEAL MATERIALS

Final Report

by

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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FINAL REPORT
(AUGUST 1963 - DECEMBER 1964)
NAS3-4162

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PREFACE

The work reported here was sponsored by the Nuclear Power Technology Branch of NASA Lewis Research Center under Contract NAS 3-4162. Mr. R. A. Lindberg of NASA has provided the Project Management for the program. His review and suggestions as well as those of T. A. Moss, also of NASA, are gratefully acknowledged. The work was accomplished at the Westinghouse Aerospace Electrical Division, which was the prime contractor, and at the Westinghouse Research and Development Center, which was a subcontractor. The Eitel-McCullough Corporation also acted as a subcontractor conducting the ceramic-metal bore seal investigation.

In a project of this type, many skilled engineers and scientists are consulted. While the reporting of electric material technology is given in three Topical Reports entitled: Magnetic Materials, Electrical Conductor and Insulation Materials, and Bore Seal Materials; no attempt will be made to single out a person's specific contribution, since, in many cases, it was in several areas. Those who actively contributed during the total program are recognized below:

Westinghouse Aerospace Electrical Division	Westinghouse Research and Development Center	Eital-McCullough Inc.
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SUMMARY

This is the Final Report on NAS 3-4162 and summarizes over 1600 pages of data and technical analysis presented in Three Topical Reports on Electrical Materials for Advanced Space Electric Power Systems.

The areas investigated included Magnetic, Electrical Conductor, Electrical Insulation and Bore Seal Materials. The bore seal represented ceramic-to-metal seal technology.

Over a thousand references were reviewed and are presented in the Topical Reports. Over ninety percent of the magnetic, electrical, thermophysical and mechanical data presented in the reports were the result of tests conducted during the program because little effort has been concentrated in this technical area before. The prime temperature range of interest was 500 to 1600°F except for the organic insulating materials where -65°F to 1000°F represented the interval. Environments considered included air, inert gas, vacuum, and alkali-metals. The alkali-metals were restricted to the ceramic-to-metal seal investigations.

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SECTION I

INTRODUCTION

This is the final report on NASA Contract NAS 3-4162 summarizing the program and technical observations on magnetic, electrical conductor, electrical insulation, and bore seal materials suitable for application to advanced space electric power systems. The bore seal represents ceramic-to-metal technology needed to isolate the sensitive insulation components of the stator from the alkali metal vapor in the cavity of an electric motor or generator. The program was conducted after it was recognized that the design of advanced space electric power systems was dependent upon the availability of reliable design data. The absence of reliable data was confirmed during the literature search which was completed in the first three months of the program.

The thermophysical properties tested included: specific heat, electrical resistivity, thermal expansion, and thermal conductivity. Magnetic tests conducted included: d-c magnetization, a-c magnetization and core loss, and constant-current flux-reset properties for high-quality, saturable core reactors. Mechanical tests included: tensile and compressive strength; elongation and modulus; Poisson's ratio; creep in vacuum, inert gas, and air; fatigue and fatigue under steady stress. Electrical properties measured included: dielectric constant, electric strength, power factor, and volume resistivity. Material stability, weight-loss in a thermal-vacuum, and the corrosion resistance of ceramic-to-metal seals in alkali metals were also evaluated.

The work has been compiled in three Topical Reports: Magnetic Materials (WAED 64.52E)(586 pages), Electrical Conductor and Electrical Insulation Materials (WAED 64.53E)(760 pages), and Bore Seal Materials (WAED 64.54E) (260 pages). Each report also presents the bibliography in its technical field in a punch card format. Over a thousand references are listed and the presentation includes a keyword and the material property data available from that reference. The last section of each report presents the material properties by type (thermophysical, magnetic, mechanical and compatibility) with a summary for comparison of materials. The presentation makes it suitable as a design manual.

All the tests were conducted under similar standards using ASTM specimens and procedures except were no acceptable test was known. Table I-1 summarizes the test points and the number of specimens used in the investigation.

Sections II, III and IV summarize the technical observations on magnetic materials, electrical conductor and insulation materials, and bore seal materials. Section V contains recommendations.

TABLE I-1. Summary of Test Program

TEST	MAGNETIC MATERIALS		INSULATION MATERIALS		CONDUCTOR MATERIALS		BORE SEAL MATERIALS	
	Test Points	Specimens	Test Points	Specimens	Test Points	Specimens	Test Points	Specimens
I. MAGNETIC								
1. Alternating Current (AC)	2500	17						
2. Direct Current (DC)	3800	22						
3. Constant Current Flux Reset (CCFR)	375	25						
II. MECHANICAL								
1. Tensile	296	79	15	5	310	62	58	58
2. Compressive	50	20	72	10				
3. Poisson's Ratio	4	4					3	3
4. Creep	372	148			10	6		
5. Impact			7	24				
6. Flexural Strength			186	93			147	147
7. Shear Strength							34	34
8. Abrasion Resistance			62	28				
9. Thermal Shock			16	16				
10. Adhesion			40	40				
11. Cut Through Resistance			16	8				
III. THERMOPHYSICAL								
1. Electrical Resistivity	66	3	720	180	245	105	7	1
2. Thermal Expansion			16	12	116	6	8	1
3. Thermal Conductivity	12	1	63	21	21	3	16	2
4. Specific Heat	47	6					10	1
5. Electric Strength			461	153				
6. Dielectric Constant and Power Factor			456	114				
7. Arc Resistance			60	6				
8. Insulation Life			69	207				
9. Interlaminar Insulation Resistance			36	18				
10. Specific Gravity			10	5			3	3
IV. ENVIRONMENTAL AND OTHERS								
1. Alkali Metal Compatibility							151	151
2. Leak Tightness							128	128
3. Metallography (light and electron)					8	8	31	31
4. Thermal Stability	27	9	75	30	48	48		
5. Fabricability	6	6					262	262
6. Gas Analysis	36	12					13	12
7. Chemical Analysis	25	5					34	7
8. Water Absorption			21	7				
9. Weight Loss in Vacuum			300	48				

SECTION II

MAGNETIC MATERIALS

A. SUMMARY OF TECHNICAL OBSERVATIONS

Depending upon specific requirements of different space power system components, the following major groups of magnetic materials were considered in this study:

1) Materials for the stator core: Ring laminations of Hiperco 27 alloy (27% Co-Fe) and Hiperco 50 alloy (2% V, 49% Co, 49% Fe) as well as of Cubex, a doubly-oriented 3-1/4% Si-Fe alloy, are suitable materials for advanced applications. Major magnetic requirements include a high-flux carrying capacity and low-core losses at high temperatures; only serviceable mechanical properties are required for these low-stressed parts.

2) Materials for the rotor core: Forgings and ring laminations of H-11 Steel (5% Cr, 1% Mo, Fe), Maraging Steels (15 and 18% Ni, 9% Co, Fe) and Nivco alloy (approximately 72% Co, 23% Ni and certain other elements), represent characteristic rotor materials. A solid or laminated rotor for a generator or motor is subjected to high rotational speeds which place high stress on the material. For example, the material is expected to possess a high-creep strength at operating temperatures preferably under 0.4% strain in 10,000 hours at stresses in excess of 40,000 psi. Although magnetic requirements are secondary for the solid rotor core, an induction exceeding 8 to 10 kilogauss at operating temperature under normal excitation conditions is expected. The rotor pole pieces are subject to losses which suggest that they might be either "slotted" or built from laminations since their magnetic performance requirements are more critical than their mechanical needs.

3) Materials for controls and electronic applications, including magnetic amplifiers: Tape and ring laminations of Supermendur (domain oriented 2% V, 49% Co, 49% Fe) and Cubex alloy were considered suitable. High saturation, high permeability, combined with a square hysteresis loop are desirable in these specific applications.

4) Pole materials for standard control apparatus: AMS 5210 (1% Si-Fe) casting was considered primarily because of its lower losses and better casting characteristics and higher resistivity than iron.

Figure II-1 displays the high-field induction of all the materials tested as a function of temperature. At 1400°F both Hiperco alloys reached induction of 18 to 18.5 kilogauss and Nivco induction of about 10 kilogauss.

Creep data for 0.4 percent creep strain for rotor-type materials and Hiperco 27 at temperatures up to 1100°F as a function of temperature are shown in Figure II-2.

Nivco alloy requires a stress of 67,000 psi to produce 0.4 percent creep strain at 1100°F in 10,000 hours. This surpasses the temperature capability of all other materials tested. The 15% nickel Maraging steel has outstanding creep strength at 700°F, but a temperature increase to 900°F brings about a rapid decrease in creep strength. The H-11 steel has very useful creep strength of about 90,000 psi at 800°F, but loses it rapidly as the temperature increases.

In considering the above data, the following grouping of materials can be attempted with respect to three temperature ranges.

1) <u>600-800°F</u>: Most materials qualify for this temperature range. However, Cubex alloy is preferred for use in stators at inductions up to 18 kilogauss. H-11 steel and Maraging steel are recommended for rotors and Supermendur in controls using high-quality, saturable-core reactors.

2) <u>800-1100°F</u>: Hiperco 27 alloy is suggested for high inductions and Cubex alloy for inductions up to 15 to 18 kilogauss in stators. In rotors, H-11 steel qualifies for the lower temperatures and Nivco alloy for the higher temperatures in this range. Supermendur and Cubex alloys can be used for controls with Cubex preferred for the higher temperatures.

3) <u>1100-1400°F</u>: Hiperco 27 alloy is recommended for stators and Nivco alloy for rotors in this temperature range.

Specific data and descriptions of the materials and test procedures discussed above may be found in the Magnetic Materials Topical Report (WAED 64.52E).

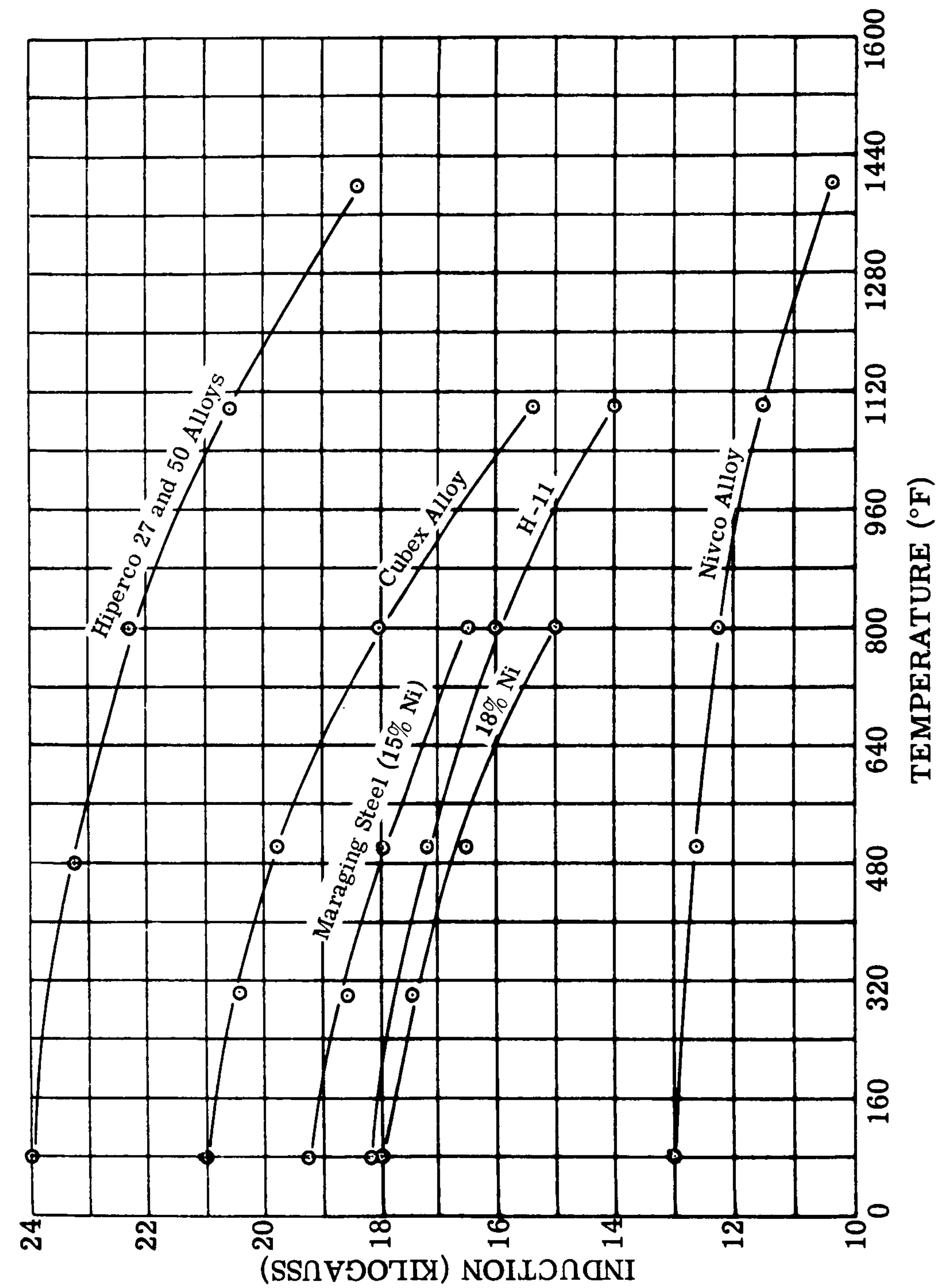

FIGURE II-1. Summary of Induction for Materials Tested at a Magnetization of 250 to 300 Oersteds as a Function of Temperature (Reference: NAS 3-4162)

Figure II-1. Maximum Induction Summary - Magnetic Materials

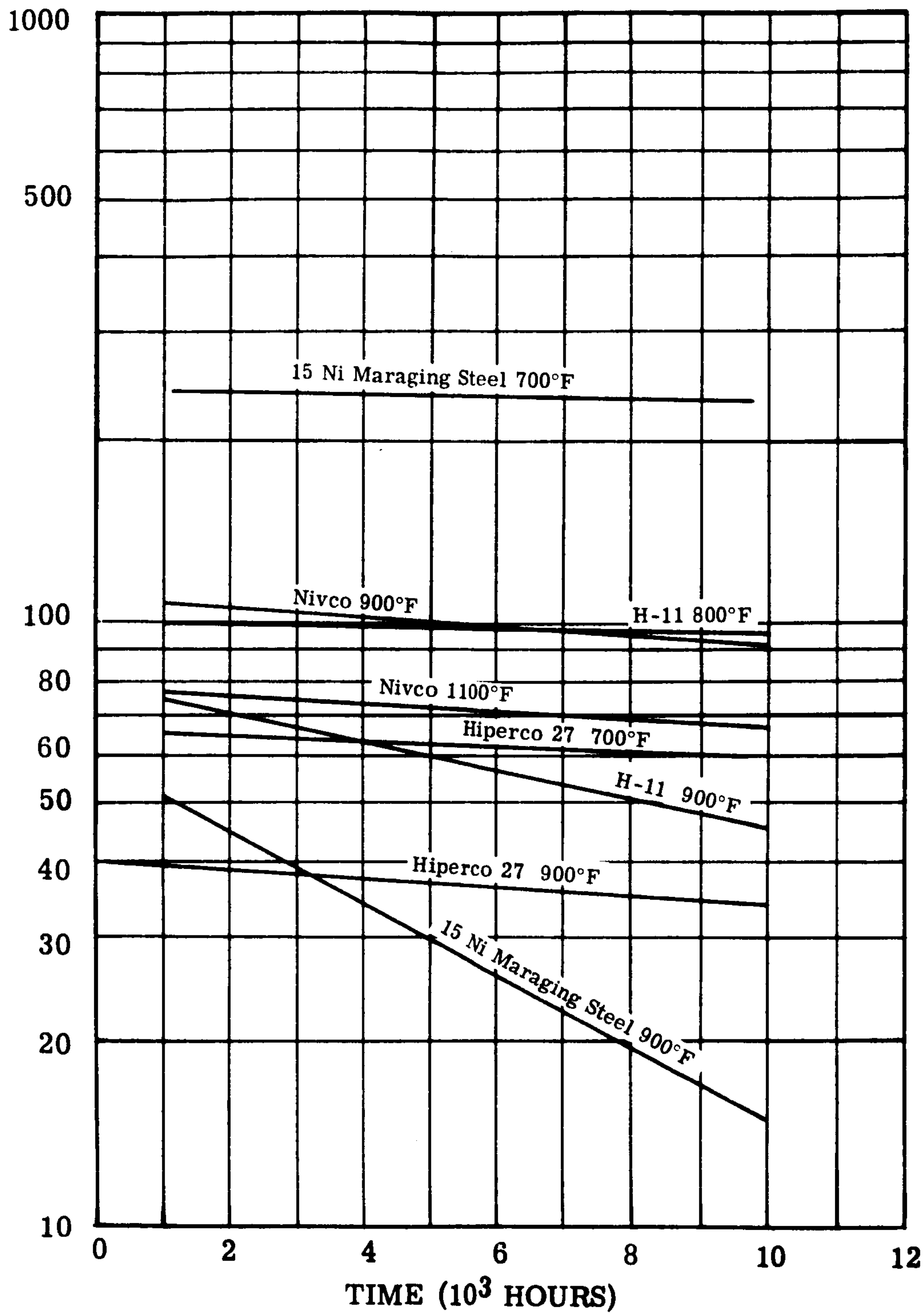

FIGURE II-2. Comparison of Stresses Required to Produce 0.4 Percent Creep Strain at the Indicated Temperature. Data Extrapolated from Larson-Miller Presentations. (Reference: NAS 3-4162)

Figure II-2. Creep-Summary Data Sheet

B. NEW TECHNOLOGY DEVELOPED

Shortly after the start of Contract NAS 3-4162, it was recognized that thin gage (0.015 inch) H-11 and Nivco alloy were not production items. Nivco alloy was not manufactured into forms other than bar stock and H-11 had not been rolled thinner than 0.050 inch. It was likely that heat treatment of H-11 thin gage material would be difficult because of a basic material susceptibility to decarburization. All of the technical problems associated with manufacture of thin gage material were overcome by an extension of existing metal forming technology and material was successfully made.

The measurement of high-temperature magnetic material properties were established and the winding of test cores with high-temperature, insulated clad wire developed.

A comprehensive analysis of mechanical, thermophysical, electrical, and magnetic properties was conducted on all magnetic materials suitable for high-strength, high-saturation and square loop applications at elevated temperature in advanced space electric power systems.

SECTION III

INSULATION AND ELECTRICAL CONDUCTOR MATERIALS

A. SUMMARY OF TECHNICAL OBSERVATIONS.

The electrical conductors selected for evaluation and their maximum recommended operating temperature were:

1) Nickel-clad, oxygen-free copper (1000°F).

2) Austenitic stainless-steel-clad zirconium copper (1200°F).

3) Austenitic stainless-steel-clad silver (1400°F).

4) Inconel-clad over columbium-clad over dispersion-strengthened copper (1500°F).

5) Inconel-clad fine silver (1500°F).

6) Bare dispersion-strengthened copper (Cube alloy)($>$ 1600°F)

7) Bare dispersion-strengthened nickel (TD Nickel)($>$ 1300°F).

The above conductors have a wide range of temperature and environmental capabilities. In some applications, the conductors may be required to withstand temperatures between 500° and 1600°F and/or an oxidizing atmosphere, inert gas, hard vacuum, or alkali metal vapor.

Ideally, it would be desirable that a conductor for high temperature use (500°-1600°F) have the following characteristics:

1) Low electrical resistivity.

2) A low-temperature coefficient of electrical resistivity.

3) Good resistance to oxidation and alkali-metal corrosion.

4) Acceptable mechanical properties over the temperature range 72°-1600°F such that the conductor may be easily bent into coils yet able to retain its physical shape in operation.

5) Easily joined to itself and other conductors.

6) Possesses a magnetic permeability approaching 1.00.

7) Possesses a low vapor pressure (for vacuum applications).

It was realized that no one material could possibly meet all the above criteria for a high-temperature conductor and still be a reasonably priced item. It was also apparent that the more stringent the operating conditions, the higher the cost and the more difficult it would become to make, insulate, and form the conductor coil. For this reason, a group of different and progressively more complex conductors were selected for evaluation. The maximum safe operating temperatures for long-time operation and both the desirable and non-desirable characteristics are listed for each material in Table III-1. Electrical resistivity as a function of temperature for these conductors is listed in Figure III-1.

The electrical insulation material evaluated are grouped into three temperature ranges.

1) -65° to 400°F Polyimide base materials which are well suited to long-term exposures to the environment of outer space. This class of materials may be used in the form of magnet-wire insulation, flexible sheet (both supported and unsupported), and rigid laminate. Diphenyl-oxide glass laminate also shows good stability through the -65° to 400°F range. At temperatures to 250°F, the epoxy-glass laminates are also stable. Rigid or molded parts made of filled polyester or epoxy resins may be used to 250°F while the polyimide molding resin (though somewhat more difficult to fabricate) is good to 500°F.

2) 400° to 1200°F This temperature range is above the practical operating limit of organic insulating materials. Magnet wire with ceramic-base insulation coatings satisfactory for 1000°F application were Anaconda CeramicEze (fused glass coating containing mixture of refractory oxides) and Westinghouse R2554B (refractory oxides and glass frit in an organic binder). Anaconda Anadur insulated wire (an E-glass fiber with refractory oxide and glass frit) proved to be the most durable and has an operating limit of about 1100° to 1200°F. Of the flexible inorganic sheet insulations, the mica-glass-silicone materials have the best working characteristics and a temperature capability of 1100°F in hard vacuum. Synthetic-mica paper (Minnesota Mining & Mfg. Co. Burnil CM-1) and silicate-fiber paper (Carborundum Company Fiberfrax) have satisfactory characteristics to 1300°F, but consideration in design and special care in handling must be used to obtain satisfactory performance. Boron-phosphate-bonded asbestos laminate may be used to 1600°F in a gas-filled system but only to 1200°F in a hard vacuum because of outgassing of the material. Inorganically-bonded mica laminate (General Electric Co. Mica Mat 78300) maintains adequate electrical and mechanical

TABLE III-1. Electrical Conductor Materials Selected for Investigation

Material	Desirable Characteristics	Maximum Long-Time Use Temperature[a]	Non-Desirable Characteristics
Bare Dispersion Strengthened Copper (Cu-1% BeO)	1. Highest strength conductor 2. Highest conductivity conductor 3. Most stable conductor on aging	Greater than 1600°F	1. Not resistant to alkali metal 2. Difficult to form and insulate
304 Stainless-Steel-Clad Zirconium Copper	1. Alkali metal resistant 2. Core resistant to grain growth to approximately 1200°F 3. Non-magnetic clad at all temperatures	to 1200°-1300°F	1. Somewhat difficult to make 2. Joining difficult
Nickel-clad Oxygen-free Copper	1. Low cost 2. Stable to 900°F for long times 3. Easy to insulate and wind	to 900°F	1. Use limited to temperatures below 1000°F 2. Joining difficult
Inconel-Clad, Columbium-Clad, Dispersion-Strengthened Copper	1. Alkali-metal resistant, high-strength conductor	to 1500°F	1. Difficult to insulate and wind 2. Somewhat difficult to make 3. Joining difficult
Inconel-Clad Fine Silver[b]	1. Alkali metal resistant 2. High conductivity for clad conductor 3. Easy to insulate and wind	to 1500°F	1. Somewhat difficult to make 2. Joining difficult
321 Stainless-Steel-Clad Fine Silver	1. Alkali metal resistant 2. High conductivity for clad conductor 3. Easy to insulate	to 1300°-1400°F	1. Somewhat difficult to make 2. Joining difficult
TD Nickel	1. Exceptional high-temperature strength	Greater than 1600°F	1. Very high resistance 2. Difficult to insulate and wind

a - Estimated capability for 10,000 hours based on 2,000 hour data.

b - Inconel cladding was chosen for its improved oxidation resistance in comparison to nickel. Nickel-clad silver exhibits similar electrical and stability properties. (See WAED 64.53E for discussion.)

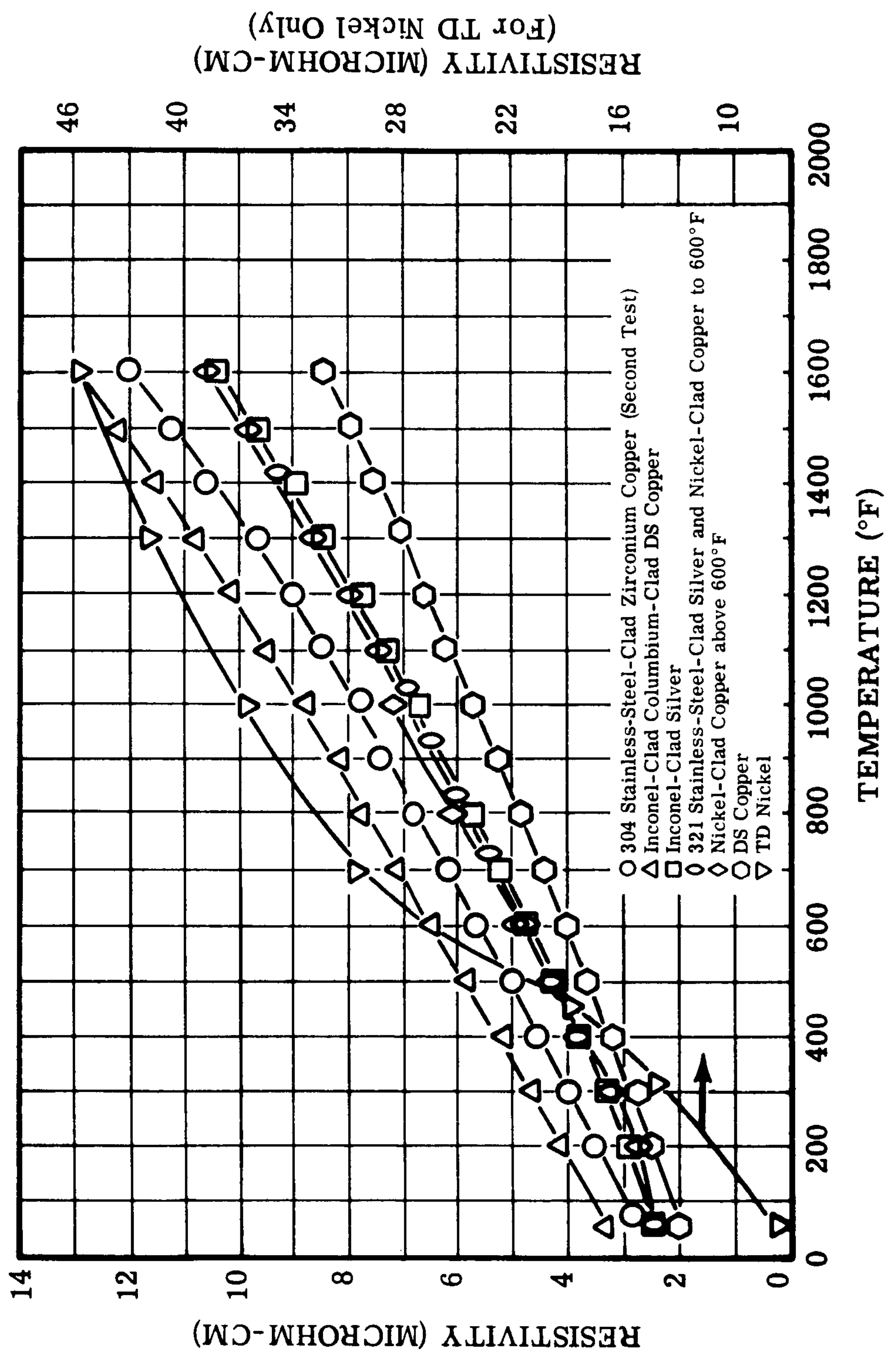

FIGURE III-1. Electrical Resistivity Versus Temperature of Conductors in Vacuum. All Cladding is 28% of Conductor Area Except Dispersion-Strengthened Copper Which is Columbium-Clad (8%) Inconel-Clad (28%).

Figure III-1. Electrical Resistivity - Conductors properties to 1100°F. Rigid insulation forms of 94 percent pure alumina perform well up to 1200°F. Alumina is generally rated as having very high stability at temperatures in excess of 1200°F, but the impurity content level of the 94 percent pure material prevents its application at high electrical stresses above 1200°F. The encapsulation compounds suitable for the temperature range 400° to 1200°F are Anaconda Anacap (refractory oxides and glass with cementatious bonding materials) and Sauereisen Cement Co., Sauereisen 8 (insulating cement of refractory materials); however, both compounds are limited to a maximum operating temperature of 1100°F.

The interlaminar insulations incorporating glass, aluminum, orthophosphate, or aluminum orthophosphate filled with either mica or Bentonite, used on the magnetic materials, perform well under all operating conditions to 1000°F.

3) 1200° to 1600°F Materials satisfactory for use in this temperature range are limited to the higher-purity alumina and beryllia bodies (99%). These bodies, molded and pressed and sometimes precision ground into shapes with proper attention to equipment design, may be used satisfactorily as electrical insulation. None of the ceramic-base wire coatings studied on this program were satisfactory for use in this temperature range. A promising plasma-jet-sprayed, high-purity alumina wire insulation being developed on other contracts is described in the Electrical Insulation and Electrical Conductor Topical Report (WAED 64.53E).

The mechanical and electrical properties of Westinghouse W839 encapsulation compound (inorganic bonded refractory oxide) show this material to be good to 1400°F. Outgassing properties, however, indicate that if the material is to be exposed to a space vacuum at temperature, 1200°F may be a more realistic operating temperature.

Specific data and descriptions of the materials and test procedures discussed above may be found in the Electrical Insulation and Electrical Conductor Topical Report (WAED 64.53E).

B. NEW TECHNOLOGY DEVELOPED.

No standard tests exist for determining the thermal conductivity of insulated magnetic wire. Since the thermal conductance in a radial direction across the diameter was desired for design purposes, a special spiral coil test method was developed and the data are reported as "apparent" since they include the complete wire construction.

Dispersion strengthened copper (Cu-1% BeO) was developed into bare, high-strength wire and into Inconel-clad wire with a columbium diffusion barrier. This provides the highest temperature electrical conductor available with good electrical conductivity.

A comprehensive comparative analysis of mechanical, electrical, weight loss in vacuum at elevated temperature, thermal stability and thermophysical properties were conducted on insulation and electrical conductors suitable for advanced space electric power systems operating in the -65° to 1600°F range.

SECTION IV

BORE SEAL

A. SUMMARY OF TECHNICAL OBSERVATIONS.

The bore seal provides a hermetic division between the corrosion sensitive insulation portions of electric generators and motors and the alkali-metal working fluids which are used in advanced space power systems.

The objective of this program was to identify properties of bore seal material systems which are capable of long life at 1000°F and 1600°F when exposed to potassium, sodium-potassium eutectic, and to lithium.

Static capsule tests were used to determine alkali-metal corrosion effects on ceramic materials and ceramic-to-metal seals. The compositions of the test materials were defined. The determination and control of alkali-metal purity in the test capsules was emphasized particularly with regard to oxygen contamination.

Alkali-metal loading of capsules was conducted in a vacuum-purge, inert-atmosphere chamber. Use of this chamber limited the oxygen and water content of the alkali metals to a combined total of five parts per million.

The materials tested on this program were selected for their thermodynamic stability, physical and mechanical properties, and fabricability.

Two major methods of joining ceramics to metals were investigated: the metallizing-braze method and the direct-bonding, active-metal braze process.

In the seal development effort, thermodynamically stable secondary phases were incorporated with the refractory metal metallizing base to replace the more conventional manganese, titanium, or silica containing secondary phase. Nine metallizing compositions were evaluated with alumina ceramics and five with beryllia bodies. In general, the use of metallizing with high-purity ceramics provided joints with lower strength than by active alloy brazes. Electroforming and evaporated thin-film metallizing were also investigated. The use of evaporated thin films of refractory metals on ceramics was found to have promise as a wetting aid for active-alloy brazes.

Fourteen active-metal braze alloys from the Titanium-Zirconium-Columbium-Vanadium-Beryllium (Ti - Zr - Cb - V -Be) systems were evaluated with two ceramics and two metal members. Three ceramic-braze-metal seal systems and five alumina and beryllia bodies were evaluated after 500 hour exposures to potassium, NaK, or lithium saturated vapors at 1000°F or 1600°F. Evaluation was made by strength degradation measurements and metallographic examination.

The most promising system for lithium exposure at 1000°F or for potassium exposure at 1600°F consists of a ceramic body of Thermalox 998 beryllia, brazing alloy of 56% zirconium 28% vanadium 16% titanium, and a metal member of columbium-1% zirconium. All tested specimens were vacuum tight after exposure. Table IV-1 summarizes the performance of ceramic-to-metal seals in alkali metal environments.

Materials and test procedures are reported in the Bore Seal Topical Report (WAED 64.54E) as are the thermophysical, electrical, and mechanical properties of potential bore seal materials.

TABLE IV-1. Preferred Ceramic-to-Metal Seal Configuration Based Upon 500 Hour Tests in Alkali Metal Vapor

Environment	Ceramic Material	Metal Member	Braze	Average Flexural Strength		Vacuum Tightness
				Before Test	After Test	
Potassium (1600°F)	99.8% Beryllia	Cb-1Zr	56Zr-28V-16Ti	13, 500	11, 810	--
Potassium (1000°F)	99.7% Alumina	Cb-1Zr	75Zr-19Cb-6Be	25, 655	21, 432	3 out of 3
NaK (1000°F)	99.7% Alumina	Cb-1Zr	48Zr-48Ti-4Be	23, 342	10, 390	4 out of 4
Li (1000°F)	99.8% Beryllia	Cb-1Zr	56Zr-28V-16Ti	13, 500	12, 000	4 out of 4

B. NEW TECHNOLOGY DEVELOPED.

Silica has been recognized as one of the main influences on the alkali-metal corrosion of ceramics. The quantitative effects of this compound have now been determined in sintered alumina and beryllia bodies.

The use of ceramic modulus-of-rupture bars has made it possible to evaluate both ceramic and ceramic-to-metal seal strength after exposure to alkali metals.

Active-metal brazes have been processed which allow the satisfactory joining of high-purity alumina and beryllia ceramics to metal members and the resulting joints are hermetic and have good strength. These joints are also resistant to alkali-metal corrosion at temperatures between 1000°F and 1600°F based upon the 500 hour tests conducted.

SECTION V

RECOMMENDATIONS

The following recommendations are the result of major observations made during the program.

1) High-strength magnetic materials suitable for use in the rotor must be developed so that lightweight generators and motors can be constructed in the 1000° to 1600°F range. Emphasis in this area should be on improvement of the magnetic properties.

2) Magnet wire insulation is presently available to only 1200°F. Flexible insulation systems suitable for clad conductors in the 1500° to 1600°F must be developed.

3) Larger bore seals should be constructed and the effects of larger sizes under stress should be evaluated.

4) Materials have been evaluated under single environments at present. Combinations of materials in the application geometry should be tested to evaluate the effects of combined environments such as high-vacuum and electric and magnetic fields.