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ALTERNATOR BORE SEAL -
UNSEALED ALTERNATOR
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ALTERNATOR BORE SEAL -
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ABSTRACT

The Mercury Rankine Program utilizes a hermetically sealed Combined Rotating Unit as the basic turboalternator machinery. The liquid mercury used in this unit is incompatible with the alternator stator in two respects: first, it will dissolve the silver stator windings during even brief exposure, and secondly, it will cause electrical continuity (shorting) between windings and to ground. Basically, the resolution to this problem is to exclude mercury from the stator by using a hermetically sealed stator bore containment.

The optimum bore sealing materials were the electrically and chemically inert glasses and ceramics. In late 1962, a program was started to investigate the use of coated windings rather than a coated bore. Just prior to completion of the program, the use of an evacuated stator, which tolerated small bore seal leaks and the exposure of silver wires to dry mercury vapor, was conceived. This program verified feasibility of the unsealed stator concept. Concurrently, efforts to improve leak tightness by stator redesign and utilization of a pyroceramic glaze indicated significant improvement over the previous glass application. This report covers work performed jointly by TRW, AiResearch, and AI.

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I. INTRODUCTION

The requirements for sealing the bore of the alternator stator in the mercury Rankine Program (MRP) combined rotating unit (CRU) occurs because mercury (Hg), the working fluid, is not compatible with the silver windings. Accordingly, the windings must be isolated from the Hg environment. In developing an effective isolation or bore seal for the stator, three concepts were evaluated by Thompson Ramo Wooldridge (TRW) (subcontractor for development of the CRU); these concepts were:

- 1) Metal sleeves,
- 2) Ceramics, and
- 3) Thin glass coating.

Glass was selected as the material which best met the requirements of:

- 1) Minimum air gap between rotor and stator,
- 2) Thermal shock resistance,
- 3) Compatibility with Hg vapor,
- 4) Good sealing to metals, and
- 5) Minimum electrical losses.

Metallic bore seals were abandoned because of the high losses in the metal due to the generation of excessive eddy currents. The high operating frequency of the CRU and relative low resistivity of the metal bore seal were the prime contributors to the prohibitive eddy current losses. A material of high resistivity which could be formed and be impervious to Hg at elevated temperatures was not available.

Initially, the ceramic bore seal approach was thought to be less acceptable than glass because the small air gap for a permanent magnet generator required the ceramic to be thin and consequently fragile and porous.

As it turned out, there were several major technical problems to be overcome before glass could be used in the bore seal. To begin with, glass has properties which are extremely difficult to define. In general, it is considered a plastic rather than elastic material. Therefore, its viscosity is more important than such things as tensile strength and other mechanical properties. Glass is considered to have virtually no tensile strength and tensile stresses must be avoided to prevent cracking. Therefore, TRW had to minimize differential thermal expansion through proper selection of materials and to assemble them in a manner which prevented tensile stresses from occurring. The problem of minimizing differential thermal expansion is complicated by the fact that the CRU stator consists of multiple elements and materials (Figure 1).

Approximately two years ago, the bore seal material was changed to a pyroceram type of coating. Improvement in significantly reducing the Hg leak rate has already been achieved. A newly designed stator with a pyroceram seal is in the initial stages of verification.

To provide further protection to back up the glass bore seal, AI, in January of 1963, began a program to develop an unsealed winding rather than a sealed bore. AiResearch Manufacturing Company was selected as the subcontractor because of their previous experience in evaluating such a concept for AI during a CRU study.

The program, devised in conjunction with AiResearch, consisted of two major phases: (1) evaluation of materials and (2) design and fabrication of stators, and tests. The program continued for a period of approximately 1 yr and was terminated prior to completion of the last phase.

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Figure 1. CRU-V Alternator Stator

The program was not completed in detail for three reasons: (1) changes in program direction of SNAP 2 no longer required the development of a prototype unsealed stator by a specific schedule date; (2) the AiResearch program had satisfactorily established the feasibility of the unsealed stator concept; and (3) AI had demonstrated analytically the possibility of permitting glass bore seal stator operation with small leaks for an extended period of time. This possibility was suggested as feasible because silver was found to be reasonably compatible with dry Hg vapor. One year of operation without detrimental effects to the stator did not appear unreasonable. Such operation might be further improved by evacuating the stator and thereby limiting the extent to which Hg could diffuse into the silver wire. Evacuating the stator to space would provide the low pressure required.

TRW has conducted Hg autoclave tests on the stator to verify satisfactory operations with cracked bore seals and evacuated stators.

This report describes the work done by AiResearch, TRW, and AI directed toward eliminating the hermetically sealed bore seal in the CRU and improving the leak resistance of the bore seal.

The data presented in this report have been assimilated from the numerous reports on the subject published by TRW, AiResearch, and AI during the period from 1962 to the present. Concurrently, the improvement in the basic bore seal processing has been carried along with partial satisfactory results.

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II. UNSEALED ALTERNATOR DEVELOPMENT PROGRAM PLAN

The major phases of the unsealed stator program (i. e., evaluation of materials compatible with Hg vapor and design, fabrication, and testing of a prototype stator) were logically organized into a step-by-step program from proof of principle to stator qualification. The first phase of the program consisted of a limited effort to establish proof of principle. To do this, the following were considered important:

- 1) Determine if fairly conventional materials were available for stator windings;
- 2) Determine if the stator materials were compatible with Hg vapor (gross effects);
- 3) Determine if the presence of Hg in the stator would compromise electrical performance;
- 4) Determine if the presence of Hg vapor and radiation would compromise electrical performance;
- 5) Determine if stator winding techniques were available (i. e., conceptual design);
- 6) Determine if proposed winding materials were fabricable (bend tests).

Due to the very large number of possible stator design concepts, AiResearch was directed to restrict the detailed design to the basic CRU stator adapted to a pretested winding concept. This concept was to be usable in either a brushless electromagnetically excited

machine (BEEM) or a permanent magnet machine.

The second phase, proof of feasibility, was initiated with the following objectives:

- 1) To determine long-term stator-materials compatibility in Hg vapor;
- 2) To determine probable effects of winding configuration on stator electrical and thermal performance;
- 3) To design (layout) the reference stator winding configuration;
- 4) To design (layout) the winding fixtures;
- 5) To determine the capability of producing rectangular wire from round clad wire (i. e., to fit TRW stator slots);
- 6) To conduct wire winding tests to verify the reference technique;
- 7) To investigate the fabricability of other stator materials such as multiple-place slot liners;
- 8) To plan suitable tests to qualify stators to AI's specification;
- 9) To design (layout) test rigs for endurance and startup testing.

The third phase of the program consisted of further capsule testing at low-pressure conditions, and performance testing of complete stator assemblies.

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III. DESIGN CONSIDERATIONS

There were several design factors to be considered in developing an unsealed generator that would perform satisfactorily and durably under the severe environmental conditions required by the CRU application. The materials used in the generator had to be selected with regard to their satisfactory resistance to deterioration under these environmental conditions as well as the usual electromagnetic and mechanical criteria. The more pertinent design factors that were considered are discussed in the following text.

A. ENVIRONMENTAL CONDITIONS

The environmental factors can be classified into (1) static factors which are independent of generator operation, and (2) dynamic factors which arise from actual operation. The more important static factors are operating temperature, gas composition and pressure, and ionizing radiation.

1. Static Factors

The ambient temperature adjacent to the generator package will be approximately 610° to 620°F, being determined by the condensation point of Hg vapor at about 9 psia. Generator losses will raise the interior temperature somewhat above this value with the hottest points occurring near the mid-points of the slots on the the conductor windings. This peak temperature is dependent on the heat transfer characteristics of the design and can be held within a prescribed range most suitable for operation. As discussed later, it is felt that operation in dry Hg vapor is essential to reliable operation. Since a minimum peak superheat of 80°F seems advisable to prevent cold spots from approaching condensation, an allowable variation of 3 to 1 in heat transfer properties would result in a maximum peak superheat of 240°F. Thus,

conductor operation in a range of about 700 to 850°F would be necessary. Insulators will experience similar temperatures, but the magnetic laminations can operate at slightly lower temperatures.

The gas composition will be essentially pure Hg with small traces of volatile impurities and possibly inhibitors such as magnesium. The nominal pressure will be 9 psia, but can be varied somewhat in the generator cavity by a suitable pump-vane configuration if necessary.

The radiation field will consist of gamma and neutron fluxes with the former about 1 r/sec and the latter about 10^5 n/cm²/sec. The integrated dosages are not large enough to create a serious radiation damage problem for metals or inorganic compounds, but the ionizing gamma radiation may affect the insulating properties of dry Hg vapor.

2. Dynamic Factors

Dynamic environmental factors arise from the operation of electrical machinery in the static environment. These include thermal and mechanical stresses, dielectric stresses, magnetic stresses and power loss effects.

Thermal stresses will be taken to include the effects of thermal gradients and expansion coefficient mismatches between various materials. Pure mechanical stresses will generally be low for stator assemblies, but vibrational levels and aerodynamic effects may require consideration. Dielectric stresses in solid insulation and Hg vapor must be kept somewhat below the breakdown strength of the respective media. The peak voltage required will be approximately 170 v, apart from switching transients. Magnetic stresses will include stator and air gap forces, magnetostriction of laminations and

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electromagnetic forces on conductors. Electromagnetic stresses may influence the rate of attack of generator materials by Hg vapor. Power loss effects include ohmic losses in conductors, dielectric heating, magnetic hysteresis and eddy current losses, viscous aerodynamic heating, etc. Their principal effect will be simply a heat load to be dissipated by the various components.

B. MATERIALS CONSIDERATIONS

Materials compatibility is a major consideration for operation of a generator winding directly in a Hg vapor environment. Surface resistivity of the insulation will be seriously affected if the Hg vapor reacts chemically or is appreciably absorbed by the materials. Conductors must not alloy with Hg. At room temperature, Hg will wet and amalgamate with a large group of materials. Tin, aluminum, silver, gold, copper, etc., are all susceptible to amalgamation. Mercury will not amalgamate perceptibly with iron, steel molybdenum, and tungsten. Resistance to amalgamation is affected by impurities, such as water, vapor, hydrocarbons, and oxides. Clean iron, glass, and quartz surfaces will not resist Hg wetting even at normal room temperatures. Mercury has not been known to wet graphite. Glass or refractory materials containing large proportions of phosphorus or nitrides may be resistant to Hg wetting, but this must be confirmed by tests. Although Hg is a good electrical conductor, it has a very high surface tension which causes Hg particles to have very limited contact area. This property is possibly an advantage for the generator insulation materials. The following table compares the surface tension of Hg with other liquids.

	Surface Tension (d/cm)
Hg	488
Water	72.7
Benzene	28.9
Toluene	28.4
Chloroform	27.1
Ether	17.0

Material compatibility in Hg vapor had not been thoroughly explored in the 600 to 1000°F temperature range. Accordingly, it was necessary for AiResearch to conduct Hg test programs to evaluate the effects of temperature, pressure, and surface preparation on the mechanical and electrical properties of a large group of materials.

C. STARTUP CONSIDERATIONS

The major problem areas which may be encountered in the application of an unsealed generator stator to the SNAP 2 CRU occur during startup. Before the generator has reached design power output, Hg vapor can be expected to condense on the stator windings causing temporary electrical shorts. Temporary shorting of the windings can in turn cause demagnetization of the permanent magnet rotor resulting in a loss of electrical output from the power system. With the use of a BEEM type alternator, it is felt that the windings can be shorted out during startup with a fixed excitation of such magnitude supplied to the field that the short-circuit current will be limited to a nondestructive value.

The startup studies (discussed in the following) are based on the high-pressure, Hg-injection, orbital-start concept, which appeared to be the most promising for the unsealed generator concept since the time between initial introduction of Hg vapor into the conversion system and full power output of the CRU will be minimized. Minimum startup time will in turn

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minimize the possibility of winding short circuits.

The conditions existing in the generator cavity prior to startup are expected to be pressures in the low micron range and temperatures ranging between 25 and 50°F (average), depending on the final choice of reactor coolant pumping method. At steady-state operating conditions the cavity is expected to operate with the Hg vapor at 9 psia and with 100°F of superheat.

1. Startup With Preheat

To preclude the possibility of rotor demagnetization because of short-circuits in the stator windings, the stator windings could be preheated just prior to system startup. If the wire is heated to a high enough temperature, then no condensation will form on the wire during start-up; thus, no shorting or grounding will take place to cause short-circuit currents.

The energy required to heat the windings to various temperatures is shown in Figure 2 as a function of how much heat leaves the wire. This latter will depend primarily on how fast the energy is imparted to the stator wire. It is assumed that at the beginning of this preheat, the stator temperature is about 50°F and that space vacuum surrounds the stator. The amount of current fed to the stator wire will depend on how much current can pass through the stator windings without demagnetizing the rotor or damaging the windings.

If 30% of the heat energy is retained by the stator wire during the warming period only 40 w-hr of energy are required to heat the windings to 1050°F (Figure 2). According to calculation all other parts of the stator will reach at least 700°F, and no condensate should form on any part of the stator during a startup.

A silver zinc battery capable of heating this stator would weigh less than 1 lb.

Figure 2. Energy Required to Preheat Stator Coils

The rotor is expected to cause condensation, but the excess temperature in the stator is expected to flash this condensate into vapor, continuing to do so until the rotor temperature is up sufficiently to prevent condensation. Heat, to warm up the rotor will come mostly from the rotational losses in the air gap (approximately 50 watts).

2. Startup Without Preheat

Liquid Hg, in shorting the stator windings between turns or phases or from a conductor to ground, causes high currents to flow in the conductors affected, thus not only heating up the shorting liquid Hg and vaporizing it, but also heating up the conductors themselves.

In general, due to the limited excitation produced by the magnet, a permanent magnet generator can withstand short circuits an order of magnitude longer in time than conventional synchronous generators (from a thermal standpoint). Aircraft generators with current densities of 10,000 amp/in.² can withstand a 3 per unit (300%) short-circuit current for 10 sec.

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In this case, the stator current density is 4000 amp/in.² and the short-circuit current is less than 3 per unit. The insulation is made of inorganic materials. Therefore, from a thermal standpoint, it is estimated that the short circuit can safely be applied for at least 2 min. However, from an electrical standpoint, the short-circuit current may cause serious rotor demagnetization. These points can be easily verified by tests.

D. DIELECTRIC PROPERTIES OF Hg VAPOR

A major consideration in developing an unsealed generator are the breakdown voltage characteristics of Hg vapor, which has a relatively high breakdown voltage compared with other gases, as shown in Table 1. The breakdown voltage characteristics for Hg vapor with two different types of electrodes are shown in Figure 3. It is significant to note that no combination of vapor pressure and electrode separation can cause breakdown at a voltage less than 400 v, provided that electron injection due to field or thermionic emission can be avoided. If the generator cavity operates at 9 psia, the electrode separation which will cause breakdown at 400 v is 0.003 in., as determined from Paschen's Law and Figure 3.

In the actual generator design, minimum conductor separation is approximately ten times the previous value with a pd value of 30 and a breakdown voltage of approximately 1600 v. A three-phase generator would permit a peak voltage transient of approximately double the operating voltage. The CRU-V generator with a line-to-line voltage of 115 v will remain well within the discussed breakdown voltage limits. If the generator cavity pressure is reduced by evacuation to space, the minimum breakdown voltage could still be 400 v (as shown in Figure 3) with a pd value different than 30. However, if any outgassing occurs in the stator,

TABLE 1
MINIMUM BREAKDOWN VOLTAGE IN VOLTS
(PARALLEL PLATES)

Hg	400 (steel electrode) 480 (nickel electrode)
Hydrogen	300
Argon	270
Helium	220
Neon	250
Oxygen	440

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Figure 3. Breakdown Voltage Characteristics
in a Hg Vapor Environment

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the Hg vapor could be contaminated and the voltage breakdown curve will be different than shown in Figure 3. Possibly the minimum breakdown voltage will be reduced below 400 v. For the present CRU-V configuration (Figure 1), there probably is still an adequate margin since the stator cavity is completely potted, which will increase the minimum breakdown voltage considerably over that shown by the gaseous atmosphere conditions of Figure 3. This could be verified by tests.

Electrical breakdown phenomena between conductors in a gaseous atmosphere follows Paschen's Law:

$$V = f(pd)$$

where

V = breakdown voltage,
p = pressure of the gas, and
d = distance between electrodes.

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IV. MATERIAL EVALUATION

A. MATERIAL SELECTION

Dependable operation of an unsealed generator in a Hg atmosphere demands materials that will perform satisfactorily and resist deterioration during extended periods of exposure to the environmental factors previously discussed.

The environmental factors may be expected to affect the material properties in a nonadditive manner, which would indicate the desirability of performing tests in an environment simulating the actual operating conditions as closely as possible. Practical considerations, including cost, time, and test apparatus development problems favor limitation of materials screening tests to a judicious choice of environmental factors deemed important to defining operating limits.

Since static and dynamic temperature properties of most commercial materials in air are available from the manufacturers, it was felt that little could be gained by direct testing of these properties except as a control. Chemical compatibility at operating temperature was considered to be the most critical problem for successful operation in Hg vapor; therefore, the compatibility tests were designed to measure the deterioration of material properties with time after exposure to dry Hg at elevated temperatures. The exposure tests thus were intended to measure resistance to the static environmental factors previously mentioned (excluding radiation). The evaluation, however, was based on the functional or dynamic properties at both room and elevated temperatures.

Generator stators require materials for electrical conductors, the magnetic path, and insulation. In addition, an unsealed generator will require insulated hermetic seals to permit

transfer of the power outside the Hg vapor enclosure.

Satisfactory conductor materials are limited to a small number of pure elements. Copper and silver are by far the best materials in regard to conductivity, but are deficient in their resistance to liquid Hg. Aluminum has fairly good conductivity but melts at a temperature dangerously close to operating temperature and is even less resistant to Hg than copper or silver.

It was felt that a copper or silver wire, clad with an impervious coating of a Hg resistant metal, would provide the most satisfactory conductor for this application. Based on liquid-Hg corrosion data, refractory metal coating would be favored, but no commercially available material could be obtained. A possible drawback to such a wire might occur through inherent brittleness of the refractory metals, especially tungsten and molybdenum, after cold working. Commercial sources of nickel-clad silver and copper, and stainless steel-clad copper were located, and representative samples (except nickel-clad copper) were obtained for testing. Pure molybdenum and tungsten were also selected for screening tests in the event that the clad wires should prove unsatisfactory. Since additional materials could be tested quite easily in simple capsule tests, it was decided to examine other less promising conductor materials. Table 2 lists the conductors chosen for screening tests along with measured resistivities.

Magnetic frame or lamination material was considered to be less of a problem than conductor material, since most iron-base alloys show good resistance to liquid Hg. Several common materials for ac magnetic applications, including several silicon steels and high cobalt

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TABLE 2
CONDUCTOR MATERIALS RESISTANCE TESTS
(Sheet 1 of 2)

Sample No.	Materials	Wire Gauge (AWG)	68°F Resistivity		Exposure Time (hr)	Resistance, mΩ		Percent of Pre-exposure Resistance		Notes
			(μΩ/cm)	(Ω/cmf)		(75-80°F)	(800°F)	(75-80°F)	(800°F)	
1	28 vol % 430 SS clad Cu	19	2.40	14.4	0 100	13.0 13.0-13.5	36.0	100-104	277	Sylvania oxalloy 28
2	28 vol % 430 SS clad Cu	19			0 100	12.2 13.6-12.5	35	111-102	287	Erratic value
3	W		5.46	32.8	0 100	18.5 14.6	45	79	243	Sylvania
4	W				0 100	18 15.4	52	86	289	
5	20 vol % Ni clad Ag	19	2.00	12.01	0 100	6.4 6.3	17.8	98	278	Sylvania nickel-clad silver (20%) wire
6	Ni-Ag				0 100	6.3 6.3	17.5	100	278	
7	OFHC Cu	20	1.724	10.37	100	4.0 3.55-3.60	11	89-90	275	Leeds & Northrup TC wire Hg - penetration
8	Cu	28			0 100	23.3 21.0	58	90	249	
9	Mo		5.63	33.8	0 100	56 52-56	140	93-100	250	Fansteel Co.
10	Vapor dep. W clad Cu	20			0 100	2.5 2.8		112		Sylvania pilot plant experimental coating. Brittle before Hg exposure
11	Vapor dep. W clad Cu	20			0 100	2.05 2.3		112		
12	SS-Cu				0 100	4 5		125		Rh plated ends
13	Ni-Ag				0 100	4 5.1		128		Rh plated ends
14	Rh plated Cu				0 100	8.4 8.7		104		Rhodex - Sel Rex 0.4 mil plated at 8 ma/cm ² undermined

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TABLE 2
CONDUCTOR MATERIALS RESISTANCE TESTS
(Sheet 2 of 2)

Sample No.	Materials	Wire Gauge (AWG)	68°F Resistivity		Exposure Time (hr)	Resistance, mΩ		Percent of Pre-exposure Resistance		Notes
			(μΩ/cm)	(Ω/cmf)		(75-80°F)	(800°F)	(75-80°F)	(800°F)	
15	Anodized Al	22			0 100					Re-anodized in borate solution to 300 v after folding; blackened, attacked
16	Fluoridized Ni-Ag				0 100					Coating formed at dull red heat in F ₂ chamber; blackened in Hg
17	SS-Cu				0 1000	17.2 17.2				No attack
17'					1000*	14-14	33	100	236	
18	SS-Cu Flattened to 0.020 in.				0 1000	19.7 19.4		98		No attack
18'					1000*	15.6-15.6	37		233	
19	Ni-Ag				0 1000	15 13.5		90		No attack
19'					1000*	11.8-11.8			215	
20	Ni-Ag Flattened to 0.020 in.				0 1000	18 16.2		90		No attack
20'					1000*	15-15.2	35.2	90-91	211	
21	Cu	20			0 1000	21.1 12		99		Intergranular attack, embrittled
21'					1000*	5.32	11		205	
22	Cu	28			0 1000	8.4 9.6		114		Intergranular attack, embrittled, short section measured
23	Ag 99.9%	20	1.60	9.6	0 1000 1000*	11.4 25.5 19-19		224	407	Handy & Harman, attacked in Hg

*Resistance measured over shortened length after metallurgical specimen was removed.

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steels, were obtained. Since eddy current losses at 1800 cps might be expected to dominate hysteresis effects, a high resistance chromium aluminum steel (Carpenter 1-JR) was also tested. The magnetic materials tested and their important properties are listed in Table 3.

Insulation material is largely limited to ceramics at the operating temperatures involved. Most ceramics show excellent resistance to liquid Hg, but little data is available on changes in their electrical properties. Insulating material is used as a spacer in this concept, the dielectric medium being dry Hg vapor itself. The presence of univalent ions, such as alkali metals, leads to increased electrical leakage as the temperature is raised; in addition, boron containing compounds are susceptible to neutron damage, although this reaction is negligible at

the levels to be encountered. Alumina, beryllia, and silica were considered to be most satisfactory in terms of Hg resistance, and were tested along with composite or fibrous materials such as ceramic-bonded miccas, papers, felts, etc. The insulators tested with the results of dielectric breakdown tests are listed in Table 4.

Mercury vapor is employed as a dielectric in an unsealed generator. This insulation is obviously self-compatible but forms mobile charge carriers in the presence of ionizing radiation which might adversely affect the dielectric strength of the medium.

No direct experimental testing of hermetic seals was undertaken but some information was gathered on commercially available seals

TABLE 3
MAGNETIC TEST

Sample No.	Material	Thickness (mil)	Exposure Time (hr)	B _{max} (Kgauss)	H _{eff}	Notes
1	M-19 Si Steel	7	0 1000	16.5	2.34	Armco
2	Hiperco 50	10	0 1000	18.7 16.7	2.63	Westinghouse Vacuum annealed 1500°F
3	Hiperco 27	8.7	0 1000	19.2 18.5	1.75	Westinghouse Vacuum annealed 1500°F
4	Supermendur	4	0 1000	21.8 22.7	3.22	Arnold Eng. Co. Vacuum annealed 1500°F
5	2v-Permendur	4	0 1000	21.6 21.2	2.34	Arnold Eng. Co. Vacuum annealed 1500°F
6	M-5 Oriented Si Steel	12.6	0 500	17.6 18.7	2.93	Armco Vacuum annealed 1700°F Cooled in magnetic field
7	M-7 Oriented Si Steel	14	0 500	16.8 18.7	1. 1.75	Armco Vacuum annealed 1700°F Cooled in magnetic field
8	1-JR 13 Cr-4Al Steel	2	0 100	12.4 11.9		Carpenter Steel Co. Vacuum annealed 1900°F

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containing insulating materials and metals undergoing test. No serious problems are expected since Hg resistant brazes are available.

B. MATERIALS TESTING - 100-HOUR AND 1000-HOUR EXPOSURE TESTS

Materials selected for testing according to the criteria previously outlined were obtained and appropriate samples prepared. The materials test program consisted of two parts, exposure and measurement. Since the developmental time schedule would not permit exposure testing for the full time period required in the application, some sort of accelerated testing was mandatory.

Chemical reaction rate theory predicts the velocity of rate of reaction to be proportional to concentrations of reactants and a temperature factor of the form $\exp(-\Delta U/RT)$ where ΔU represents an activation energy, R is the gas constant, and T is the absolute temperature. By conducting an experiment at 900°F instead of 800°F one will obtain an initial reaction rate increased by the factor $\exp(1.05 \times 10^{-4} \Delta U/R)$ or a factor of about e or e^2 for $\Delta U = 20$ or 40 kcal per mole, respectively. (Activation energies for diffusion through metals generally occur in the range $\Delta U = 20$ to 100 kcal per mole with a similar range likely for polyvalent ionic crystals.) A nominal temperature of 900°F was chosen for testing with initial screening tests of 100 hr exposure and extended tests on samples exposed for 1000 hr and subsequently for 90 days exposure. Since solid-state reactions are generally diffusion limited, the reaction rates decrease with time, as evidenced by the familiar parabolic oxidation rates for most metals. Thus, the test data may be linearly extrapolated to 10,000 hr with reasonable confidence of calculating an upper limit to the total deterioration which might be encountered over that period.

Measurements on test samples were confined to the functional properties important to generator operation, i.e., resistivity for conductors, alternating current magnetization of magnetic materials, and dielectric strength and leakage for insulation. Qualitative visual and mechanical observations were noted, with attention directed toward possible embrittlement or loss of ductility of metallic samples. Micrometallurgical examination was also made of metallic samples to detect possible minute structural changes.

The following measurement sequence was carried out on most samples. After sample preparation, a measurement was made at room temperature; the sample was then cleaned and inserted in the test capsule, which was evacuated, filled with Hg, and sealed. After furnace exposure, the capsule was opened and measurements were made at room temperature and at 800°F.

For insulation, the procedure was varied to use parallel samples for unexposed and exposed material. Tests were also run at 800°F on some of the unexposed samples, while the exposed samples were tested at 800°F in Hg vapor at 1 atm. This was done to test possible lowering of surface resistance in contact with Hg vapor, which might be destroyed in an oxidizing atmosphere.

Due to limitations in dimensions of the test capsule, a maximum sample width of approximately 105 mm was imposed. This resulted in a gas breakdown path only 6 mm longer than the sample thickness, with the rounded 6-mm electrodes employed. Since sample thicknesses were typically in the range of 1 mm, breakdown usually occurred around the insulation rather than through it for the nonporous materials. Under these conditions, the dielectric strengths measured are lower limits rather than actual

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TABLE 4
INSULATION DIELECTRIC STRENGTH TESTS
(Sheet 1 of 2)

Sample No.	Material	Thickness (mil)	Exposure Time (hr)	Minimum Breakdown Potential, kv		Minimum Breakdown Field Strength, v/mil		Notes
				(75-80°F)	(800°F)	(75-80°F)	(800°F)	
1	96% Al_2O_3	28	0	17		608		McDanel Av-30
2		28	100	4.5-4.6		160-164		
3		24	1000	5.8-7.5	3.2-3.5	242-312	133-146	
4	Sapphire Al_2O_3	42	0	16	10	380	238(670°F)	Linde Co., Single Xtal
5	Sapphire Al_2O_3	42	100					
6	Sapphire Al_2O_3	42	1000	3.6	2.8-3	86	67-71	
7	99.9% Al_2O_3	64	0	11		172		G.E. Lucalox
8		70	100	10	4-4.5	143	57-64	
9		65	1000	6.6-7.2	5.3-5.4	102-111	82-83	
10	98% BeO	60	0	12		200		Coors BD-98
11			100	10-11	4.2-4.5	167-183	67-75	
12			1000	8.8-9	5.6-6.2	147-150	93-103	
13	96% BeO	80	0	16		200		Coors BD-96
14			100	9	5.6-5.8	113	70-72	
15			1000	8.1-9.3	5.7-6.1	101-116	71-76	
16	Supramica 620	31	0	8		258		Mycalex Corporation
17		64	100	9.5	5	144	76	
18		57	1000	8.3-9	3.5-4	146-158	61-70	
19		57	0	11-12		193-210		
20	Supramica 620 BB	35	0	13.5-14		386-400		Mycalex Corporation

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TABLE 4
INSULATION DIELECTRIC STRENGTH TESTS
(Sheet 2 of 2)

Sample No.	Material	Thickness (mil)	Exposure Time (hr)	Minimum Breakdown Potential, kv		Minimum Breakdown Field Strength, v/mil		Notes
				(75-80°F)	(800°F)	(75-80°F)	(800°F)	
21	Supramica 620 BB	53	100	5	3.4-3.8	94	64-72	
22	Supramica 620 BB	36	1000	7.3-7.4	4.0	203-206	111	
23	Supramica 620 BB	55	0	14.5		264		
24	BN	36	0			389-417		Carborundum Co.
25		74	100	6.5	4.7-4.8	88	63-65	
26	Pyrolytic BN	26	0	11	5.6-6.2	215-238		Metals Technology, Inc.
27		23	1000	7-7.6	4.3-5	304-330	187-218	
28	MgO	31	0	12.5-13		404-420		Norton Co., Single Xtal GE Type 101
29		21	100	8-9	3.8-41	381-429	181-195	
30	SiO ₂	65	0	6.8		105		
31			100	10	3.5-4	154	54-62	
32	Silicone	47	0			245-256		Dow-Corning DC-302 Scorched - Outgassed
33	Molding Resin	43	100	4.8	2.6(100)	111 L*	61 L*	
34	Fiberfrax 970A	16	0	3.8		238		Carborundum Co.
35	Fiberfrax 970A	16	100	2.1-2.3	1.1	131-144	69 L	
36	Fiberfrax 970A	17	0	3.2-3.3		188-194		Al ₂ O ₃ SiO ₂
38	Tissuglas 60G	3	0	1.0		333		AMF 4 layers
39		3	100	0.5(400)	0.5(100)	167 L	167 L	
40	Tissuquartz 200Q	7	0	2.0		286		AMF 4 layers
41		7	100	1.5	1(400)	200-214	143 L	

*L = Lossy

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a. First Group at Termination of Furnace Test

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b. Second Group Before Furnace Test

Figure 4. 100-Hr Hg Exposure Capsules

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breakdown values. The use of this data will lead to conservative design and increased reliability.

Some parallel testing, including measurements at 800°F on unexposed samples, was carried out for conductors. Alternating current measurements were also made on some clad wires to obtain skin effect data.

1. Sample Preparation

Preparation of most commercially available material was straightforward. Insulation was merely cut to size and cleaned in most cases. No attempt was made to reduce the stock thickness of the hard materials (Al_2O_3 , BeO , SiO_2). Single crystal MgO and pyrolytic BN were cleaved to thickness. All conductor samples except for fluoridized wire, were left in a wire-drawn (unannealed) state prior to furnace exposure. Electroplated samples were prepared in the AiResearch laboratory, as noted in the tables. The clad wire samples were sealed at the cut ends by etching back the core and spot welding or alternatively melting out the core for a short distance and welding on small diameter stainless steel tubing caps. Refractory metal cladding was not end sealed satisfactorily, but metallurgical examination revealed that end penetration was not a problem over long distances. Resistance measurements were always made some distance from the end seals after folding to fit the capsules.

Magnetic lamination material was generally received in the cold rolled condition; therefore, the samples were annealed, after cutting to size, using the cycles listed in Table 3.

All samples except cleaved material were degreased in an ultrasonic cleaner using isopropyl alcohol as solvent. They were then outgassed and dried under high vacuum in the capsules.

2. Capsule Loading

Capsules (shown in Figure 4) were made from 13-mm pyrex tubing and consisted of an 8-in. section with a side arm 2 in. from one end. An indentation was made about 1 in. beyond the side arm and the sample placed above this point. The free end was then sealed and the side arm was attached to a high-vacuum, Hg-filling manifold. The assembly was evacuated to below 10^{-4} torr for approximately 1 hr and heat was then applied to outgas the system. Clean Hg was inserted through a hypodermic syringe and the capsule was then sealed. After another 30 min of vacuum pumping, the Hg was distilled and condensed on indentations cooled by dry ice. The condensate dropped from the indentations down the side arm into the capsules. When sufficient Hg had collected in a given capsule, the indentation was simply warmed. After all capsules had been loaded, evacuation was continued for approximately 15 min, and the capsules were then pinched off with a torch. After furnace exposure, the capsules were spot heated with a torch to test for possible leakage. All samples retained vacuum except for a silicone molding resin which apparently degraded to gaseous products and was under positive pressure.

3. Furnace Exposure

The samples were inserted in a 3-in. diam, 24-in.-long clamshell furnace with a vertical axis. The furnace was cross-wired to permit independent current or voltage inputs to upper and lower halves. The capsules were inserted in a perforated asbestos board disc (Figure 5) which was retained by a narrow steel ring at the furnace center. Temperature control was maintained by relays, activated by IC thermocouples, which switched the input turns to variacs in a ratio of 140:120 = 1.167. This changed the secondary voltages fed to the furnace windings by the same amount. This

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Figure 5. 1000-Hr Hg Exposure Capsules

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system was designed to prevent excessive temperatures in the event of relay failure. The lower half of the furnace was set to maintain 620°F at the lower end of the capsules, which should hold the vapor pressure at 9 psia. The upper half was set to maintain 900°F at the mid-points of the samples. A slight temperature gradient existed in the upper half resulting in a temperature as high as 950°F at the upper end of the capsule. If the sample gradient were uniform, a maximum differential of about 40°F would occur across a sample. However, metallic samples possess much higher thermal conductivities than Hg vapor, pyrex, or air, so the actual gradients were much smaller. Temperature-time records were kept on a strip chart recorder.

4. Conductor Measurements

Direct-current resistance of wire samples was measured on a 4-terminal network using a constant current power supply and a calibrated ammeter. Voltage between fiducial marks was measured on a HP 412A dc voltmeter, 1 MΩ with an input impedance of 10 MΩ. Relative resistance values depend only on the linearity and reproducibility of the voltmeter and reproducibility of the ammeter readings. These values have a maximum spread of ±1% and ±0.5% respectively, giving a maximum error of ±1.5% and a maximum probable error of about ±0.5%. Absolute resistance values depend on instrumental accuracies of 3.3% and 1%, respectively, giving a maximum error of 4.3% and maximum probable error of about 1.5%. This latter quantity can generally be obtained from manufacturer's data with greater accuracy.

Alternating-current bridge measurements were made of several clad wire samples to determine skin effect of frequencies up to 1800 cps. The circuit shown in Figure 6 was utilized. Oscilloscope readout was employed

and records of voltage imbalance and phase shift relative to OFHC copper were made.

Figure 6. Resistance Measuring Circuits

The results of resistance measurements for samples exposed to Hg vapor at 900°F for 100 and 1000 hr, respectively, are summarized in Table 2.

The exposure tests, with few exceptions, showed little or no adverse effect due to Hg vapor. The clad wire showed no resistance change after 100 hr, within experimental error. Tungsten, copper, and molybdenum showed a measurable decrease in resistance, indicating annealing effects. Anodized and fluoridized nickel-silver blackened after Hg exposure and a short piece of anodized aluminum in contact with liquid Hg dissolved completely. These coatings were studied primarily as a possible insulating rather than protective coating.

The results for bare copper were somewhat surprising and, as a consequence, one could not expect electrical resistance measurements to satisfactorily measure the integrity of cladding or plating on copper. Metallurgical sections (shown in Figure 7) showed an apparent

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a. 0-Hr Hg Exposure
(Bare)

b. 100-Hr Hg Exposure
(Bare) (100X)

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c. 1000-Hr Hg Exposure
(Bare)

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d. 1000-Hr Hg Exposure
(Clad)

Figure 7. Microstructure of Bare and SS-Clad Copper Wire (200X)

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penetration of Hg along grain boundaries of the bare copper samples. At the exposure temperature, considerable recrystallization also occurs for copper.

A sample of silver wire was included in the 1000-hr exposure to provide a control for the nickel-silver wire. Its resistance more than doubled after exposure and metallurgical examination showed considerable attack. The bare copper showed significant changes after 1000 hr with resistance increasing from the values shown after 100 hr and significant embrittlement occurring. The clad wires again showed no attack (see Figures 7 and 8), with the nickel-silver resistance values even lower than at 100 hr, indicating additional annealing effects.

Alternating-current resistance measurements were performed on the clad wires to determine skin effect at frequencies up to 1800 cps and currents to 10 amp for AWG 19. Resistance ratios were $(R_C - R_B + R_O)/R_O$ where R_C , R_B are the resistances of clad and bare wire at 1800 cps whose dc values were R_O . Resistance ratios at low currents were as follows: stainless steel-copper, 1.55; nickel-silver, 1.09. At larger currents, magnetization of the cladding produces a reactance voltage that distorts the waveform. For the nickel cladding, the possibility exists for operating above the Curie point (677°F).

The plated wires, rhodium-copper and rhenium-copper, showed intergranular attack similar to bare copper (see Figures 9 and 10). Tungsten-clad copper, obtained as pilot plant samples from Sylvania, were also attacked (see Figure 11) and the tungsten layer was too brittle to allow winding.

In summary, the clad wires, nickel-silver and stainless steel-copper appear to offer the most promise for this application, with the former material having lower losses.

5. Magnetic Measurements

Alternating-current magnetization measurements were made on a silicon steel laminated yoke, as shown in Figure 12. The magnetizing coil consisted of two layers of 20 turns/in. nickel-silver wire potted in a ceramic material. The pickup (B) coil consisted of 10 turns of flattened nickel-silver wire leading to an RC network which effectively integrated the $d\phi/dt$ or dB/dt signal and yielded ϕ or B. A shunt resistor in series with the magnetizing coil (H) permitted measurement of current. Oscilloscope display of the voltage across the capacitor vs the voltage across the shunt resistor produced B-H traces, which were photographed. The magnetizing power supply was a signal generator feeding a 60-watt MacIntosh audio amplifier. The 4- Ω output terminal was connected to the primary of a 4:1 stepdown transformer employing a ferrite core (Indiana General T-1). The secondary fed the shunt resistor in series with the magnetizing coil.

Several 1800 cps magnetization curves before and after Hg exposure are shown in Figures 13 and 14. None of the materials tested showed any deleterious effects due to Hg exposure either magnetically or metallurgically (see Figure 15). The saturation values of B run somewhat below the quoted static values, as expected, with the thinnest laminations approaching closest to static values. This may have been due to annealing, since no thorough study was made of the effect of annealing cycles which might change saturation values.

Magnetization curves were also run at 800°F. Little difference was noted except a slight decrease in saturation flux density as predicted by theory (Figure 16). The test results are summarized in Table 3.

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a. 0-Hr Hg Exposure (Bare)

b. 1000-Hr Hg Exposure (Bare)

c. 1000-Hr Hg Exposure (Nickel-Clad)

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Figure 8. Microstructure of Bare and Nickel-Clad Silver Wire (200X)

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Figure 9. Microstructure of Rhodium-Plated Copper Wire (0.4 mil) After 100-Hr Hg Exposure (200X)

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Figure 10. Microstructure of Rhenium-Plated Copper Wire (<0.2 mil) After 100-Hr Hg Exposure (200X)

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a. 0-Hr Hg Exposure

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b. 100-Hr Hg Exposure

Figure 11. Microstructure of Tungsten-Clad Copper Wire (200X)

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Figure 12. Magnetization Measuring Circuit

6. Insulation Measurements

Dielectric testing was performed using the circuit shown in Figure 17. A Sorenson Hi-V power supply was used. The sample width limitations frequently resulted in breakdown paths around the sample; however, dielectric strength measurements were invariably more than adequate for the intended application. Visual observation of the dielectric samples after Hg exposure could indicate chemical reaction in many cases, if present. However, no interaction is expected with stable oxides on the basis of available data.

*Proc. Phys. Soc. (London 52, 207 (1938))

The insulation test results are listed in Table 4. The only insulation showing deterioration was the silicone molding resin. This apparently suffered simple thermal degradation since it was exposed at a temperature more than 100°F above its nominal maximum service temperature. The dielectric strength remaining was still appreciable, however.

7. Breakdown Tests on Hg Vapor

In addition to the tests made on solid dielectrics, the breakdown characteristics of dry Hg vapor, with and without a radiation field, were measured. The previous test apparatus was fitted with a quartz spacer and breakdown measurements at gaps of 37 and 103 mils were made at atmospheric pressure (14.2 psia). The breakdown strength vs temperature is shown in Figure 18. The dielectric strength of Hg vapor compares favorably with that of air, as reported by Jones and Calloway.*

The effect of ionizing radiation was studied in a test lamp shown in Figure 19. A General Electric x-ray spectrometer with a Machlett Pt target tube was employed at 50-kv, and beam currents of 6 and 50 ma. The radiation level, 2-3/4 in. from the target, was calibrated with a Lauristen electrometer dosimeter giving measured levels of 0.43 and 3.67 r/sec. Since irradiation is with x-rays instead of the reactor gamma ray spectrum, a correction to obtain comparable ionization levels is desirable. The output spectrum of the x-ray tube is not known, but the cutoff wavelength for 50 kv is 0.248 Å. The ratios of mass absorption coefficients for Hg to air at $\lambda = 0.26 \text{ Å}$, $\lambda = 0.497 \text{ Å}$, 1.5 Mev, and 3.0 Mev are approximately 42, 111, 0.88, and 11, respectively. Thus, the x-ray beam at peak current is equivalent to a gamma ray level of over 100 r/sec in ionizing power. In the irradiation test the beam had to pass through a 0.005-in. stainless steel resistance heating shell (0.09 g/cm²). This would attenuate the beam to a value not less than 1/e times its original strength.

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a. M-19 - 0-hr Hg Exposure

b. M-19 - 1000-hr Hg Exposure

c. M-19 (800°F) 1000-hr Hg Exposure

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d. 1-JR - 0-hr Hg Exposure

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e. 1-JR - 100-hr Hg Exposure

Figure 13. Magnetization Characteristics of Representative Lamination Materials

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a. Hiperco 27 — 0-hr Hg Exposure

b. Hiperco 27 — 1000-hr Hg Exposure

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c. 2V — Permendur — 0-hr Hg Exposure

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d. 2V — Permendur — 1000 hr Hg Exposure

Figure 14. Magnetization Characteristics of Representative Lamination Materials

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a. M-19

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b. Hiperco-27

Figure 15. Microstructure of Magnetic Alloys
After 1000-Hr Hg Exposure

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Figure 16. Curie Curves for Ferromagnetic Materials (Magnetic Saturation vs Temperature Ratios)

Figure 17. Dielectric Measuring Circuit

Figure 18. Breakdown Characteristics of Dry Hg Vapor

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Figure 19. Electrical Breakdown Cell and Furnace for Radiation Test

The results of this test are shown in Figure 18. It can be seen that the influence of radiation at appreciably higher levels than encountered in the application has a very minor effect on breakdown strength of Hg vapor equivalent to about a 10 to 20°F rise in temperature. This result, which may be entirely thermal in character, is not unexpected from consideration of breakdown theory, since ion generation by multiplication is necessary for breakdown irrespective of the source of initial charge carriers. The calculated leakage current in air due to 1 r/sec ionizing radiation, even if no recombination were to occur, is about 1 esu/cm³ sec or about 3.3×10^{-7} amp/liter.

C. MATERIALS TESTING - 90-DAY EXPOSURE TESTS

The selection of the materials for the 90-day exposure tests was based principally on the results of the 100- and 1000-hr exposure tests. The results of these earlier tests were as follows: (1) none of magnetic core materials tested showed any deleterious effects, either magnetically or metallurgically, due to Hg-vapor exposure; (2) clad conductors withstood the Hg-vapor environment better than the plated or bar wires, with nickel-clad silver having lower losses than stainless steel-clad copper; and (3) differences in structure or composition of insulation materials from various sources affect the insulation properties during extended exposure to high temperature Hg vapor, and electrical stresses.

Accordingly, the magnetic core materials are not critical with regard to procurement; however, conductors are unique in that the materials tested are available only from the vendors who provided the test samples. Insulators must be evaluated on an individual basis since materials obtained from different sources, although nominally the same, are not identical

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in all their constituents and therefore react differently under the conditions of these tests. Further, the insulation material evaluation procedure following the 100- and 1000-hr exposures provided only lower limits to the dielectric strengths and did not provide information on dielectric heating. Therefore, it was decided to test various grades of insulation from different sources, in particular, alumina, which proved satisfactory in the earlier tests.

The material selection was thus limited to two magnetic materials, two clad conductors, and eight insulations. Seven of these insulation materials were aluminas of 94% or higher Al_2O_3 content. In addition, pure silver wire was included in the tests to assess the long-term effects of Hg vapor to the conductor core

material. The tests were conducted with 15 capsules divided into two groups. Each group included one capsule with only a vacuum environment. The contents of each capsule are listed in Table 5.

1. Test Preparation and Tests

Precision shears were used to cut all samples to appropriate dimensions for the magnetic laminations, wire cutters for the conductors, and a diamond saw for the insulation materials. The conductors were terminated by melting out the core material with a small torch a short distance from the end and then crimping and spot welding the hollow cladding. Several conductor samples were prepared with deliberate perforation of the cladding to permit Hg attack that might occur as a

TABLE 5
TEST CAPSULE CONTENTS - TABULATION OF NUMBER
AND TYPE OF SPECIMENS

<div>Capsule No.</div> <div>Material</div>		Run 1 5-17 to 8-15							Run 2 6-19 to 9-17							
		1	2	3	4	5	6	(Vacuum) V	11	12	13	14	15	16	17	(Vacuum) V'
Ni clad Ag (Sylvania)	AWG 19 AWG 14 AWG 14 Flathead		3		3		3	2	1 2	1 2	1 1	2 1	1 1		1	1
SS clad Cu (Sylvania)	AWG 19	3		3		3		2			1	1	1	1		
Silver (H & H)	AWG 20												1			
M-19 Si steel (Armco)	0.007 in.	12	10	12	12			12	12	12	12	3	12	6	6	
Hyperco 27 (Westinghouse)	0.0085 in.					10	10	10								
Alumina (Coors)	AD 94 AD 96 AD 99	4	4	4	4	4	4	4	4	2		4		2	2	1 1
(McDanel)	AV-30 AV-30 Box Section			1	1					2						1
(Wesgo)	Al 300 Al 995									2		2				1
Lucalox (General Electric)												2				1
Supramica 620 (Mycalex)													4			1

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result of defects or damage to the cladding. The magnetic material was vacuum-annealed at 1500°F for several hours. All samples were ultrasonically degreased in isopropanol and then vacuum-dried in their capsules.

Liquid Hg was added to the lower portion of the capsules before they were attached to the vacuum line. The capsules were then evacuated to the 10^{-5} torr range, and a fraction of the Hg was evaporated by warming the capsules; they were then sealed. The vacuum manifold and unsealed capsules for the second test are shown in Figure 20.

The furnace control for the first 90-day test was identical with that employed in the 1000-hr tests. As before, the samples were inserted

in a clamshell furnace which was cross-wired to permit independent temperature control of the upper and lower halves. The lower half of the furnace was set to maintain 620°F at the lower end of the capsules to hold the vapor pressure at 9 psia. The upper half of the furnace was set to maintain 900°F at the mid-points of the samples.

The furnace was controlled for the second test by using an IC thermocouple in the upper (hot) zone and a variable voltage was used to adjust the lower zone temperature. This method resulted in temperature regulation comparable to that obtained during the first test.

A small ac supply was installed to test the dynamic response of test coils in Hg, but the

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Figure 20. Capsules for Second Test Prior to Evacuation

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results were invalid since the capsules with these coils developed Hg leaks during their test.

The post-test appearance of the capsules is shown in Figure 21. Capsules 16 and 17 (see Table 5) developed leaks at their hermetic seals with resulting Hg loss and subsequent oxidation. The remaining capsules remained vacuum-tight and free of oxygen contamination.

2. Conductor Measurements

Direct-current resistance measurements of the wire samples prepared for the first test were made prior to capsule loading. This procedure was eliminated for the second test samples since previous experience has shown that annealing effects usually overshadowed the effects of Hg-vapor exposure. The second test samples were evaluated by comparison of post-exposure resistance over a measured distance ($\mu\Omega/\text{ft}$) with the same data for the vacuum annealed wire from capsules V and V'. An additional complication arose for the flattened nickel-clad silver wire in capsule 14. Some elongation of the wire had occurred during rolling; however, this was corrected by weighing identical lengths of round and flattened wire and finding the product of resistance per foot and the weight ratio of flattened to round wire. This product agreed with the mean value for the round samples within 1%.

Only a limited amount of high temperature and ac testing was performed since it was felt that little information regarding the effects of Hg-vapor exposure would be gained, and engineering data for design purposes was available from previous testing.

The results of resistance testing are given in Table 6. The clad wires showed no measurable effect of Hg exposure for the time and temperatures involved. Since the tests were run at a temperature substantially higher than anticipated in service, and the cladding thickness for the AWG 19 samples is less than 60%

of that present on the AWG 13 to 14-1/2 planned for generator service, high reliability is anticipated for the conductor in actual service. In comparison, the resistance of bare silver wire, increased to 393% of its initial value after 2160 hr in Hg vapor at 900°F. The previous result after 1000 hr was 224%.

The resistance of the perforated clad wire showed no detectable change over path lengths as short as 1/2 in., but this might be expected inasmuch as the previous result for bare silver indicates a minimum penetration depth of 0.008 in., and the removal of a hemisphere of this radius from the core would produce an undetectable change in resistance over 1/2 in. of wire length.

Metallurgical examination of several wire and magnetic specimens disclosed no new features compared with 1000-hr test results (see Figures 22 through 24). The single specimen of bare silver wire showed evidence of intergranular attack as before (Figure 23c), but the mechanical properties were not appreciably worse than after 1000 hr. Electrical resistance had increased by 393%, however. The clad wire samples showed only the usual annealing and recrystallization of the core metal.

3. Magnetic Measurements

The magnetic laminations were prepared in a manner similar to that for the earlier tests, but the measurement of properties was carried out with an improved experimental apparatus. The flux pickup coil was fed to an operational integrating amplifier instead of the previous RC voltage divider and gave a much higher signal level without distortion than heretofore. The B-H oscilloscope pattern was then fed to a waveform translator which permitted a slow manual scan of the pattern by diode voltage sampling. The outputs were traced on an X-Y plotter using a phase shifting trigger circuit.

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a. Test 1

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b. Test 2

Figure 21. 90-Day Hg Vapor Capsules After Exposure Test

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TABLE 6
CONDUCTOR RESISTANCE

Capsule	Resistance (mΩ)		Percent Change
	Initial	Final	
Nickel-Clad Silver (AWG 19)			
2	15.9	15.8	-0.63
	15.6	15.5	-0.64
	16.0	15.9	-0.63
4	15.0	14.9	-0.67
	16.0	15.7	-1.88
	15.8	15.5	-1.90
6	15.6	15.5	-0.60
	15.5	15.5	0
	15.0	15.0	0
V	15.6	15.5	-0.64
	15.7	15.4	-1.91
Resistance (mΩ/ft at 800°F)			
V	9.6	9.54	
11		9.6	
12		9.7	
13		9.74	
14		9.75	
15		9.65	
Nickel-Clad Silver (AWG 14)			
11	3.16	3.12	
		3.12	
12		3.08	
		3.10	
13		3.07	

Capsule	Resistance (mΩ)		Percent Change
	Initial	Final	
Nickel-Clad Silver (AWG 14) (Cont'd)			
15		3.03	8.0
	(AC)	3.1	8.0
V'		3.02	8.3
14 flattened		3.42	9.1
(corrected to original gauge)		3.07	8.2
Stainless Steel-Clad Copper (AWG 19)			
1	17.8	17.3	-2.8
	17.2	16.9	-1.75
	17.5	17.2	-1.72
3	15.8	15.9	+0.63
	16.8	16.8	0
	17.6	17.5	-0.57
5	17.4	17.1	-1.72
	15.9	15.5	-2.52
	17.5	17.3	-1.14
V	17.2	17.1	-0.58
	17.0	16.9	-0.59
Resistance (mΩ/ft)			
V	10.5	10.37	
13		10.5	
14		10.45	
15		10.5	
Bare Silver Wire			
15	9.6	37.7	393

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b. Vacuum Environment

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a. Hg-Vapor Environment

Figure 22. Microstructure of Nickel-Clad Silver Wire (AWG 14) After 90 Days Exposure at 900°F (200X)

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a. Hg-Vapor Environment
(Nickel-Clad)

b. Vacuum Environment
(Nickel-Clad)

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c. Hg-Vapor Environment
(Bare)

Figure 23. Microstructure of Nickel-Clad and Bare Silver Wire
After 90 Days Exposure at 900°F (130X)

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a. Hg-Vapor Environment

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b. Vacuum Environment

Figure 24. Microstructure of SS-Clad Copper Wire After 90 Days Exposure at 900°F (200X)

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The resulting hysteresis loops at operating frequency are at a magnification suitable for loss calculations by graphic integration techniques. Table 7 is a list of the properties of the materials for the capsules and Figures 25 through 29 are typical magnetization curves for various samples.

The magnetization measurements show little effect of Hg vapor exposure on the M-19 but a small degradation in performance of the Hiperco 27 is indicated. For example, the saturation flux density or induction $B_{\max}$ of the five M-19 samples (four Hg vapor and one vacuum) all lie within $\pm 1\%$ max of the mean value, while the two Hiperco samples exposed to Hg vapor show saturation inductions differing by less than 0.6% from each other but having dropped an average of 7.5% from the vacuum value. The latter agrees qualitatively with the 1000-hr test results which showed a corresponding loss of 3.6%.

No measurable change in coercive force was evident, but Hg-vapor exposure appears to improve loop squareness and lower the hysteresis loss in M-19. The apparent hysteresis losses obtained by integrating the $\phi - I$ curves are tabulated mainly for comparison of the Hg-vapor and vacuum exposed samples. The true hysteresis loss is determined by the area enclosed on a plot ϕ vs $I_{\text{net}} = I - I_e$, where I_{net} , I and I_e are the net, applied, and eddy currents, respectively. Since the net current is retarded with respect to the applied current, the true coercive force and hysteresis losses are lower than the indicated values. The principal factor in the large indicated losses as B approaches saturation appears to be connected with velocity effects in switching of

"stubborn" domains, since the apparent losses decrease rapidly as B is lowered while the ratio of I_e/I is actually increasing. Nevertheless, the losses at levels commensurate with the intended application appear to be quite tolerable.

4. Insulation Measurements

The availability of larger diameter test capsules and thinner slabs of insulation permitted true breakdown testing of all materials chosen for study. However, even 5/8-in.-wide by 1/32-in.-thick alumina specimens would usually break down in the air path around the sample. To permit true breakdown measurements, such samples were thinned down by diamond wheel grinding on one side after Hg-vapor exposure. Table 8 lists the results of dielectric testing. In no case did Hg-vapor exposure produce a significant effect on dielectric strength. Some variability in breakdown field strengths was observed, but this is characteristic of breakdown measurements. In addition, possible microscopic cracks arising from the grinding processes could lead to field intensification and lower the apparent strength of occasional samples.

No high-temperature breakdown testing has been carried out on Hg-vapor-exposed samples from this series. Exploratory work with unexposed samples has indicated that the breakdown strength of air or Hg vapor decreases more rapidly with increasing temperature than the aluminas, and additional thinning would probably be necessary. This is difficult, if not impossible, to do with present equipment without introducing cracks or other damage to the samples.

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TABLE 7
PROPERTIES OF MAGNETIC MATERIALS

Material	Capsule	B _{max} Tes la (10 ⁴ gauss)	H _C (amp-turns m)	Apparent Hysteresis Loss	
				Joule/m ³	At B _{max} (10 ⁴ gauss)
M-19	1	1.64	2700	2.84 x 10 ⁴	1.64
	2	1.65	2900		
	3	1.64	2850		
	4	1.62	2600		
	V	1.63	2900		
H-27	5	1.68	4050	3.24	1.63
	6	1.67	3900	4.06	1.68
	V	1.81	3950	4.44	1.81
M-19	1	1.54	3500	3.15	1.54
				1.93	1.46
				1.17	1.38
				0.174	0.68
800°F	1	1.44	3100	2.72	1.44
				1.75	1.37
				0.89	1.23
				0.67	1.14
				0.316	0.87
				0.124	0.58
				0.0257	0.266

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Figure 25. Magnetization Curves at 1800 cps
After 90 Days Exposure to Hg Vapor at
900°F (10 Strips H-27, Capsule No. 5)

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Figure 26. Magnetization Curves at 1800 cps
After 90 Days in Vacuum at 900°F

Figure 27. Magnetization Curves at 1800 cps
After 90 Days Exposure to Hg Vapor at
900°F (11 Strips M-19, Capsule No. 1)

Figure 28. Magnetization Curves at 1800 cps
After 90 Days Exposure to Hg Vapor at
900°F (11 Strips M-19, Capsule No. 1)

Figure 29. Magnetization Curves at 1800 cps
After 90 Days in Vacuum at 900°F
(12 Strips M-19, Capsule No. 7V)

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TABLE 8
DIELECTRIC BREAKDOWN STRENGTH

Material	Capsule	Thickness (mil)	V (kv)	E (v/mil)	Remarks
AD 94	6	14.9	15	1067	
		14.9	14	940	
	V	15.1	14	927	
		14.9	16.5	1107	
AD 96	11	13	14	1077	
	V'	9.5	10	1050	
		10.3	7.8	757	
	A	10.5	12.5	1190	
AD 99	13	9.1	11.5	1265	
		10	8	800	
	V'	9.2	12.6	1370	
		9.1	12.8	1406	
	A	12.6	16.5	1310	
AV-30	12	11.8	13	1101	
		9.0	11.2	1245	
	V'	12.9	16.2	1255	
		12.9	16.0	1240	
Lucalox	A	11.8	11	932	
		8.8	7	-	Cracked
		14	15.8*	>1128	
	V'	14	17*	>1215	
		11	15.5	1409	
		13	12.5	-	Cracked
Supramica	A	12.7	15*	>1180	
		15	5.1	138	
	V'	37	6.5	176	
		37	5.0	135	
		36.7	5.0	131	
Al 300	A	37.2	6.5	175	
	12	10	12.7	1270	
	V'	14.8	13*	>878	
Al 995	14	7.3	9.2	1260	

*Breakdown occurred in air around sample.

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V. GENERATOR STATOR DESIGN

A basic generator stator was designed (Figure 30), based on the dimensions of the existing CRU-V, which could be used to test various insulation systems. Based on the results of the materials evaluation, studies were conducted to select the details of the generator stator configuration which should be evaluated. From the results of the studies there evolved three insulation systems which merited further evaluation. These systems are summarized in the following text and are shown in Figure 31.

A. MATERIAL AND CONFIGURATION SELECTIONS

1) System No. 1

- a) Bare nickel-clad silver conductor.
- b) Three-piece slot tube.
- c) Ceramic beads fused on the end-turns for phase separation.

2) System No. 2

- a) Nickel-clad silver conductor with three sides protective wrapped in the slot with 0.005-in.-thick sheet ceramic (Al_2O_3).
- b) Three-piece slot tube.
- c) Ceramic beads fused on the end-turns for phase separation.

3) System No. 3

- a) Ceramic coated nickel-clad silver conductor.
- b) Three-piece slot tube.
- c) No end-turn spacing insulators.

In the first system, the three pieces of the slot tube will be fused to each other after winding. The fusing material will be glass frits bonded to the mating surfaces prior to assembly.

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Figure 30. Bare Wire Generator Stator

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Figure 31. Winding Insulation Systems for Stator Tests

The reasons for selecting these configurations for evaluation are presented in the following paragraphs.

1. Conductor Material

The two conductor materials under consideration were silver and copper. Neither of these two materials is resistant to Hg and would therefore require a suitable cladding.

Both stainless steel and nickel were considered as cladding material. Stainless steel is somewhat more resistant to Hg than is nickel; however, nickel is more ductile, has a higher electrical conductivity, and a higher mechanical resistance to cracking and checking. Rolling the round nickel-clad wire to form a flattened conductor has no effect on the cladding, as evidenced by tests which were previously conducted by AiResearch.

A secondary reason for rejecting stainless steel as a cladding material is that the available steel claddings are magnetic. This would result in higher flux leakages through the stator slots. On the other hand, nickel is nonmag-

netic at the operating temperatures involved. This, along with the lower electrical resistance, will result in a much lower apparent ac resistance of the winding. It was therefore concluded that nickel cladding would give better protection to the conductor and would also be the most desirable for electrical characteristics.

Since nickel is the choice for the cladding, copper is less satisfactory as a conductor. The diffusion of nickel into copper at elevated temperatures results in a greater increase in resistance than for nickel into silver. Thus, nickel-clad silver was selected as the conductor material.

2. Slot Tube Design

The three-piece slot tube design shown in Figures 32 and 33 was used. This design eases the task of forming the coils and inserting the windings and makes the concept of continuous formed windings (no internal connections) completely feasible, whereas the one-piece slot tube would make this concept impossible.

With the three-piece slot tube, the continuous formed coils can be inserted from the top of the slot and the top stick inserted from the end as the final item. This technique will be less difficult than trying to insert a one-piece slot tube and then thread the winding through, thus possibly damaging the cladding on the conductor.

The 4% silica and 96% alumina extruded tubes were selected because of their availability, ease of manufacture, and mechanical strength. The properties of this material are summarized in Table 9.

3. Magnetic Material

The selection of the magnetic material presented no particular problem. Since the required flux level is low, any silicon steel with a fairly high resistivity to minimize eddy current losses, would be satisfactory.

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Figure 32. Stator Punching and Slot Configuration

Figure 33. Slot Insulation System

TABLE 9
PROPERTIES OF 4% SILICA-96% ALUMINA

Specific gravity	3.6
Vapor permeability (μ/v) ($^{\circ}C$)	0 to 1450
Maximum operating temperature ($^{\circ}C$)	1650
Strength (10^3 psi)	
Tensile	35
Compression	300
Transverse shear	50
Dielectric strength RT (v/mil)	300
Resistivity RT	10^{15}
Ω -cm ($700^{\circ}C$)	10^8
Thermal expansion coefficient	7.8×10^{-6}
Thermal conductance (cal/sec-cm- $^{\circ}C$)	0.05

Armco M-19 silicon steel was chosen because of its low loss characteristics; 7-mil stock was selected.

Two types of stator stacks were selected for evaluation; one had each punching coated on one side with glass frits. After annealing, the material was fused to form the insulation. The second type of stator stack selected was constructed with punchings that had been oxidized in accordance with standard procedures.

4. Slot Configuration

The open slot configuration was selected for the unsealed stator design (Figure 32). The open slot was chosen over the glass bore seal closed slot design because of the following:

1) Insulation of the windings and insulation is significantly less difficult.

2) The armature leakage reactance is reduced considerably, thus requiring less magnetic strength in the rotor to realize the full load capabilities of the generator.

3) The windings can be continuous, thereby eliminating the need to braze or weld the windings together at the end turns;

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insulating these joints from the Hg would present a difficult problem.

The primary disadvantage of the open slot design is the increase in pole face losses over the closed slot design. These losses could become quite significant in the CRU-V design because of the small air gap.

If the pole face losses became excessive, a concept shown in Figure 34 could possibly be used. This design has closed slots and will permit the use of continuous preformed phase windings with no internal connections.

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Assembly Stages

1. Stator tooth section — weld on ID, finish grind on OD
2. Stator yoke section — weld on OD, finish grind on ID
3. Insert slot insulation and phase windings in tooth section. Assemble tooth and yoke sections (interference fit). Finish grind stator ID

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Figure 34. Continuous-Phase-Wound, Closed-Slot, Two-Piece Stator Core

5. End-Turn and Phase Insulation

Wire or end-turn insulation may be provided by either ceramic coated wire or a beaded structure. (The ceramic coating is porous and is merely used for spacing.) With ceramic coated wire, it is possible that no additional

end coil insulation (separation) is required if the end-turn spacing is sufficient. End-coil separation is required if bare wire conductors are used. This separation can be accomplished by fusing two halves of a split glass bead at various points on every other turn.

B. THERMAL ANALYSIS

Since the condensation of Hg vapor within the generator was felt to be detrimental to reliable operation, thermal analyses of the generator design were performed to determine its heat-transfer characteristics during steady-state operation and during startup.

Heat transfer calculations were made to determine the conductor temperature that would be attained as a function of heat dissipation rates when conductor cooling occurs entirely by radiation. To be conservative it was assumed that the ceramic slot tube insulators will act as radiation shields because of imperfect contact with the conductors and stator iron. However, full advantage was taken of the nickel cladding to obtain a higher emittance at the conductor surface than would be possible in the absence of cladding. The emittance of a nickel surface, oxidized by heating to 1110°F in air, is plotted vs surface temperature in Figure 35.

The emittance of the slot tube insulators was assumed to be very similar to that of aluminum oxide, also shown in Figure 35. The emittance of the M-19 stator magnetic material and frame was assumed to be comparable with an oxidized nickel surface.

Previous calculations have indicated that a relatively small temperature gradient exists along the conductors, even when all the heat is removed from the exposed end turns; therefore, a uniform conductor temperature was assumed for these calculations. Two heat transfer paths exist for radiation cooling (Figure 36).

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Figure 35. Surface Emittance as a Function of Temperature

Figure 36. Heat Transfer Paths

As a first approximation, the temperature gradient through the stator and ceramic slot tubes was neglected, and a mean radiation sink temperature of 670°F, based on frame heat transfer calculations, was assured. These simplifying assumptions are permissible since the radiation thermal resistance is the controlling factor.

The heat transfer rate for the embedded conductors is:

$$Q_1 = \frac{\sigma A_1 (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1} = \frac{\sigma A_2 (T_2^4 - T_3^4)}{\frac{1}{\epsilon_2} + \frac{1}{\epsilon_3} - 1} \quad \dots (1)$$

where

A_1 = effective radiation surface area of imbedded conductors

$$= \frac{(36)(3.06)(0.36 + 0.05)}{(144)} = 0.314 \text{ ft}^2$$

A_2 = effective radiation surface area between ceramic slot tubes and stator magnetic material

$$= \frac{(36)(3.16)(0.290 + 0.120 + 0.290)}{(144)} = 0.529 \text{ ft}^2$$

ϵ_1 = emittance of oxidized nickel surface

ϵ_2 = emittance of ceramic slot tube

ϵ_3 = emittance of oxidized stator iron = 0.413

σ = Stefan-Boltzmann radiation constant
 $= 0.0507 \times 10^{-8} \text{ watt/ft}^2 \text{ } ^\circ\text{R}^4$

The total length of exposed conductors in the end-turns is:

$$(36)(9.95 - 6.12) = 138 \text{ in.}$$

Due to the close proximity of the wires, the effective surface for radiation between wires and frame will be quite low. As an approximation, the effective radiating surface of the end-turns will be taken as the outer edge of each loop directly facing the frame.

The heat transfer rate from the end-turns to the frame is:

$$Q_o = \sigma A E_1 (T_1^4 - T_4^4) \quad \dots (2)$$

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where

A = effective radiating surface area of end-turns

$$= \frac{(36)(3.83)(0.05)}{(144)} = 0.0479 \text{ ft}^2$$

The nominal heat dissipation rate from the conductors was calculated to be 54 watts at a wire temperature of 800°F. Assuming constant current, the dissipation will be proportional to resistance (ohms) which increases with temperature. Hence, the heat dissipation rate for the silver wire is:

$$Q_r = 54 \left[1 + \frac{0.0038}{1.8} (T_1 - 1260) \right]$$

$$= 0.114 T_1 = 89.8 \quad \dots (3)$$

where

T_1 = conductor temperature in °R

Neglecting heat conduction through the terminals, a steady-state heat balance requires that:

$$Q_r = Q_i + Q_o \quad \dots (4)$$

The previous equations were solved graphically to yield the intersecting curves of heat dissipation vs wire temperature shown in Figure 37. An equilibrium wire temperature of 836°F is indicated for the assumed frame temperature of 670°F.

Approximately 70% of the conductor heat dissipation occurs within the stator, the remainder being accounted for by radiation from the exposed end-turn turns.

A check was made to verify the assumption of negligible temperature drop through the ceramic slot tubes as follows. The average temperature drop through the ceramic material is:

$$\Delta T_c = \frac{Q_i t_c}{k_c A_c} \quad \dots (5)$$

where

Q_i = heat transfer rate through the ceramic insulation = 39.0 watts

t_c = slot tube wall thickness

$$= \frac{0.028}{12} = 0.00233 \text{ ft}$$

k_c = thermal conductivity of Al_2O_3 at mean slot tube temperature
= 2.27 watt/ft-°F

A_c = mean cross-sectional area normal to heat flow

$$= \frac{A_1 + A_2}{2} = 0.426 \text{ ft}^2$$

Substituting in Equation 5:

$$\Delta T_c = \frac{(39.0)(0.00233)}{(2.27)(0.426)} = 0.094^\circ\text{F}$$

The temperature drop through the stator laminations adjacent to the slot tubes can be estimated by combining the radial gap windage loss with one half of the radiant heat flux from the ceramic slot tube insulators as indicated in Figure 38.

Figure 37. Conductor Heat Dissipation Rate vs Temperature

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Figure 38. Heat Flow Through Stator Lamination

The radial temperature gradient through the stator laminations opposite the slot tubes is:

$$\Delta T_s = \frac{Q t_s}{k_s A_s} \quad \dots (6)$$

where

Q = equivalent one-dimensional heat conduction rate

$$= 49.3 + (0.5)(0.7)(58) = 69.6 \text{ watts}$$

$$t_s = \text{radial depth of stator teeth} \\ = \frac{0.290}{12} = 0.0242 \text{ ft}$$

k_s = thermal conductivity of M-19 stator material = 2.76 watts/ft-°F

$$A_s = \text{mean cross sectional area normal to heat flow} \\ = \frac{(0.126 + 0.0732)(3.06)(36)}{(2)(144)} = 0.757 \text{ ft}^2$$

Substituting in Equation 6:

$$\Delta T_s = \frac{(69.6)(0.0242)}{(2.76)(0.0757)} = 8.07^\circ \text{F.}$$

Hence, it is concluded that the original assumption of negligible thermal resistance through the metal and ceramic parts was valid.

The calculations indicate that internal cooling of the stator by radiation and conduction only is

adequate. Also, the generator operating temperature gradient is sufficient to maintain dry Hg within the stator.

As a second phase of the heat transfer analysis, a study was conducted to determine the heating rate of the various generator components which are exposed to Hg vapor. This information was needed to estimate the amount of Hg that will be condensed during the startup procedure.

Initially, the generator components will be cold and the Hg vapor flowing from the turbine exhaust, as shown in Figure 39, will condense on the cold metal surfaces, and continue to do so until the generator reaches vapor temperature.

To be conservative and also reduce the complexity of the calculations, certain heat sources were neglected such as (1) heat entering the stator and windings from the external cooling fins, (2) heat transmitted to the rotor from the turbine shaft, and (3) self-heating of the rotor resulting from losses. The major source of

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Figure 39. Generator Cavity with End-Turn Shield Removed

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heat for the generator is the flow of Hg vapor and the heat released by condensation. All other sources of heat are insignificant during the first few minutes.

The areas where condensation can form during this period are shown in Figure 40. These areas represent the portion of the generator in the immediate vicinity of the end-turn cavity.

The heat absorbed by the stator laminations was assumed to be negligible since the resistance to heat flow is high. Heat absorption calculations were performed for each of the other areas along with the heat available from the flow of Hg vapor through the orifice. The results of these calculations are plotted in Figure 41 as a function of time and show that the housing area and the winding end-turns will reach vapor temperature in just a few seconds. The rotor, however, indicates a large thermal capacity and will take several minutes to attain a sufficient temperature to prevent condensation.

The calculations were based on a continuous sonic flow of the Hg vapor through the orifice, which is only true for the first few seconds, after which time the rising cavity temperature will develop a back-pressure, thus reducing the flow of Hg.

The amount of Hg that will condense in the cavity in 4 sec, for example, was calculated to be 0.058 lbm or a volume of 0.087 in.³ In 20 sec, approximately 0.292 lbm or 0.438 in.³ of Hg will be condensed. These values are extreme because of the basic assumptions; therefore, it is reasonable to expect the actual test results to be considerably less. The curves of Figure 41 verify the fact that condensation will take place for many minutes.

Based on the results of this study, it is felt that the condensation rate of Hg in the generator end-turn cavity will not be sufficient to create short circuits even if the end-turn shield cannot be used.

Figure 40. Areas of Generator Where Condensate Can Form

Figure 41. Total Heat as a Function of Time

C. POLE FACE LOSS CALCULATION

In connection with this project, AiResearch developed an equation for pole face losses from fundamental electromagnetic theory.

Consider a thin rectangular fabrication. In the MKS system of units, the eddy current loss for a uniform flux distribution is:

$$W = \frac{(d\phi)^2 ahs}{(dt)4\pi b\rho}$$

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where

W = loss in watts

ϕ = magnetic flux

t = time

a = width of segment

h = thickness of segment

s = number of segments

b = length of segment

ρ = resistivity.

For the actual flux distribution in a rotor pole face, the loss is about one-half of this value.

In the case of the SNAP 2 actual rotor with

$\rho = 100 \mu\text{-ohm-cm}$ this loss becomes:

$W = 353$ watts using the flux distribution as shown on Figure 42.

Figure 42. Rotor High-Frequency Flux Density

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Figure 43. Generator Stator Core in Holding Fixture

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VI. STATOR FABRICATION AND TEST RIG DESIGN

A. STATOR FABRICATION

Fabrication techniques were, by necessity, developed along with the stator tooling since both the tooling and the fabrication require careful coordination and some trial and error. The first stator core is shown in the holding fixture in Figure 43, three others were stacked and heat-treated. The nickel-clad silver conductor material was obtained, along with the ceramic slot tubes and top sticks.

Two major tools for forming the continuous phase windings were developed with no major problems. The pull-out fixture (Figure 44) required only minor adjustment when the actual stator conductor material was used.

The preliminary winding fixture is shown in Figure 45 and required some modification when the details of the continuous phase windings were finalized. The winding fixture is used to form the coil continuous winding that is com-

posed of six segments of two turns each. The pull-out fixture forms each segment that represents one of the six poles by pulling the coils the proper distance to obtain a precise fit in the respective stator slots. In addition to the two major tools, some hand tools were required for final adjustments and handling; these were standard tools modified to have nonabrasive surfaces.

Originally it was planned to build nine stators for environmental and startup testing. However, because of the previously mentioned program reorientation, only three units were completed. The first stator was assembled using copper wire to check out the winding fixtures and the assembly procedures. Some modification to the tooling was required as a result of this assembly. Following modification of the tooling, the second stator was assembled

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Figure 44. Generator Stator Winding Pull-Out Fixture

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Figure 45. Generator Stator Coil Winding Fixture and
Partially Formed Coil

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with the use of the nickel-clad silver wire. Although the assembly is satisfactory as far as electrical checkout is concerned, many of the ceramic slot liners were cracked during insertion of the wire and final shaping of the crossover end-turns. The third stator was wound with slightly smaller wire; and, although the cracking problem was avoided, the wire is probably too loose in the ceramic slots for successful completion of shock and vibration testing. Figure 46 shows this stator prior to shipment to AI for pole face loss tests.

In addition to the winding effort, additional work was performed on the method of assembling and preparing the surfaces of the stator laminations. An assembly was made using laminations coated with a glass frit for insulation; it was not a success due to the unevenness of the thin coating which resulted in an assembly with various lengths around the circumference. Also, when the assembly was heat-treated, it was distorted enough to lock the jig in the stator slots, and it was necessary to machine the jig from the stator. This approach to insulating the laminations was discarded because of these problems and because of the successful assemblies and insulation characteristics being obtained with the oxidized laminations.

B. TEST RIG DESIGN

Design of a startup test loop and of a 90-day environmental test loop, for testing the unsealed generator stators was conducted. The design of the environmental test capsule is shown in Figure 47. This test rig can contain three stators, two of which will have dc power applied to maintain the stator at the approximate design operating temperature, and the third will have 1800 cps ac power applied at the design voltage. A dummy rotor will be inserted in the ac-powered stator and the air gap clearance adjusted to obtain rated current flow in the stator.

To cool the ac stator the test rig wall will simulate the actual heat flow path expected in the CRU. Mercury vapor flow in the rig will be accomplished by connecting the test rig to a small thermal convection loop. The Hg will be boiled at 15 psia (680°F) and flow up past the two dc-powered stators and through the gap between the ac-powered stator and its dummy rotor. The flow leaves the test rig at the top and returns to the small boiler in an external pipe acting as a condenser. The expected flow rate based on a 14.5 psia to 9.0 psia pressure drop across the ac stator with an 0.007-in. air gap clearance is 0.17 lb/min, and the expected velocity is 44 fps.

The hermetic seals used to bring out the stator leads will be of the type planned for the actual generator, and the test rig adjacent to the hermetic seals will be maintained at a temperature of 680°F to demonstrate the suitability of the seal at the expected operational conditions.

The design of the startup test rig was completed based on a blowdown system in which the stator was located in an evacuated test capsule, the walls of which could be heated above the condensation temperature of the entering Hg vapor. Figure 48 is a layout of this test system. This approach was discussed with AI personnel and it was decided to change the design so that the thermal transient expected in the actual CRU could also be simulated.

A second conceptual design, similar to the ac stator capsule configuration, was begun to provide a method of simulating with electric heaters the heating and cooling path created by the external cooling fins. In further discussions between AI and AiResearch it was concluded that even this second conceptual design did not adequately simulate the starting transient that the stator would experience in a CRU. It was decided to abandon the attempt to simulate startup conditions by means of a test loop and

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Figure 46. Generator Stator No. 2

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Figure 47. Environmental Rig

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Figure 48. Stator Startup Rig

that this test would be performed in an actual CRU at such time as prototype development took place.

The 90-day environmental test loop, though, represented a very good investment not only for evaluation of these stators but for materials evaluations in general. For that reason, de-

tailed design was accomplished and parts and equipment procured. The loop was not assembled by the time that this generator development program was terminated, but it has been transferred to TRW for use in their continuing CRU development efforts.

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VII. DESIGN EVALUATION TESTS

Because of the program reorientation, limited tests were conducted with the unsealed stators that were fabricated. One of the stators was sent to TRW for electrical performance evaluation, primarily for rotor pole face loss tests. It was anticipated that the pole face losses would be quite significant because of the open slot design. Considering basic electromagnetic theory and using flux plots it is possible to predict the amount of pole face loss. Calculations show 353 watts and the test gave 375 watts for the open slot configuration.

As it turned out, the pole face losses of the open slot configuration were, indeed, significantly larger than the closed slot design. This can be shown by comparing Figures 49 and 50. This loss is significantly larger because of the small air gap required of a permanent magnet generator. For a BEEM type generator design, this loss would be less than 50 watts for the same open slot. The results of the test also showed that the conductor losses were greater for the open slot design. This was occasioned by the use of commercially available wire known to be undersize and to have a cladding thickness of 20% of the cross-sectional area.

It should be noted that the test was on a first experimental unit without the benefit of any prior development tests. Both of the discussed problems can be resolved by further development. The high pole face losses can be reduced by decreasing the slot width, increasing the air gap, and/or by machining grooves on the rotor pole face. The conductor losses can be reduced by using full sized wire with a minimum cladding thickness.

The circumferential grooves on the rotor surface reduce the pole face losses because of the increased path length for the surface cur-

rents. Calculation shows that grooves 0.004-in.-wide by 0.025-in. deep and 0.050-in. apart would reduce the pole face losses by a factor of 2. This was verified by subsequent test on an inductor alternator.

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Figure 49. Alternator Loss Separation vs Power Output, Open Slot

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Figure 50. Alternator Loss Separation vs Power Output, Closed Slot

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If it should be necessary that a closed slot design be utilized for the unsealed generator, the configuration shown in Figure 34 can be used. This configuration permits using the continuous windings with closed slots by inserting the windings from the back of the slots. Another possible approach to the closed slot design is to use a normal stator configuration and the preformed noncontinuous windings, by necessity, inserted from the end. The required end connections then could be protected from the Hg by electro-deposition of refractory metals on the connections. This process has been developed recently by Union Carbide.

Further performance test results of the unsealed generator are shown in Figures 51 through 53. The results of these tests are compared to test data from the closed slot CRU-V stator obtained under identical test conditions.

The negative load voltage regulation shown in Figure 51 is characteristic of the SNAP 2 system and is caused by the reactance of the short-circuit capacitors. The capacitors also function as power factor correction devices for the alternator. Their reactance is such that with the exception of inductive loads below 3 kw, the alternator terminal power factor is leading.

With the leading power factor conditions prevailing, the mmf generated by the direct component of the armature reactance is in phase with the main field mmf. This condition produces the rising voltage characteristic at the terminals of the alternator as shown in Figure 52. Since the armature reactance is approximately 30% lower in the open slot unit than in the closed slot unit, the terminal voltage regulation or increase in voltage for a given load is less in the open slot unit. Hence, for a given load the load current is greater in the open slot unit.

The load current for both machines is shown in Figure 53. The rapid increase in the open slot load current at unity power factor results in a corresponding increase in the short-circuit capacitor voltage drop. This capacitor voltage drop limits the load capacity of the open slot unit at unity power factor loads to 3 kw. The inversion in the 0.8 power factor lagging load curves of Figure 53 is due to the power factor change at the alternator terminals from lagging to leading.

Figure 51. Load Voltage Regulation vs Power Output

Figure 52. Terminal Voltage Regulation vs Power Output

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Figure 53. Load Current vs Power Output

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VIII. GLASS BORE SEAL STATUS

The current CRU-V alternator configuration has a pyroceram bore seal with an evacuated stator cavity. Pyroceram can be considered to be a glass ceramic. Before firing, the Pyroceram consists of finely powdered glass that has been modified with a nucleating agent. Upon firing, it first melts as a normal glass but then begins to devitrify (crystallize) due to the presence of the nucleating agent. This crystalline state is typical of ceramics. Once this material has crystallized, re-exposure to the firing temperature of 800 to 850°F will not cause it to remelt. Viscosity is not meaningful after devitrification begins because it then becomes a time and temperature variable. When normal glass would have a fixed viscosity for any given temperature, the Pyroceram devitrification process causes the viscosity to increase with time. The time required to fully crystallize (cure) is a function of the curing temperature.

Even with the improved properties of the Pyroceram bore seal over the previous bore silicate glass seal, the current CRU-V alternator can be expected to have bore seal cracks and leaks. This may appear to be more serious than it really is. The seriousness of the bore seal cracks can be assessed by evaluating the loss of Hg as a function of time, the effect of Hg vapor on the stator materials, and the effect on operation due to condensed Hg vapor.

The results of the capsule tests conducted by AiResearch showed that silver could withstand many hours of operation in Hg vapor without serious degradation. The electrical resistance of the silver wire in Hg vapor at 900°F increased only 200% after 1000 hr of exposure and slightly less than 400% after 90 days. In the CRU-V alternator, due to the great length of silver with relatively low resistance, a 400% change, if it were uniform,

would not be of great concern. However, if the resistance change is due to a localized attack on the silver wire by a Hg droplet, this could be of concern since the wire could "blow out" at this point when any sizeable current is supplied.

This is much less of a change in resistance than what would occur if the diffusion of minute amounts of Hg vapor into the silver resulted in perfect amalgamation (as shown in Figure 54).

This is because the diffusion of Hg is interstitial and apparently affects only a small zone around the grain boundaries. This type of effect can clearly be seen in Figure 7.

Based on the history of bore seal leak rates and the relative minor degradation of silver windings exposed to 900°F Hg vapor, it seemed reasonable to conclude that the CRU stator would tolerate small leaks for a year or more without serious degradation. Further, if the stator cavity were evacuated the amount of Hg diffusion in the silver wire would be considerably lower than the results indicated by the AiResearch tests. In orbit the low pressure

Figure 54. Change in Electrical Resistance for Homogeneous Hg-Silver Amalgam

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desired can be obtained by venting the stator cavity to space.

In order to verify the discussed conclusion, tests were conducted by TRW and AI. The objectives of the tests were:

- 1) To determine the time effects of superheated Hg vapor upon the integrity of the silver conductor and other internal stator elements,
- 2) To determine the effects of temperature upon helium leakage rate through typical bore seal cracks,
- 3) To determine effects of Hg condensation in the stator cavity and liquid Hg leakage rates through bore seal cracks,
- 4) To correlate Hg-vapor leakage rates with measured helium leakage rates through bore seal cracks, and
- 5) To determine the effect of long term exposure of Pyroceram bore seal to con-

densing Hg at the CRU-V operating temperature.

Items (4) and (5) did not require special tests but were to be determined from the tests of item (1).

A. TIME EFFECTS OF SUPERHEATED Hg VAPOR

Tests were conducted by AI and TRW on the time effects of Hg vapor on the stator elements. AI's tests were similar to the capsule tests conducted by AiResearch except that the silver conductors were exposed to lower pressures (0.4 and 1.0 psia) and temperatures (600°F) to simulate the evacuated stator concept. The results of the AI tests, shown in Figure 55, indicated an insignificant change in resistance after a 2000-hr exposure to dry Hg vapor.

The TRW tests were conducted on complete stator assemblies with Pyroceram bore seals and evacuated stators. The test setup to perform the TRW tests is shown in Figure 56.

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Figure 55. Percent Change in Silver Conductor Electrical Resistance vs Time in 900°F Hg Vapor Environment

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Figure 56. Hg Vapor Endurance Test

CRU-V Hg-vapor conditions were simulated by immersing a cracked stator in an autoclave containing Hg vapor at approximately 680°F. The vapor temperature was controlled by one of the three thermocouples suspended within the autoclave. The stator cavity and stator connector temperatures were measured to be certain that these areas were above the saturation temperature of Hg for the existing internal stator cavity pressure.

The autoclave total pressure was monitored to detect any admittance of noncondensibles. These noncondensibles were removed by a cold trap-purge system incorporated in the setup.

Mercury vapor leaking through the cracked Pyroceram bore seal was condensed and collected in the cold trap in the stator cavity vacuum line. The stator cavity was evacuated to 150 millitorrs (150 μ Hg). This vacuum was maintained by throttling the continuously operating system vacuum pump, and was purposely kept higher than the pump capability to force Hg condensation in the cold trap rather than in the pump casing. Periodic liquid Hg inspection of the cold trap was accomplished by venting the system between the stator shutoff valve and

vacuum pump to atmosphere after temporarily shutting off the stator line valve. Following the inspection, the system was re-evacuated by an auxiliary vacuum pump because the pumping rate of the throttled system vacuum pump was too slow and it was undesirable to change the setting of the throttle valve. The auxiliary pump, which was only briefly operated following cold trap inspection also served as a backup to the system vacuum pump in case of its failure.

Periodic measurements of the dielectric strength and resistance of the stator windings were recorded to determine the effect of Hg vapor. The physical effect on the silver winding was determined by autopsy at the termination of the test.

The desired duration of the endurance test was 6 months; the test was terminated prematurely after 706 hr because of a leak in the vacuum line valve which prevented adequate control of the system vacuum. A check on the stator after removal from the autoclave indicated no change in either the resistance or dielectric strength of the stator windings. The helium leak rate for this particular stator was 1.6×10^{-4} std cc/sec prior to test and 1.1×10^{-2} std cc/sec after the 706 hr of exposure to 680°F Hg vapor. The liquid Hg extracted from the cold trap was only 1 mg. Because of the small leakage, an autopsy of this stator was not conducted.

The test was restarted using a second stator; it was ended after a total of 3884 hr. The total amount of Hg collected during this period was 380 mg and is shown as a function of time in Table 10. The 14.2 mg was in the stator lead tube at stator disassembly. The plot of liquid Hg vs time is shown in Figure 57. The plot shows the average Hg mass flow rate of 9.78×10^{-2} mg hg/hr, which is theoretically equivalent to 3.06×10^{-5} std cc/sec helium. Also shown in Figure 57 is a spread of Hg mass flow rates

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Figure 57. Liquid Hg Leakage vs Test Hours

corresponding to their theoretically equivalent helium leak rates. The range of leak rates shown is from 10^{-5} to 10^{-4} std cc/sec helium, which is the best prediction of the actual leak rate of the stator bore while immersed in the autoclave. A fairly good agreement between the actual and theoretical mass flow rates is shown.

The winding resistance and dielectric strength prior to and after removal of the stator from the autoclave showed no change. The winding

resistance and dielectric strength as a function of time are presented in Table 10. The winding resistances shown include test lead resistances.

The helium leak rate was checked prior to and after the autoclave test to determine any change in leak rate resulting from the endurance test. The results are summarized as follows:

- 1) Prior to autoclave test at 70°F, 1.1×10^{-4} std cc/sec
- 2) After removal from autoclave at 70°F, 0.95×10^{-6}
- 3) After removal from autoclave at 700°F, 0.84×10^{-4}
- 4) After removal from autoclave at 70°F, 4.8×10^{-4}

The data are in fairly close agreement (except for the first post-test measurement at room ambient) with what would be expected based on previous helium leak test experiments. The noted discrepancy may be due to clogage of leak paths with condensed Hg which was removed during the 700°F bake out, test 3 above.

TABLE 10
MERCURY AUTOCLAVE TEST - SUMMARY OF TEST DATA

Cumulative Test Time (hr)	329	929	1505	2682	2850	3186	3522	3690	3858	3884
Stator vacuum (Hg)	42	80	20	150	175	190	190	200	190	150
Stator temperature (°F)	565	575	563	561	568	568	564	566	559	557
Lead tube temperature (°F)	301	326	301	307	312	316	311	310	306	302
Autoclave press (psig)	0.5	-1.0	0	-0.8	-0.5	0.2	0.3	-1.0	0	0
Autoclave temperature - top (°F)	647	652	638	619	628	666	662	595	635	683
Autoclave temperature - middle (°F)	700	665	675	680	685	690	700	685	690	685
Autoclave temperature - bottom (°F)	665	660	660	660	660	670	675	655	665	670
Resistance (Ω)										
No. 1 to N	0.1831	0.1852	0.1877	0.1846	0.1861	0.1848	0.1870	0.1860	0.1872	0.1843
No. 2 to N	0.1825	0.1826	0.1862	0.1825	0.1844	0.1835	0.1851	0.1840	0.1853	0.1824
No. 1 to No. 2	0.2565	0.2574	0.2593	0.2553	0.2557	0.2559	0.2575	0.2559	0.2568	0.2548
Dielectric strength (Ω)										
No. 1 to G	∞	-	∞	∞	-	-	∞	∞	-	-
No. 2 to G	∞	-	∞	∞	-	-	∞	∞	-	-
N to M	∞	-	∞	∞	-	-	∞	∞	-	-
Cumulative Hg Collected (mg)	55.6	61.7	102.0	211.2	220.2	258.8	287.5	305.4	328.6	365.8
										+14.2
										TOTAL 380.0

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A visual examination of the electrical conductors and insulation after stator disassembly revealed no evidence of Hg attack. However, a chemical analysis of the Hg extracted from the stator revealed a minor amount of dissolved silver. Similarly, a spectrographic analysis of sample silver conductors and lead tube insulation indicated a very faint trace of minor amounts of Hg. The Pyrocera™ bore seal was unaffected by its exposure to 680°F saturated Hg vapor even though condensation was occurring on the bore seal surface.

The correlation between measured helium leakage and Hg vapor leakage through a bore seal crack, determined during the autoclave tests, was applied to several CRU-V stators to determine the time effect on Hg inventory loss (Table 11). The stators listed have the present Pyrocera™ bore seals. The largest leak rate results in less than 0.02 Hg/yr; an insignificant loss in Hg inventory.

TABLE 11
CRU-V TEST STATOR LEAK RATES
PYROCERAM BORE SEALS

CRU-V Unit	Helium Leak Rate STP cc/sec	Equivalent Hg Leak Rate (gm/hr)	Equivalent Hg Inventory Loss (lb/yr)
2D	3.2×10^{-6}	1.0×10^{-5}	0.00019
3C	8.3×10^{-8}	2.7×10^{-7}	0.0000052
4B	2.5×10^{-4}	8×10^{-4}	0.0155
4C	9×10^{-8}	2.9×10^{-7}	0.0000056
5A	2.9×10^{-5}	9.3×10^{-5}	0.00180
5B	7×10^{-7}	2.2×10^{-6}	0.000043

B. EFFECT OF TEMPERATURE ON HELIUM LEAK RATES

Six tests were performed on two different stators to determine the effects of temperature on helium leakage through bore seal cracks. The test setup used to perform these tests is shown in Figure 58. Table 12 is a summary of the test results. Complete results of all six

tests are shown in the curves of Figures 59 and 60. The results demonstrate increased leakage with increased temperature for a stator with a freshly induced crack. The increase, however, is within one order of magnitude. For a stator crack that has been heat cycled to 700°F, a slight decrease in leakage occurs with increasing temperature. Another interesting aspect of the test was shown when the leak rate through the stator crack remained fairly constant upon decreasing the temperature. This apparent "hysteresis loss" is also shown in Figures 59 and 60. This condition may result from the fact that data were obtained during cool-down without establishing equilibrium temperatures for each data point.

In each case, the measured helium flow rate was obtained at standard conditions so that mass flow rate through the leak is represented. The results indicate that mass flow through the crack is relatively unaffected by temperature in comparison with the experienced scatter of leak rate data at room temperature for all stators.

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Figure 58. Test Schematic, Helium Leak Rate vs Temperature

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TABLE 12
EFFECT OF TEMPERATURE ON HELIUM LEAK RATES

Test No.	Stator S/N	Method of Crack Inducement	Leak Rate (10^{-4} cc/sec He)		Change (%)
			Prior to Test	At Maximum Deviation	
1-1	148	Water quench	1.16	3.92 (500°F)	+240
1-2	148	Repeat of test 1-1	7.70	7.47 (700°F)	-3
1-3	148	Hammer impact	2.18	3.63 (300°F)	+67
1-4	148	Repeat of test 1-3	2.00	1.04 (700°F)	-48
1-5	151	Water quench	1.0	6.60 (500°F)	+560
1-6	151	Repeat of test 1-5	2.14	0.87 (700°F)	-59

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Figure 59. Helium Leak Rate vs Bore Seal Temperature

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Figure 60. Helium Leak Rate vs Bore Seal Temperature

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C. EFFECTS OF LIQUID Hg IN THE STATOR CAVITY DURING STARTUP AND SHUTDOWN

During the operation of the CRU with a cracked bore seal, there are two possibilities of liquid Hg existing in the stator cavity; (1) liquid Hg leakage through bore seal cracks during startup, and (2) Hg vapor condensation during shutdown.

To determine liquid Hg leakage through a bore seal crack, two tests were conducted by TRW on one stator. The crack was induced by rapping the stator housing with a mallet. The helium leak rate prior to any tests was 1.4×10^{-2} std cc/sec.

The first test was performed with a pressure differential of approximately 11.3 psi. The stator bore and its associated plumbing were completely filled with Hg, and this acted as a reservoir for a 5 ml burette. Liquid Hg leakage would be indicated by a head loss in the burette. Also, the stator was accurately weighed prior to start of the test and any increase in weight at the completion of the test would indicate Hg leakage into the stator cavity.

The second test was performed with the stator cavity evacuated to less than 30μ Hg to simulate the evacuated stator core. The differential pressure was approximately 26 psi.

The first test was performed for a duration of 575 hr and the second test for 550 hr. The results demonstrated that at differential pressures of 11.3 and 26 psi, room temperature liquid Hg did not leak through a glass bore seal crack whose helium leak rate was 1.4×10^{-2} cc/sec. The 1.4×10^{-2} cc/sec helium leak rate is several orders of magnitude greater than the demonstrated history of CRU-V bore seal leaks. Helium leak rates from 10^{-8} to 10^{-4} cc/sec can be expected.

With the present CRU preheat start concept and evacuated stator, the possibility of con-

densed Hg vapor causing a short circuit during startup is very remote. The Hg vapor that condenses in the stator cavity on shutdown, which for 9 psi vapor is calculated to be only 62 mg, should completely vaporize during the preheated startup, especially with the evacuated stator concept.

Aside from the discussed analyses and experimentation performed on the current pyroceram stator configuration (shown in Figure 1), TRW has been working on a redesign of this stator to achieve the following objectives:

- 1) Improve the ability of the stator bore to act as a solid substitute for the brittle glass seal;
- 2) Isolate the prestressed laminated stack assembly from the severe thermal gradients caused by condensing Hg vapor at startup, and from internal mechanical restraints.

The cross-section of the redesigned stator is shown in Figure 61 and can be compared with Figure 1 to see the basic changes.

The primary purpose of the redesign is to allow unpreheated CRU startups. The present stators require preheat to insure integrity of the bore seal. To date, TRW has fabricated three stators of the redesigned configuration and the major portion of the fabrication techniques have been established. Initially, there was a problem of contamination of the inter-laminate glass causing bubbles in the bore seal that must be resolved, and a valid thermal-mechanical evaluation has not yet been achieved.

Recently a fourth stator of the new design was fabricated with a pyroceram bore seal. Initial test results are very encouraging. The leak rate is very small ($\sim 10^{-10}$ cc/sec STP) and thermal cycling defects have not yet been observed.

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Figure 61. CRU-V Alternator Stator Redesign

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IX. CONCLUSIONS AND RECOMMENDATIONS

The purpose of the unsealed alternator stator program was to investigate a backup to the glass bore seal concept. With this purpose in mind, a logical step-by-step program was conducted by AI, TRW, and AiResearch.

The fundamental problem confronting the unsealed stator concept was that of materials compatibility with Hg vapor. Little data were available on the compatibility of materials comprising the alternator in the severe environmental conditions encountered in the CRU. Accordingly, material evaluation tests were conducted on insulations, conductors, and magnetic materials. The results of these tests permitted the selection of materials suitable for fabrication of developmental test units. A significant result was that the properties of nickel-clad silver wire were affected very little when exposed to high temperature Hg vapor at a pressure of 9 psi.

In addition to the materials consideration other major factors which could affect the operation of the unsealed alternator were evaluated. The voltage breakdown characteristic of Hg vapor and the effect of radiation on this characteristic were studied and found to compare favorably with that of air.

Although the program substantiated the feasibility of an unsealed alternator concept there were two unresolved areas that would require fairly substantial development before a reliable, long-life, permanent magnet alternator design was assured. These are the potential short-circuit problems during startup, and integration of the winding configuration with the stator slot configuration to achieve an acceptable pole face loss. For a BEEM type alternator, these particular problems could readily be solved. Short circuits are only a heating problem with the BEEM alternator since it is not subject to permanent field demagnetization. Also, open

slots can be used and pole face losses minimized using a large air gap permitted by the BEEM design.

Because of the major development areas required for the unsealed stator design, the glass-ceramic bore seal with cracks was evaluated for its expected life. The fact that the unsealed alternator capsule tests showed that silver conductors could tolerate dry Hg vapor at 950°F for 90 days was very encouraging. This indicated that the hermetically sealed glass bore seal stator with cracks had a life of at least 90 days.

With the current Pyrocera glass bore seal, experience has shown that the leakage rate is very small, approximately 10^{-8} to 10^{-4} cc/sec of helium or approximately the same order of magnitude of Hg leakage in mg/hr. The Pyrocera glass has also improved the design from the standpoint of design predictability and confidence in the ability to limit the leak rate.

An outgrowth of these investigations was the present evacuated glass bore seal stator concept. The mechanism of Hg diffusion into the silver windings indicated a pressure dependency. AI and TRW tests verified this fact. AI capsule tests of silver conductors in Hg vapor at 600°F and evacuated to 50 μ showed negligible change in conductor resistance after 2000 hr of exposure. TRW autoclave tests on complete stator assemblies evacuated to 150 μ showed no change in resistance after over 3800 hr exposure to 630°F Hg vapor. These tests indicated that the evacuated glass bore stator would tolerate dry Hg indefinitely.

A method of achieving the evacuated stator cavity is to vent to space atmosphere. Any Hg vapor leakage through the seal cracks will then constitute loss in Hg inventory. As previously stated, experience shows the leakage rate of the

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Pyroceram seal is very small. A loss of less than 0.02 lb/yr Hg inventory is indicated.

A significant fact that further makes the evacuated glass bore seal concept attractive is the triple redundancy offered by this design. First, the glass bore seal is the primary Hg vapor seal. The glass has been shown to be reliable with predictable leak rates. Second, the interlaminar glass affords a secondary seal to Hg vapor. Third, the vent opening in the stator cavity can be carefully sized to limit the maximum loss in Hg inventory.

The result of these studies on the unsealed alternator and glass bore seal indicates that an acceptable design of the MRP stator is the current CRU-V design (Figure 1) with an evacuated stator. However, for future applications the unsealed alternator of the BEEM type with nickel-clad silver wire should be considered.

It is recommended that the method of evacuating the stator should receive further evaluation including a method of limiting the maximum inventory loss rate. Also, further tests on a component level to verify satisfactory startup and shutdown performance should be performed.

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