SD 68-85

APOLLO BLOCK II WIRE AND WIRE BUNDLE CURRENT RATING

3 January 1968

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TECHNICAL REPORT, INDEX, ABSTRACT

ACCESSION NUMBER DOCUMENT SECURITY CLASSIFICATION UNCLASSIFIED							
TITLE OF DOCUMENT	LI	BRARY USE ONLY					
APOLLO BLOCK II WIRE AND WI							
BEDFURD, J.R. * SCHAEFER, J	. L. * SEITZ, Т.Н.						
ORIGINATING AGENCY AN	D OTHER SOURCES	DOCUMENT NU	MBER				
QN085057 SPACE DIVISION, N	ORTH AMERICAN ROCKWELL CORP,	SD68-85					
DOWNEY, CALIF							
PUBLICATION DATE	CONTRACT NUMBER						
03JAN68	NAS9-150						
DESCRIPTIVE TERMS							
CORRENT-CARRYING CAPACITY,	*WIRE BUNDLE, *HEAT TRANSFER,	*ZERO					
GRAVITI, *APULLO SPACECKAFT, *VACUUM, *OVERLOAD, *SHORT CIRCUIT,							
*RADIATION, "GABLOUD CONDUCTION, "CONTACT CONDUCTANCE, "DERATING,							
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ABSTRACT

THIS REPORT DOCUMENTS TEST RESULTS INDICATING THAT THE ORIGINAL APOLLO WIRE/WIRE BUNDLE DESIGN CRITERIA FOR CURRENT-CARRYING CAPACITY IN FREE AIR /SPECIFICATION MIL-W-5088B/ RESULTED IN A 10- TO 150-PERCENT OVERDESIGN FOR THE APOLLO POWER DISTRIBUTION SYSTEM. WHILE GENERAL DESIGN GUIDES RECOMMEND DERATING THE FREE AIR CURRENT-CARRYING CAPACITY WHEN OPERATING WIRES IN A VACUUM, TEST RESULTS INDICATE THAT WRAPPED BUNDLES REQUIRED ONLY 20-PERCENT DERATING, AND SINGLE WIRES ONLY 35- TO 40-PERCENT DERATING. ANALYTICAL RESULTS SUPPORT THE TEST FINDINGS FOR ENVIRONMENTAL PRESSURE LEVELS BETWEEN 2 AND 14.7 PSIA. THE REPORT POSTULATES A THEORY TO EXPLAIN THE ENHANCED WIRE BUNDLE HEAT TRANSFER DURING VACUUM TESTS, WITH RECOMMENDATIONS FOR FURTHER ANALYTICAL EFFORTS AND TESTING TO VERIFY THE THEORY.

FOREWORD

Significant theoretical and experimental work on heat transfer and current-carrying capacity of Apollo wire/wire bundles, in support of Contract NAS9-150, was conducted between May and September of 1967. The results of this work are contained in this report, which was prepared by J.R. Bedford, and T.H. Seitz, of the Life Support and Systems department, and J.L. Schaefer, of Apollo CSM Propulsion and Power Technology department.

ABSTRACT

This report documents test results indicating that the original Apollo design criteria for wire/wire bundle current-carrying capacity in free air (Specification MIL-W-5088B) resulted in a 10- to 150percent overdesign for the Apollo power distribution system. While general design guides recommend derating the free air current-carrying capacity when operating wires in a vacuum, test results show that wrapped wire bundles required only 20 percent derating, and single wires required 35- to 45-percent derating. Analytical results support the test findings for environmental pressure levels between 2 and 14.7 psia. A theory is postulated to explain the enhanced wire bundle heat transfer that occurred in the vacuum tests, with recommendations made for further analytical efforts and testing to verify this theory.

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I. INTRODUCTION

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I. INTRODUCTION

The dissipation of heat is the primary factor for establishing the current-carrying capacity for electrical wiring that must operate reliably under continuous overload or transient short circuit conditions. The heat generated in a wire can be determined by the equation

$$Q = I^2 R$$

where, Q equals heat generation in watts, I equals the current in amperes, and R equals the wire resistance in ohms. The heat generation in a wire increases at a greater rate than the current squared because the temperature rise that accompanies the current increase, raises the conductor resistance which increases the heat generation further. The current-carrying capacity is normally limited to an overload or short circuit condition that results in temperature levels which cause the insulation to break down, or cause the conductor to fuse. Common practice for commercial applications is the use of oversized conductors, heavy insulation jackets over the conductors, and wide spacing between the wires. However, a number of constraints associated with the Apollo spacecraft and its mission had to be considered before the electrical distribution system could be designed. The significant considerations involving the heat transfer for the spacecraft wiring are:

- 1. Spacecraft weight limitations require that the copper conductor be selected for each circuit with a minimum of overdesign. The Block II Apollo wire insulation, consisting of an extruded thin wall TFE Teflon jacket with an outer coating of polyimide, was selected as possessing the best combination of low weight and high temperature capability. A similar insulation (FEP Teflon) was originally recommended for Surveyor (Reference 1). However, the thin wall insulation places a greater constraint on the conductor's current-carrying capacity than a heavier, thicker insulation would, when applying the design limit of 400 F for the maximum surface temperature within the spacecraft.
- 2. It is necessary to use several smaller wires in parallel rather than a single wire in many spacecraft circuits to improve the reliability of transmitting the power/signal, and to provide flexibility for installing wires in relatively inaccessible areas. An

overload condition occurring in a smaller wire results in higher wire temperature because of the higher resistance, lower heat storage capacity, and smaller surface area of the wire. In addition, the limited space for routing wiring necessitates many wires being tied together to form large wire bundles. General design practice (Reference 2) for wire bundles consisting of Teflon insulated wire indicates 20-percent derating for a bundle of 3 to 5 wires, 30-percent derating for 5 to 15 wires and 40-percent for 15 to 30 wires. However, these derating factors do not cover many of the Apollo wire bundles, some of which contain in excess of 200 wires.

3. The environment for the wiring during a space flight is very different than that which normally exists on earth. The environment in the Apollo cabin during space flight normally consists of 100-percent oxygen at 5 psia. This environment not only requires more rigorous control of high temperature operations to avoid fire hazards, but provides less heat transfer by convection than air at 14.7 psia. However, this reduction is small compared to the loss of free convection due to zero or low gravity, that exists throughout spaceflight, or due to the more severe condition of space vacuum that could exist in the Apollo cabin during short periods of astronaut extravehicular activity, or for as long as 100 hours if the cabin sustained a nonrepairable micrometeroid puncture.

As a result of the level of complexity and the small degree of actual experience presently existing in spacecraft wiring design, a theoretical and experimental program was conducted. This program was designed to determine the criteria for sizing Apollo wire and wire bundles for overload/short circuit conditions. The results of this study, which are documented in this report, may be applicable to the design of wiring systems for future spacecraft.

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II. SUMMARY

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II. SUMMARY

II. SUMMARY

The continuous-duty free air current-carrying capacity of wires and cables, as defined in Table I of Specification MIL-W-5088B (Reference 3), was used as the original criteria for Apollo wire/wire bundle design. In addition to free air, the Apollo spacecraft wiring had to be designed to operate in environments of 100-percent oxygen at 5 psia, and in a space vacuum. Analyses and testing to establish the current-carrying capacity of single wires and wire bundles for these Apollo environments are summarized in this report. Comparison of the test results for single wire currentcarrying capacity, tabulated in Section III, with the Specification MIL-W-5088B criteria indicates that the Apollo wiring is overdesigned by 70 to 150 percent for free-air operation, and even after vacuum derating, by 10 to 50 percent. The overdesign factor is even greater when comparing the wire bundle test results tabulated in Section V with the MIL-W-5088B wire bundle criteria. The Apollo wire bundles are overdesigned by 280 to 415 percent for free-air operation, and by 100 to 240 percent for vacuum operation.

The major portion of the theoretical study and testing was directed toward determining the electrical current levels that would cause a single wire, alone or in close contact with other wires, to operate at 400 F under vacuum conditions. While test results indicate 35- to 45-percent derating is necessary for a single wire operating alone in a vacuum, analysis of idealized wire bundles carrying nominal currents, indicates that a lesser degree of derating is necessary for the single overloaded wire in a bundle operating under free air or vacuum conditions. Test results for three typical Apollo wire bundles confirmed this analysis for the 14.7 and 5.0 psia environments.

The higher current-carrying capacity for a wire in a lightly-loaded bundle is the result of gaseous conduction that provides a low resistance path for the heat flow away from the overloaded conductor to the surrounding wires. However, test results for wire bundles operating in a vacuum indicated significantly higher current-carrying capacities than predicted by analysis, which assumed no gaseous conduction below the environmental pressure level of 0.1 Torr. The derating factor for wire bundle operation in the vacuum tests was found to be 20 percent when the wire bundle was wrapped with a continuous overlapped outer wrap of Teflon tape. These lower wire temperature measurements could not be explained by the most

optimistic estimates for radiation, contact, and solid conduction. Gaseous conduction appears to be the only feasible explanation for the enhanced wire bundle heat transfer. While the identification and source of the conducting gas has not been established, a 100-hour vacuum test has shown the heat transfer to remain constant in the 1×10^{-6} Torr vacuum, long after the outgassing of absorbed air and moisture from the insulation should have been complete. Recommendations for further testing and analysis are made in Section VII of this report. If the mechanism of gaseous conduction can be identified and its effectiveness quantitatively determined, appreciable reduction can be made in the weight of electrical wiring for spacecraft applications.

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III. SINGLE WIRE TEST/ANALYSIS

V. WIRE BUNDLE TESTING

TEST DATA ANALYSIS

III. SINGLE WIRE TEST/ANALYSIS

A series of tests were conducted using single wire specimens of American wire gauge (AWG) sizes 4, 6, 8, 12, 16, 20, 22, and 24, manufactured in accordance with Apollo Procurement Specification MB 0150-035. While the testing included measurements of conductor resistance, dielectric withstanding voltage, and transient short circuit response, only the major test objective for establishing the wire current-carrying capacity for the Apollo environments will be discussed herein. Each test specimen was subjected to an environmental temperature of 100 ± 10 F, at three pressure conditions: (1) air at 14.7 psia, (2) oxygen at 5 psia, and (3) 1 x 10⁻⁶ Torr. Each specimen was ten feet long and was instrumented as shown in Figure III-1.



THERMOCOUPLES ON INSULATION OUTER SURFACE: T1, T3 AND T5 THERMOCUOPLES ON CONDUCTOR OUTER SURFACE: T2 AND T4

Figure III-1. Single Wire Thermocouple Location

The concentration of thermocouples at the mid-length of the specimen reduced the error caused by axial conduction heat transfer. Environmental temperatures of 200 and 300 F were also used in the 14.7 psia tests, with #20, #22 and #24 AWG specimens. The test results shown in Figures III-2, III-3, and III-4 indicate that the change in conductor temperature is relatively constant for the three levels of environmental temperature with a given current level change. Therefore, the 200 and 300 F levels were not applied in subsequent

runs. The test procedure consisted of applying current in increments of 50 percent of a specific value for each specimen. The current was maintained at that increment until the specimen temperature was stabilized and the data were recorded. The current then was removed and the specimen allowed to cool to the environmental temperature. The current level then was increased by another 50 percent increment, and the procedure was repeated. When a stabilized conductor temperature level above 500 F was reached, the testing of that specimen was concluded. In this manner, the eight specimens were tested in the three pressure environments, 14.7 psia air, 5 psia oxygen, and 1×10^{-6} Torr vacuum, and in that order. The data, consisting of two conductor and three insulation temperature measurements for each specimen, were averaged and plotted. Figures III-2 through III-9, inclusive, contain plots for 14.7 psia air; Figures III-10 through III-17, inclusive, contain the plots for 5.0 psia oxygen; and Figures III-18 through III-25, inclusive, contain the plots for $1 \ge 10^{-6}$ Torr vacuum. Table III-1 gives the current levels obtained which cause an equilibrium temperature of 400 F on the wire conductor during testing. Figure III-26 depicts graphically the derating factors based on Table III-1.

	14.7 Psia-Air	5 Psia-100% Oxygen	1 x 10 ⁻⁶ Torr Vacuum					
Wire Size (AWG)	Current (amps)	Current (amps)	Current (amps)					
4	280	258	1.00					
6	207	180	138					
8	150	134	103					
12	70	65	46					
16	44	38.5	25					
20	28	25	16					
22	21	18.2	11.7					
24	14.3	13.1	8.5					
* Current carrying care situ is based on a 400 E								

Table III-1. Current-Carrying Capacity* for Single Wire

* Current-carrying capacity is based on a 400 F conductor temperature in a 100 F environment.





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111-7



III-8



14.7 psia Air

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111-15



5 psia Oxygen

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111-16



III-17



111-18



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Ш-21





Ш-23



5







*CURRENT-CARRYING CAPACITY IS BASED ON A 400 F CONDUCTOR TEMPERATURE IN A 100 F ENVIRONMENT

Figure III-26. Derating Factors Based on Single Wire Test Results

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An average derating factor of 10 percent for the 5-psia oxygen environment is sufficient for ground operation with free convection, while 35 to 45 percent is required for vacuum operation. However, the current-carrying capacity of a single wire operating in 14.7 psia air, which was demonstrated in test and tabulated in Table III-1, is 70 to 150 percent higher than that shown in Table III-2 (the original Apollo design criteria from MIL-W-5088B). Even under the most stringent test condition, vacuum operation, the Table III-2 single wire current-carrying capacity is 10 to 50 percent conservative.

	Continuous-Duty Current (Amperes)			
Wire Size (AWG)	Single Wire in Free Air	Wires and Cables in Conduit or Bundles		
4	135	80		
6	101	60		
8	73	46		
12	41	23		
16	22	13		
20	11	7.5		
22	-	5		
.24	-	-		

Table III-2. Current-Carrying Capacity* of Wires and Cables—From Specification MIL-W-5088B**

*Current-carrying capacity is based on a 400 F conductor temperature in a 315 F environment.

**MIL-W-5088B, Military Specification Wiring, Aircraft, Installation of, dated 18 June 1956 has been superseded by MIL-W-5088C, dated 26 May 1965. However, table values remained unchanged.

The major reason for this difference is the result of the ambient temperature of 315 F, which is assumed in MIL-W-5088B, and the 100 F used for the Apollo design.

It should be noted that the temperature difference between the conductor and insulation measurements shown in Figures III-2 through III-25, inclusive, should not be used to determine the heat transfer resistance across the wire insulation. Analyses using the average rate of heat dissipation indicated significantly higher resistance values from the test data than those determined by theory. Since the resistance increased with reduced

pressure, photomicrographs of the cross-section of several wires were made to determine if air gaps existed between the conductor strands and the inner surface of the Teflon insulation. As shown in Figure III-27, the cross-section of a #20 AWG wire, magnified many times its actual size, the extruded Teflon is in close contact with all of the exterior strands of the conductor, and therefore, no significant difference in insulation heat transfer resistance should occur with environmental pressure change. The difference in resistance was finally resolved when the contribution of the thermocouple leads to the test specimen's heat transfer was evaluated. Heat conduction into the thermocouple leads and radiation from these leads caused a significantly higher local heat transfer than the average heat dissipation, especially for the smaller wire sizes in the 5 psia and vacuum tests, where little or no free convection occurred. Therefore, the



Figure III-27. Photo-Micrograph of #20 AWG Wire Cross-Section

resistance calculations, in which an average rate of heat transfer was assumed, should have used the higher local heat-transfer rates, thereby resulting in lower computed values for insulation resistance. As the heat transfer resistance path for the insulation is higher than for the conductor, a greater error occurs in the measurement of the insulation outer surface

temperature than in the measurement of the conductor temperature. This was verified using the vacuum test data, which before correcting for the heat transferred to the thermocouple leads required an emissivity greater than the theoretical value of 1.0 for the radiation heat balance, using the measured insulation temperature, as shown in Figure III-28. By contrast, a comparison of the average measured conductor temperatures with the required theoretical temperatures for various emissivities, indicates the closest fit for an emissivity of 0.95, which at high temperature is in the expected range of 0.8 to 1.0 for insulation emissivity. Thus, the failure to properly isolate the instrumentation from the basic heat transfer of the specimen required the use of the measured conductor temperature as the best indication of the true insulation surface temperature for establishing current-carrying capacity under vacuum conditions. In Section IV it will be shown that this uncertainty in the true temperature of the radiating surface is of little significance in determining total wire bundle heat transfer.





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VI. TEST DATA ANALYSIS

RECOMMENDATIONS

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IV. IDEALIZED WIRE BUNDLE

IV. IDEALIZED WIRE BUNDLE

Various arrangements of wires were examined to develop an idealized wire bundle for the purpose of heat transfer analysis. The wire configuration shown in Figure IV-1 was selected because this arrangement represented the maximum packing density for heat transfer by contact conduction, gaseous conduction, and radiation. The primary purpose of this phase of the analysis was to determine the contribution of each of these modes (alone and in combination) on the transfer of heat from an overloaded center wire to the surrounding environment. The analytical results were not intended for use in establishing the current-carrying capacity for wires in bundles, but to be used for the purpose of quantitative comparison.

The idealized bundle was assumed to consist of three hundred sixtyseven #20 AWG wires, resulting in a wire bundle diameter of approximately one inch (about the same size as bundles which at that time were being prepared for test). The bundle model used in the digital computer program consisted of the pie-shaped segment of one-sixth of the circular area shown in Figure IV-1. The numbered elements shown in Figure IV-1 represent each of the wires as the nodes used in the program, while the necessary boundary assumptions were made in the resistance values to correct for the symmetrical partitioning of the complete wire bundle. Two-dimensional heat transfer analyses were performed after the radiation, contact, and gaseous conductance values (or range of values) were determined.

As shown in Figure IV-2, the idealized wire bundle configuration presents a three-sided symmetrical enclosure, so that the geometric view factors between surfaces are of equal value, 0.5. Because the emissivity and surface area of the three wires are equal, the radiation interchange factors are equal, and can readily be determined by the wye-delta relationship shown in the radiosity network of Figure IV-2.

The same geometric relationship was used to establish the gaseous conductance values between wires. Thermal conductivity, as a function of temperature and pressure, was assumed to be in accordance with Figure IV-3 which is based upon the interstitial nitrogen gas pressure function cited in Reference 4. As illustrated in Figure IV-3, the thermal conductivity is independent of pressure at levels greater than 1×10^{-1} Torr, and less than 1×10^{-4} Torr. Thus, the maximum values for thermal conductivity at specific temperatures were used to establish the gaseous conductance values for the 5.0 and 14.7 psia environments, and a value of zero was assumed for gaseous conductance at 1×10^{-6} Torr.

IV-1



Figure IV-1. Idealized Wire Bundle Configuration

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RADIOSITY NETWORK :







Figure IV-3. Thermal Conductivity Function for Nitrogen

IV-4

The definition of contact conductance presented the most difficult problem in the analysis of the idealized wire bundle. The ability to conduct energy across the solid contact interface between wires is dependent upon the contact area and the contact interface resistance. For the idealized wire bundle, the contact area was assumed to be continuous along the length of the bundle, with the minimum contact width defined as the chord, common to two circular wires that subtend a 5-degree circular arc. and for the maximum width, a chord subtending a 20-degree circular arc. It also was necessary to assume a range for the value of contact interface resistance for the Teflon/polyimide insulation jacket. A range of 5.0 to 50.0 Btu/ hour-square foot-degree F was selected, based upon information given in Reference 5, for contact conductance of materials in a vacuum. Three values for contact conductance were determined from this data: (1) "best," based upon the maximum contact area and minimum interface resistance, (2) "poor," based upon the minimum contact area and maximum interface resistance, and (3) "nominal," which was based upon mid-range values of contact area and interface resistance.

Six analytical cases, representing various combinations of heat transfer modes, were evaluated under the identical condition of overload current and environmental temperature. The results of these analyses (Figure IV-4) relate the equilibrium temperature of the center #20 AWG wire (Node 1), carrying a 30-ampere current in a 75 F environment. In all cases shown in Figure IV-4, including (1) and (2) which represent sea level operation, heat transfer by convection was ignored. The importance of gaseous conduction can be seen in comparing cases (1) and (2). Equilibrium temperature in case (2), depending solely on gaseous conduction, was only 18 F higher than that for case (1), which had the "best" contact conductance and "nominal" radiation, in addition to gaseous conduction. Again, the importance of gaseous conduction can be seen in case (3) where, with gaseous conduction eliminated, the temperature rise above the environment is approximately four times that found in case (1) with gaseous conduction. In cases (3), (4), (5), and (6), where gaseous conduction was assumed to have no effect, contact conductance was found to have the greatest influence on equilibrium temperature. The equilibrium temperature is almost 300 F higher in case (4), using the "nominal" value of contact conductance, and almost 500 F higher in case (5) with the "poor" value, than the equilibrium temperature in case (3), using the "best" value. While these results could not be used to analytically establish the current-carrying capacity of #20 AWG wire in a bundle, the results were used to establish the following qualitative relationships before the wire bundle test program was started:

1. The center wire in a nominally loaded Apollo wire bundle will operate at a lower temperature than a single wire of the same size at sea level and 5 psia oxygen environments.

IV-5



RADIATION	NOMINAL	0	NOMINAL	NOMINAL	NOMINAL	NOMINAL
CONTACT CONDUCTANCE	BEST	0	BEST	NOMINAL	POOR	0
GASEOUS CONDUCTANCE	NOMINAL	NOMINAL	0	0	0	0
CASE	1	2	3	4	5	6

Figure IV-4. Idealized Wire Bundle Analytical Results

CD (0 05

- 2. Under vacuum conditions, the contact between wires will be the primary factor in determining the equilibrium temperature of the center wire. A continuous outer wrap of Teflon tape which maintains the wires in closer contact than normal spot-ties every two inches along the length of the bundle would result in lower temperature operation.
- 3. Radiation has little effect on total heat transfer below 400 F.
- 4. The loss of gaseous conduction under vacuum conditions necessitates derating wrapped and unwrapped wire bundles to approximately the same levels as for single wires under vacuum.

This last prediction was proved wrong for wrapped wire bundles in subsequent tests which are reported in following sections.

V. WIRE BUNDLE TESTING

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ulation. V-2), and wn in

ble designated 31 #22 AWG Apere was mainwas maintained on 3 overload current Apere was mainwas maintained on 3 overload current Apere was first feflon tape wrap. After bundle was wrapped Apere was and one inch wide, was and one inch wide, was and one inch wide length. A the three environments. A the foreground in

V. WIRE BUNDLE TESTING

Three wire bundles, simulating actual bundles used in the Apollo spacecraft, were tested to determine the level of overload current that could be carried by a single wire at the center of each bundle. Each bundle was tested under the same environmental conditions as the single wire specimens, 100 F in 14.7 psia air, 5.0 psia oxygen, and 1×10^{-6} Torr vacuum. Each bundle had five thermocouples attached to the center in a manner shown in Figure V-1. Thermocouples 2 and 4 were located on the



THERMOCOUPLES ARE THREE INCHES APART WITH NO. 3 AT MIDLENGTH

Figure V-1. Thermocouple Installation on Central Wire in Wire Bundle Test Specimen

conductor, and thermocouples 1, 3, and 5 were located on the insulation. Five other thermocouples were located within the bundle (Figure V-2), and installed in a similar fashion as thermocouples 1, 3, and 5, shown in Figure V-1.

Wire bundle Test Specimen A simulated the Apollo cable designated as Panel 2-J2/P422, and consisted of 16 #24 AWG wires, 31 #22 AWG wires, and 42 #20 AWG wires. A constant load of 0.4 ampere was maintained on each of nine #24 AWG wires, and 0.6 ampere was maintained on each of 24 #22 AWG wires and 25 #20 AWG wires. The overload current was imposed on the center #22 AWG wire, following the same procedure as was used for the #22 AWG single wire test. The wire bundle was first tested as it is normally spot-tied without an outer Teflon tape wrap. After testing the bundle in the three environments, the bundle was wrapped externally with a Teflon tape, without removing the original ties. The tape, which was approximately 0.030 inch thick and one inch wide, was wrapped helically with a 0.5-inch overlap along the entire bundle length. This wrapped configuration was then tested in the three environments. Figure V-3 shows a portion of a wrapped bundle in the foreground in

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THERMOCOUPLES FOR TEST DATA REFERENCE

Figure V-2. Thermocouple Placement in Wire Bundle



Figure V-3. Closeup View of Wrapped and Unwrapped Wire Bundle Test Specimens contrast to a portion of an unwrapped bundle. Figures V-4, V-5 and V-6 show plots of the center conductor equilibrium temperatures, in both the unwrapped and wrapped bundle, versus imposed current in 14.7 psia air, 5.0 psia oxygen and 1x10⁻⁶ Torr vacuum, respectively.

Wire bundle Test Specimen B, which simulated the Apollo cable designated as Panel 8-P3/J483, consisted of four #24 AWG wires, 23 #22 AWG wires, and 34 #20 AWG wires. A constant load of 0.25 ampere was maintained on each of two #24 AWG wires, and 0.7 ampere was maintained on each of 19 #22 AWG wires and 20 #20 AWG wires. The overload current was imposed on the #22 AWG center wire, the same size as tested in wire bundle Test Specimen A. The center conductor equilibrium temperatures versus current plots are shown in Figures V-7, V-8 and V-9. A comparison of #22 AWG wire current-carrying capacity, which is tabulated in Table V-1, shows a maximum difference of 1.6 F between the test specimen bundles A and B for the same configurations (wrapped/unwrapped) and environment. While all of the #22 AWG center wire/bundle data indicate

ſ	Wire		14.7 Psia - Air	5.0 Psia - Oxygen	lx10-6 Torr Vacuum	
	Size (AWG)	Specimen - Bundle Type	Current (amps)	Current (amps)	Current (amps)	
PNL 2	22 22	A - Unwrapped A - Wrapped	24.3 25.8	23.9 27.6	12.4 17.0	3365 AM/0/100
PAL 8	- 22 - 22	B - Unwrapped B - Wrapped	23.5 24.9	25.0 26.0	13.7 16.7	3 415 LM Mons 2
H/c WIRES)	16 - 16	C - Unwrapped C - Wrapped	49.0 49.5	49.7 52.2	27.5 35.8	3 5870 AM
	*Current	- t-carrying capaci	ty is based on a 4	400 F center conduct	tor tempera-	

Table V-1.	Current-Carrying Capacity* for a Center W	Vire
	in a Wire Bundle	

ture in a 100 F environment.

higher capability than the single wire data shown in Table III-1, the greatest difference is seen for the wrapped test bundle configuration when operated in a vacuum. Using the single wire current-carrying capacity at 14.7 psia air as the base of 100 percent, the #22 AWG wire requires only 20-percent derating when operated in a wrapped bundle under vacuum condition, as compared to 44-percent derating for a single #22 AWG wire,

and 41-percent derating for the central #22 AWG wire in an unwrapped bundle.

V-3



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V * 5



SJ SB

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V-7



V-8

SD

68-85

Cable B-5 psia Oxygen

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V-9

Wire bundle Test Specimen C, which simulated the Apollo main d-c power distribution cable, consisted of 17 #12 AWG wires and 28 #16 AWG wires. The overload current was applied to the center #16 AWG wire, while a 6.0-ampere load was maintained on each of 16 of the #12 AWG wires and one #16 AWG wire, and 3.0 amperes was maintained on each of five #16 AWG wires. The specimen was tested in both the wrapped and unwrapped configurations, and reached the center wire conductor temperatures shown in Figures V-10, V-11 and V-12. As in the case of the other wire bundles, the center conductor in the wrapped bundle operated a lower temperature in the three environments. Again, the difference was greatest in a vacuum between the wrapped and unwrapped bundles, as well as between the wrapped bundle and single wire current-carrying capacity. The comparison of #16 AWG wire current-carrying capacity shown in Table III-1 and Table V-1 indicates the center conductor in the wrapped bundle requires only 18.5-percent derating, while 37.5-percent derating is necessary for the unwrapped bundle, and 43.0-percent derating is required for the single wire under vacuum conditions.

As in the case of the single wire current-carrying capacity, the original Apollo design criteria for wire bundles (Table III-2) were found to be overly conservative when compared with the test results in Table V-1. Based upon the test results, the Apollo wire bundles are overdesigned by 280 to 415 percent for 14.7 psia air operation, and by 100 to 240 percent for vacuum operation.

Initially, it was believed that the enhanced heat transfer was due to outgassing of air and water vapor from the surface of the insulation, and that this effect would have been eliminated if the test had been of longer duration. Because the original specimens (A, B, and C) had been subjected to an overload-to-destruction test in 5.0 psia oxygen environment, two new wire bundles were fabricated as duplicates of the original Specimen C. The two test specimens, one wrapped with Teflon tape and the other spot-tied as shown in Figure V-13, were subjected to a 100-hour vacuum test with the same loads on the surrounding wires as imposed in the original Specimen C tests. A constant overload current of 34 amperes was maintained on the wrapped bundle, and 27 amperes on the unwrapped bundle. The equilibrium conductor temperatures which did not vary as functions of the time were 441 F for the wrapped bundle and 423 F for the unwrapped bundle. While these data indicate slightly higher temperature levels than the original bundle data shown in Figure V-11, the derating value of 27 percent for the unwrapped bundle is less than the 43-percent derating required for the single #16 AWG wire. With no indication of temperature change during the 100 hours of vacuum operation, the test results refuted the original concept that the outgassing from the insulation would be completed

V-10



Cable C-14.7 psia Air

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V-11



21-



after 10 hours in vacuum, causing the gaseous conduction to cease and the overloaded wires to reach equilibrium temperatures in excess of those measured in the single wire vacuum test. Further discussion of these results, and a comparison with analytical results, can be found in Section VI.



Figure V-13. Wrapped and Unwrapped Wire Bundle Test Specimens

VI. TEST DATA ANALYSIS

pped , as n the test act conductgaseous conerve to explain out further testing conductance may te made in analysis, inally considered for the
VI. TEST DATA ANALYSIS

A thermal analysis was performed using a model of the actual Specimen C wire bundle. Figure VI-1 is a photograph of the cross-section of Specimen C, with the nodes numbered for the analytical model. Nodes 1 through 45 were allocated for each wire in the bundle. Nodes 46, 47, 48 and 49 represent the thermocouple leads. Node 50 represents the Teflon tape and Node 51 represents the ambient environment. Photographs of other cross-sections of the same specimen indicate that the geometric relationship of the wires did not remain constant. To compensate for this variation, wires which were observed to be in contact in Figure VI-1 were assumed to have "nominal" conductance values, and those which were not observed in contact, but could be in direct contact elsewhere in the bundle, were given a "poor" conductance value. Radiation was assumed as "nominal" because of its low contribution to the total heat transfer process found in the idealized bundle analyses. Gaseous conduction was assumed as zero for the vacuum condition.

The analytical and test results for the unwrapped configuration of the Specimen C wire bundle are shown in Figure VI-2. Because the original analysis proved excessively conservative when compared to the test results, two other cases were analyzed. The basic analytical model remained unchanged, with the exception of a threefold increase in all contact conductance values in one case, and a tenfold increase in all contact conductance values in the second case. These results are plotted in Figure VI-2 as C x 3 and C x 10. The case with the threefold increase in contact conductance correlates best with the test data above 20 amperes. It is possible to explain the use of the C x 3 conductance values on the basis that these values are in the range between the "best" and "nominal" values established in the analysis of the idealized wire bundle.

However, when a similar analysis was performed for the wrapped configuration, a ten- to twentyfold increase in contact conductance, as shown in Figure VI-3, was necessary to achieve correlation with the test results. This is beyond the most optimistic estimate for contact conductance. Since radiation is relatively ineffective below 400 F, gaseous conduction is the remaining mode of heat transfer that could serve to explain the low temperature operation of the wire bundle. Without further testing it is impossible to rule out the possibility that contact conductance may have been significantly higher than the "best" estimate made in analysis, and that gaseous conduction is insignificant as originally considered for the



Figure VI-1. Analytical Model Based on Actual Wire Bundle

VI-2



Figure VI-2. Current/Temperature Rating Based on Analytical and Empirical Data for #16 AWG Unwrapped Wire Bundle

VI-3



Figure VI-3. Current/Temperature Rating Based on Analytical and Empirical Data for #16 AWG Wrapped Wire Bundle

vacuum condition. In view of the significant weight savings that can be made in spacecraft wiring because of the higher current-carrying capacity of the wire bundle in a vacuum, a more complete understanding of the wire bundle heat transfer process is required.

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VII. CONCLUSIONS AND RECOMMENDATIONS

VII. CONCLUSIONS AND RECOMMENDATIONS

Analysis and testing performed in this study indicate that the original design guides used for the Apollo spacecraft power wiring require more conductor cross-section than necessary. Test results indicate 70- to 150-percent higher current-carrying capacity for single wire free-air operation than given in MIL-W-5088B. Using the single wire free-air test results as a base of 100 percent, the average derating criteria for a single wire in 5.0 psia oxygen and 10^{-6} Torr vacuum are 10 percent and 40 percent, respectively. The average derating for a wire in a wrapped wire bundle is 20 percent for vacuum operation. The wire in a wrapped wire bundle demonstrated a higher current-carrying capacity in free-air and 5 psia oxygen tests than did the single wire in free-air tests.

Tests performed for both wrapped and unwrapped wire bundles operating at overload conditions in a vacuum for periods up to 100 hours showed that the wiring is not heated to the extent predicted by present analytical studies. In these analyses the mechanism of gaseous conduction was assumed as negligible for a vacuum environment of 10^{-6} Torr or lower. As indicated in Section VI, gaseous conduction, which is postulated as causing the cooler wire bundle operation in the vacuum tests, permits lower conductor weight for a given current/temperature limit.

Every effort should be made to exploit the appreciable weight savings offered through the higher current-carrying capacity of the individual wires in a wrapped bundle. In order to obtain quantitative data for future spacecraft wire design and analysis, the present study should be extended. The following presents an outline of the recommended effort:

- 1. Perform tests to identify the outgassing constituents that provide the gaseous conduction in wire bundles under vacuum conditions.
- 2. Determine the thermal conductivity for the major outgassing constituent(s) as a function of temperature and pressure.
- 3. Conduct long-duration vacuum tests to establish if, and when, outgassing is significantly reduced.

- 4. Determine the values of contact conductance for Teflon and H-film (polyimide) electrical insulation as a function of conductor diameter, insulation thickness, and contact force.
- 5. Define the heat transfer mechanisms for wire bundles.

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VIII. REFERENCES

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