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MgO INSULATED COAXIAL INSTRUMENT CABLE DEVELOPMENT FOR FFTF IN-VESSEL TEMPERATURE AND VOLTAGE CONDITIONS

Hanford Engineering Development Laboratory

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Austen I.Y. Chan

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October 1978

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ABSTRACT

MgO insulated nuclear instrument cable designed for use in the Fast Flux Test Facility or breeder reactor in-vessel service environments were successfully tested to temperatures to 650°C. Breakdown Pulse Noise (BPN) thresholds in excess of 800 Vdc at 650°C were achieved on the bulk cable; cable resistivities at 650°C were 10⁸ ft. The effect of 1000°C annealing was a minimal reduction of cable resistivity with no observed effect on BPN threshold.

No differences in insulation resistance and BPN thresholds were detected between cables containing copper electrical conductors and cables containing Inconel 600 conductors. Thus a copper conductor cable type was established to be suitable for both signal transmission and high voltage bias applications. The tested bulk cables exceeded final cable development program objectives: no BPN at 650°C, 800 Vdc continuous, and 10⁸ ft. resistivity at 550°C in copper conductor MgO insulated bulk cables.

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EXECUTIVE SUMMARY

The Hanford Engineering Development Laboratory is developing nuclear instrument cables capable of meeting the stringent in-vessel service conditions of the Fast Flux Test Facility (FFTF) or future breeder reactors. No commercial U. S. source presently exists for such cables. In-vessel cables must be able to operate in a radiation flux of 10^{15} nv and 10^{10} R/hr and possess a radiation lifetime of 10^{21} nvt. They must also be capable of 650°C, 800 Vdc continuous operation to supply a high voltage bias to instrumentation such as fission chambers. There are also applications, such as single ended fission chambers, which require a single cable to serve as a high voltage bias supply as well as a signal transmission cable; this requires a copper conductor high voltage cable.

The program to develop a high temperature, high radiation instrument cable divides naturally into three tasks: 1) development of bulk cable, 2) development of cable end seals/connectors, and 3) development of an end seal-bulk cable attachment procedure. End seals are required to maintain the hermeticity of the cable insulation. This report discusses the procurement and testing of bulk instrument cable. Both copper conductor (Inconel 600 outer clad) and Inconel 600 conductor cables were commercially procured for evaluation testing.

The cable fabrication procedures specified a vacuum bakeout of the MgO insulation after loading into the cable but prior to cable swaging to optimize insulation and backfill gas purity. The high performance of these cables during temperature tests is attributed to this vacuum bakeout, a step not normally included by the vendor. Strict controls were used during all steps of cable fabrication to maintain the purity of the cable insulation. The cables were shipped seal welded on both ends and were terminated with electrical connectors at HEDL. Temperature and voltage tests at HEDL demonstrated the following: 1) both copper and Inconel 600 conductor cable types exhibited no Breakdown Pulse Noise

(BPN) at 650°C during 300 hour tests at 800 Vdc, 2) all cable types possessed insulation resistivities greater than 10^8 ft at 650°C, and 3) annealing at 1000°C reduced cable resistivity by only 50% in copper conductor cables. The tests demonstrated that the cables met or exceeded the BPN and insulation resistance requirements of the high temperature cable development program at HEDL. The only remaining phases of the bulk cable development program are the demonstration of reproducibility by the commercial cable vendor and possibly the development of a backup vendor.

1.0 INTRODUCTION

In the Liquid Metal Fast Breeder Reactor, nuclear instrumentation operates under severe conditions, such as high temperatures (up to 650°C) and a fast neutron flux (10^{15}nv). In the Fast Flux Test Facility (FFTF), in-vessel neutron flux monitors comprised of fission chambers and instrumentation cables are required to measure the flux during the reactor startup period. These nuclear cables should possess an insulation resistance of 10^8 ohm ft (at 650°C) and operate at 800 Vdc for a radiation lifetime of 10^{21} nvt in a hostile environment. The Hanford Engineering Development Laboratory (HEDL) has been developing instrumentation cables capable of meeting these operational requirements because such cables are not available commercially in the United States.

The objectives of this investigation were as follows:

1. Perform high voltage (800 Vdc) and high temperature (up to 650°C) tests of MgO insulated cables of basically two types:
 - a) cables with Inconel 600 as outer sheath and center conductor,
 - b) cables with copper inner sheath clad with Inconel 600 and copper center conductor.
2. Establish the effect (during cable fabrication) of final annealing and vacuum bakeout, prior to drawing, on cable insulation compaction density and electrical properties.

All cables discussed in this report were fabricated by the same vendor in an identical manner except for the vacuum bakeout and final annealing procedures. These cables were categorized into four types, namely Types A, B, C, and D (see Table I), and were insulated with MgO of compaction density greater than 80%. This high compaction density is desirable to eliminate electrical breakdown problems.⁽¹⁾

Under the severe reactor environment of high temperature (650°C) and high radiation flux, it is necessary to protect the reactor cables from corrosion and radiation damage; both stainless steel and Inconel 600 are suitable materials. They are also satisfactory as center-conductor materials in high voltage cables; however, copper is preferable for the center-conductor and inner sheath material in cables to be used for signal transmission because of its increased electrical conductivity properties. The general suitability of MgO insulated, copper conductor cables for breeder reactor in-vessel service has been clearly established by their use in England.⁽²⁾

2.0 CABLE CHARACTERIZATION TESTS

2.1 HEDL Specifications of Cables

The characteristics of the cables procured for these tests are listed in Table II. BPN, which is considered the primary obstacle to high temperature operation, is an electrical pulse phenomenon, occurring under voltage and temperature conditions across ceramic insulators, with a typical charge content of 10^{-13} coulombs and a rise time of 200 nsec; it is indistinguishable from pulses occurring in a fission chamber. Thus the occurrence of BPN in nuclear instrumentation must be prevented.

Since the vendor did not possess the equipment or expertise to test for this breakdown phenomenon, a BPN threshold was not included in the procurement specifications. Emphasis was placed on meeting the cable insulation resistance specification at 315°C and upon complying with the specified fabrication procedures.

Samples of the MgO beads used in the cables were supplied to HEDL by the vendor. Analysis of these beads along with the MgO samples taken from the cables upon completion of tests at HEDL verified the MgO purity level stated by the vendor. Documentation was also required from the

TABLE I

FABRICATION DESCRIPTION OF THE FOUR CABLE TYPES

TYPE	Conductor MATERIAL	VACUUM BAKEOUT Temperature (N ₂ Cold Trap)	BACK FILL GAS	ANNEALING DURING DRAW	FINAL ANNEALING
A	Inconel 600	815°C (1500°F)	N ₂	None	None
B	Inconel 600	815°C (1500°F)	N ₂	1000°C (1850°F)	None
C	Inconel 600 Copper Inner Clad	815°C (1500°F)	N ₂	732°C (1350°F)	None
D	Inconel 600 Copper Inner Clad	None	N ₂	732°C (1350°F)	None

TABLE II

CABLE PROCUREMENT SPECIFICATIONS

A. Mechanical Specifications

a.	Length	25 ft. nominal
b.	Center Conductor O.D.	.029 in max., .025 in min (to clear .030 in I.D. tube)
c.	Sheath I.D.	$0.140 \pm .004$ in.
d.	Sheath O.D.	.240 in. nominal

B. Materials

a.	Conductor Materials	
	1. sheath	Inconel 600 or Inconel 600 with inner copper sheath
	2. center conductor	Inconel 600 or copper
b.	Insulation Purity	MgO: 99.4% + Pure
c.	Insulation Compaction Density	80% of maximum theoretical density
d.	Cable Fill Gas	99.99% N ₂ (100 ppm impurity)

C. Electrical Specifications

a.	Minimum Rated d.c. bias voltage at 500°C	800 Vdc
b.	Minimum d.c. insulation resistance at room temperature	10^{13} ohm-ft @ 1000 Vdc
c.	Minimum d.c. insulation resistance at 315°C	10^{10} ohm-ft @ 1000 Vdc

vendor on fabrication procedures, materials certification, and electrical measurements.

2.2 Vendor's Fabrication Procedures

The procedures used to fabricate the cable were similar to those already in use by the vendor. A brief description of these procedures follows.

The MgO beads (99.4% pure) used as cable insulation were air fired at approximately 1200⁰C immediately before loading in the cable. The cable conductor materials were cleaned using a series of solvents and washes; visual inspection of "lint-free" patches passed through and over the conductor surfaces established the required cleanliness level. The MgO beads were then loaded into the cable sheath (and on to the center conductor), with one end welded closed, in such a manner as to minimize contamination by ambient air, moisture, and handling. All cables except Type D were vacuum baked and back-filled with ultra pure N₂ gas. Type D cables were only evacuated and back-filled with pure N₂. Both ends of the cables were seal welded before drawing to eliminate external contamination by ambient air and to provide a hermetic cable unit. During the drawing processes only Type B cables were annealed at 1850⁰F. No final annealing was required on the cables; this allowed investigation on the need and effect of high temperature final annealing on cable properties and BPN performance. The final diameters of the sheath and center conductor of each cable were measured by the vendor. These values are listed in Table III.

A 3 ft length was cut from each cable after reduction to final diameter and the ends were immediately sealed to allow for the vendor's electrical tests. After the tests, the cable ends were seal welded to maintain hermeticity during shipment. A helium leak test utilizing procedure VI described in RDT Standard F311T, ⁽³⁾ was performed by the vendor on all cables before shipment; no leaks were evident.

TABLE III
MEASURED DIMENSIONS OF TEST CABLES

Cable Type #	Sheath		Center Conductor
	O.D. (inches)	I.D. (inches)	
A	0.2054 $\pm$.0006	0.1366 $\pm$.0006	0.0273 $\pm$.0003
B	0.2033 $\pm$.0003	0.1373 $\pm$.0003	0.0281 $\pm$.0006
C	0.2397 $\pm$.0003	0.1341 $\pm$.0014	0.0276 $\pm$.0003
D	0.2397 $\pm$.0003	0.1341 $\pm$.0014	0.0276 $\pm$.0003

2.3 HEDL Cable Termination Procedure

The following procedures were used to terminate the cables after receipt at HEDL. One end of each cable was cut and hermetically sealed with a 200°C melting temperature wax. The other end of the cable was also cut and sealed with epoxy with approximately a 1/2-in. section of center conductor extended at the end in preparation for the electrical conductor attachment. The excessive epoxy on the end of the cable was removed and the end was cleaned. A BNC connector was then attached to the end of the cable with a silver conducting epoxy (Emerson and Cuming #2741).

The following precautions were taken during this sealing process to prevent contamination by ambient air: 1) the cables were cut open and approximately 1/4-in. of the MgO insulation was removed by abrasive blasting under flowing dry nitrogen gas, 2) approximately 8 to 20 in. near the cable end was heated with a torch immediately prior to sealing with wax or epoxy, and 3) effort was made to minimize the time between the cutting of the cable by an abrasive saw and the sealing of the cable to reduce contamination to the cable interior. Cables terminated in previous tests under this procedure demonstrated good hermeticity when tested with a helium leak detector.⁽¹⁾ The fact that the room temperature resistance of all terminated remained above 10^{13} ohms also indicated that the cables were hermetic.

2.4 MgO Compaction Density and Purity Tests

In addition to the compaction density tests performed by the vendor, the density of the MgO insulation was also measured by a weighing technique performed in the laboratory. This was done by the following procedure:

- 1) The total volume, V_t , of the cable section under test was measured.

- 2) The section of cable was preheated with a torch (to eliminate moisture) and weighed (Total Weight = W_t).
- 3) The MgO insulation was removed from the cable section using an abrasive blaster.
- 4) The remaining outer sheath and center conductor were cleaned and weighed (Weight = W_s).
- 5) The total volume of the sheath and center conductor, V_s , was calculated from geometrical measurements and handbook densities.
- 6) With the above information, the density of the MgO insulation was calculated (density) $MgO = (W_t - W_s)/(V_t - V_s)$.
- 7) The MgO insulation density measured was compared to its 100% dense theoretical value to get the MgO compaction density.

The MgO insulation compaction densities measured by the above method are listed in Table IV; they were in good agreement with those determined by the vendor. All cables possessed insulation compaction densities of greater than 80%. Samples of MgO cable insulation were also sent for purity tests by the HEDL chemistry laboratory. The test results confirmed the MgO purity reported by the vendor.

2.5 Characteristic Impedance Test

A Time Domain Reflectometer (TDR) was used to determine cable characteristic impedance and to investigate variations in characteristic impedance along the cable length. The lack of irregularities was considered evidence of uniform insulation compaction density along the cable length. Characteristic impedance of each test cable is listed in Table V.

TABLE IV
EFFECTS OF ANNEALING ON MgO COMPACTION DENSITY AND RESISTANCE

CABLE TYPE NO.	COMPACTION DENSITY		RESISTANCE AT 650°C,	
			(TYPICAL LENGTH IN HEAT ZONE) = 20 ft.)	
	NO FINAL ANNEAL	30 MINUTE FINAL ANNEAL*	NO ANNEAL	30 MINUTE ANNEAL*
A	82 %	79.2 %	5.6×10^8	9×10^7
B	80.04%	77.72%	2×10^7	1.3×10^7
C	81.51%	80.61%	4.1×10^8	2.3×10^8
D	87.9 %	84.0 %	4.58×10^8	3×10^8

*These results are based on five feet heated cable length during the HEDL Final Anneal at 1000°C.

TABLE V
CHARACTERISTIC IMPEDANCE OF TEST CABLES

CABLE	REFLECTION COEFFICIENT	CHARACTERISTIC IMPEDANCE
Type A	0.1207	39.2
Type B	0.0956	40.8
Type C	0.1768	35.0
Type D	0.1497	37.1

3.0 THE EXPERIMENTS

3.1 Experimental Set-Up

The set-up of the measurement system establishing the BPN threshold for the cables is shown in Figure 1. Cables, previously terminated with a BNC connector on one end, were connected to the preamplifier in the measurement system. An ammeter was connected between the HV supply and the preamplifier to allow instantaneous current readings. A pulse generator was used for BPN calibration of the system. The test procedure to establish a cable's BPN threshold was generally the same as that described in RDT Standard F3-39T.⁽⁴⁾

3.2 Experimental Procedures

3.2.1 Random Heat-Zone Tests

Before all test cables were inserted in the oven for temperature tests, each was heat-zone BPN tested. During the zone test for BPN, 1000 Vdc as applied. A torch was used to randomly heat one or two zones near the center portion of each cable to slightly red hot (650°C). This test was performed as a preliminary check on the general suitability of a cable for tests at higher temperature. No BPN was observed during the zone heat treatment by torch with 1000 Vdc applied on any of the cables.

3.2.2 Short-Term Temperature Tests

After the heat-zone tests, all cables (two each from Types B, C, and D, one from Type A) were coiled to 1-1/2 ft diameter and placed in a Blue M furnace. Approximately 2-1/2 ft of each cable end extended out of the furnace so that terminations remained at room temperature. Prior to temperature tests, the insulation resistance and capacitance of the cables were measured.

FIGURE 1. Block Diagram of Test Apparatus Used to Determine Breakdown Pulse Noise of Test Cables

The BPN threshold was investigated at room temperature by applying 1000 Vdc for 10 minutes. No cable exhibited BPN. The oven was then turned on and adjusted to desired temperatures (300°C, 450°C, 550°C, and 650°C). At each temperature, the following tests were performed:

- 1) Measurement of insulation resistance with 500 Vdc applied on cables for 30 seconds, 60 seconds, and 5 minutes.
- 2) Measurement of capacitance of cables at 1000 Hz.
- 3) BPN test according to procedures in RDT Standard F3-39T⁴ at each step temperature with 1000 Vdc applied for 10 minutes (except with 850 Vdc applied at 650°C as a final test).
- 4) BPN test of all cables for approximately 20 hours with 800 Vdc applied continuously at each step temperature.
- 5) Resistance and capacitance tests, as described in 1) and 2) above at the end of the 800 Vdc continuous test, at each temperature, with high voltage off.

No BPN occurred on any cable during the above tests at temperatures up to 650°C; this successfully concluded the short term phase of testing. High insulation resistances were recorded on all cables (10⁸ ft); Figure 2 gives some of the more pertinent data recorded during these short term tests. The cables were then subjected to long term temperature and voltage tests.

3.2.3 Long Term Test of All Cables at 650°C, 800 Vdc Continuous

All cables were tested for 300 hours at 650°C with 800 Bdc continuously applied. Although the short term tests had given no evidence of BPN, previous tests have demonstrated that prolonged time at temperature and voltage may sometimes cause cables to incur BPN or otherwise degrade electrically. During this long term test the following checks were performed:

Photo No. 7712843-6

FIGURE 2. Time at Temperature Schedule for Bulk Cable Tests. Number Notes Give Data Pertinent to Corresponding Numbers on Graph. Approximately 20 ft of Each Cable was at Temperature; Cable Ends are at Ambient

- 1) The BPN threshold, insulation resistance, capacitance, and dissipation factor of each cable was periodically measured.
- 2) A Keithley Picoammeter recorded instantaneous total input current to the cables during the testing, thus allowing cable insulation resistance to be monitored.
- 3) The electrical noise level of the cables was monitored continuously by connecting all test cables in parallel to the BPN test apparatus.

At the end of 300 hours at 650⁰C, the high voltage was turned off. All cable resistances, capacitances, and dissipation factors were again measured. These measurements were repeated after the cables were at 650⁰C with no voltage applied for 24 hours and for 48 hours. All cables were then allowed to cool down to room temperature where resistance and capacitance measurements were repeated. This concluded all long term tests on the cables. Significantly, no degradation of electrical properties occurred during the above described tests. Also, the room temperature electrical properties remained unchanged during the above described tests, i.e., the room temperature electrical properties, such as resistance and capacitance, returned to initial values recorded prior to testing.

3.2.4 High Temperature Annealing Tests

One cable from each of the four types previously tested was placed in a tube oven. Approximately 5 ft of each cable were annealed at 1000⁰C for about 30 to 50 minutes. The tests described in Section 3.2.2 were repeated on these cables, at temperatures of 300⁰C, 450⁰C, and 650⁰C.

4.0 RESULTS AND DISCUSSION

The results of the investigation of these test cables are summarized in this section.

4.1 Breakdown Pulse Noise

No Breakdown Pulse Noise (BPN) phenomena were observed or recorded during any of the following tests (see Figure 1):

- 1) 10 minutes, 1000 Vdc BPN test at temperatures to 650°C
- 2) 69 hours/300°C temperature test (No BPN at 1000 Vdc)
- 3) 19 hours, 800 Vdc continuous BPN test at 300°C
- 4) 18 hours, 800 Vdc continuous BPN test at 450°C
- 5) 18 hours, 800 Vdc continuous BPN test at 550°C
- 6) 306 hours, 800 Vdc continuous BPN test at 650°C

The good performance of these cables is attributed to the high MgO insulation compaction density and purity and the high purity fill gas, resulting from improved fabrication procedures.

4.2 Capacitance Measurements

As shown in Figures 3 and 4, the capacitance of all cables at 1 KHz and the dissipation factor of the dielectric (MgO) increases as a function of temperature. These data agree with the results on other coaxial cables previously reported.⁽¹⁾

4.3 Resistance - Temperature Dependence

Figure 5 shows the cable insulation resistance as a function of temperature; note that it decreases approximately one order of magnitude per 100°C. All cables possessed relatively high insulation resistances ($>10^8$ ohm ft) at temperatures up to 650°C. This correlates with both the high insulation compaction density and purity of the cables. The insulation resistance of the Type B cables was generally lower than that of the other types. This was believed to be mainly due to the 1000°C annealing

Photo No. 7712843-1

FIGURE 3. Capacitance Versus Temperature for Cable Types A, B, C, and D

Photo No. 7712843-3

FIGURE 4. Dissipation Factor Versus Temperature for Cable Types C and D

Photo No. 7712843-5

FIGURE 5. Plot of Cable Resistance Versus Temperature

of Type B cables during the fabrication drawing process.

Figure 6 shows the resistance of two cables at 650⁰C, 800 Vdc continuous as a function of time. The MgO insulation resistance of these cables increased at first and then leveled off during the test. After the voltage was removed, resistances returned to their initial values.

4.4 Characteristic Impedance and Cable Dimension

Figure 7 shows TDR traces of some test cables. Cable Types A and B were Inconel 600 cables and showed less variation in characteristic impedance along the cable length. Cable Types C and D had Inconel 600 clad copper sheath with copper center conductor. These cables showed more variations in characteristic impedance along the cable length. Visual examination of X-ray negatives showed that the copper center conductors of Types C and D deformed more than those of cable Types A and B.

4.5 Effect of 1000⁰C Final Anneal

The data in Table IV demonstrate that the insulation resistance in the copper conductor cables was reduced only 50% by a final 1000⁰C anneal of five ft heated length. Although the data is certainly incomplete, apparently the effect of 1000⁰C annealing on Inconel 600 conductor cables is more severe, resulting in a reduction in cable resistivity of between a factor of 5 to 10. It is interesting to note that the whole length of cable Type B had been subjected to a 1000⁰C anneal during the vendor cable drawing process, though this was not a final anneal (see Table I). One postulated effect of a final anneal has been a reduction in insulation compaction density due to decreased "hoop strength" of the sheath. As the data in Table IV illustrates this was not the result during these tests. A possible cause of the decrease in cable insulation resistance after the 1000⁰C anneal is that the cable insulation is contaminated by

Photo No. 7712843-4

FIGURE 6. Cable Resistance Versus Time at 650°C , 800 Vdc Continuous

CABLE TYPE A

50 n sec/cm

CABLE TYPE B

50 n sec/cm

CABLE TYPE C

50 n sec/cm

CABLE TYPE D

50 n sec/cm

Photo No. 7712843-7

FIGURE 7. Typical Time Domain Reflectometer Traces

outgassing of the sheath and center conductor material. If this is the explanation, apparently the copper conductor material (OFHC) is less subject to outgassing than the Inconel 600. This could possibly be minimized by vacuum baking the "open cable assembly" prior to swaging at 1000°C instead of at 815°C as was done with these cables. A final 1000°C anneal of a whole length is considered desirable because it produces a more flexible cable. The data presented in Table IV suggests that any deleterious effects from a final high temperature anneal are minimal.

CONCLUSIONS

The test results demonstrate that bulk coax nuclear instrument cable can be commercially supplied that is capable of 650°C, 800 Vdc in-vessel breeder reactor service. The data also demonstrates that copper conductor cables perform as well as do Inconel 600 conductor cables; i.e., both cable types demonstrated BPN thresholds in excess of 800 Vdc and resistivities in excess of 10^8 ft at 650°C. This result allows the combining of signal transmission and high voltage capabilities into one cable type, a significant achievement for many applications. These tests also indicate that the effect of a final 1000°C anneal on cable performance is minimal for cable fabricated to this type specification, which included a 815°C vacuum bake-out of the cable interior and backfilling with high purity N₂ gas prior to swaging. This type cable appears suitable for attachment by a high temperature end seal/electrical connector to produce a complete 650°C, 800 Vdc instrument cable assembly; this final step in the cable development program is currently being initiated.

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