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TITLE 2000 MCM ELECTRICAL POWER JUMPER CABLE WITH CONTROLLED
FLEXIBILITY: DESIGN AND LIFE CYCLE TEST

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**2000 MCM ELECTRICAL POWER JUMPER CABLE
WITH CONTROLLED FLEXIBILITY:
DESIGN AND LIFE CYCLE TEST**

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2000 MCM ELECTRICAL POWER JUMPER CABLE WITH CONTROLLED FLEXIBILITY: DESIGN AND LIFE CYCLE TEST

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Abstract

The ZTH Reversed Field Pinch (RFP) plasma confinement experiment being built at the Los Alamos National Laboratory will use magnet coils to provide ohmic heating currents in the plasma. The ohmic heating coils are supported by a structure that will allow them limited movement with respect to surrounding hardware and the connecting electrical bus work. To minimize displacement-induced stresses in the coils, "flexible" power conducting links are necessary to accommodate the relative motion between the bus work and the coils.

A semi-flexible 2000 MCM jumper cable has been designed with enough flexibility to allow free movement of the coils, yet it is stiff enough to withstand large magnetically-induced lateral loads and minimize the effect of the lateral loads on the magnet coil leads. A full-power life cycle test of the jumper was performed under magnetic, thermal and dynamic loads that closely simulate the expected operating conditions. This test evaluated the structural and electrical integrity of the jumper as well as the quality and reliability of the bolted electrical connections at the jumper ends in a high-stress, cyclic-loading environment.

The jumper cable design is presented with an explanation of the requirements for a semi-flexible link. A description of the life cycle test and test results are given, as well as a description of the test apparatus and setup.

I. Introduction

The Controlled Thermonuclear Research Division of Los Alamos National Laboratory is constructing ZTH, an experimental air core reversed field pinch, which will be installed in the Confinement Physics Research Facility (CPRF) also under construction at Los Alamos, New Mexico.

The ZTH machine has a front end made up of a toroidal vacuum vessel, an electrically conducting outer shell and 48 toroidal field magnet coils mounted on the conducting shell's outer surface. Twenty-four poloidal field (PF) coils are symmetrically disposed above and below the horizontal mid plane of the front end. Ten of these PF coils are ohmic heating (OH) coils. Figure 1 shows the upper five OH coils with their connecting electrical bus work. A structure consisting of eight radial bulkheads made of laminated epoxy fiberglass (NE MA G-10) with connecting stainless steel ring beams support the front end and poloidal coils against gravity and magnetic loads.¹

When energized the OH coils move radially in the bulkheads and vertically when the bulkheads deflect under the coil magnetic loads. This produces relative motion between the OH coils and the rigidly mounted OH bus work. Also there are large lateral forces on the OH bus work due to the interaction of the electrical current in the bus and the OH magnetic field. A jumper cable with

Fig. 1. ZTH upper OH coil set and buswork

controlled flexibility is necessary in the buswork to accommodate the movement of OH coils and simultaneously resist lateral forces.

A 2000 MCM water cooled electrical jumper cable has been designed with an integral stiffener tube that allows free OH coil movement and also resists bending and thereby reduces tension loading of the cable and the coil leads. A full power life cycle test of this cable was conducted to prove the structural and electrical integrity of the cable assembly. Other purposes of this life cycle test were to prove the integrity of the bolted electrical joint at the cable ends and to insure that the cable could adequately dissipate heat generated by electrical resistance.

II. Jumper Cable Design

The design requirements of the jumper cable are as follows. The cable should have adequate electrical conductor cross sectional area for carrying current to the OH coils without overheating. A 50 kA, 6800 kA's electrical current pulse every 10 minutes, needs to be carried by the cable. The bolted connections between the cable and the OH coil leads and the buswork need to maintain contact surface pressure and should not deform or overheat. The cable also should produce little resistance to the relative motion between the OH coils and the connecting buswork. The cable should have adequate bending stiffness to carry the distributed magnetically induced lateral load in bending and thereby minimize tensile stress in the cable wires and terminal leads and reduce loading on the OH coil leads. It should have adequate strength in the terminal end to resist magnetically induced bending and shear stresses. The holes in the terminal ends should be slotted to aid field assembly by eliminating field drilling of holes in the buswork. The cable should not incorporate magnetic materials that cause magnetic field perturbations. The cable should have a small enough temperature rise during power

¹ Work performed under the auspices of the U.S. DOE.

² A. Jager, "The Design and Analysis of a Toroidal System for ZTH," 1990 Symposium on Fusion Engineering, October 1990, pp. 198-204.

pulses to insure that it does not reach temperatures that would damage its electrical insulation and to allow it to recover to an initial steady state temperature between current pulses.

The flexibility or stiffness of the cable needs to be controlled in order to have enough flexibility to allow motion in the buswork OH coil system without large reaction forces on the components. However at the same time the cable should not have so much flexibility that the cable axial tensile loads (due to the lateral magnetic loading) become too high.² The specific goals of the stiffened cable design are: that it produces little or no resistance to small (1.5 mm) relative lateral displacements of the cable terminal ends and that it carries the lateral magnetic load in bending to greatly reduce cable wire tension. The cable designed and tested, is a highly modified Wateredge-Uniflex¹ water cooled design. The cable contains 2000 MCM (1014 mm²) of 36 gauge ($\pm$ 23 mm) twisted wire bundles that are soldered into terminals made of CDA 11000 full hard copper. There are two lengths of flexible cable used in the buswork system 514 mm and 422 mm with 206 mm and 114 mm respectively of free (unsoldered) wire. The cables contain an axial $\pm$ 14.3 mm coolant channel formed by a stainless steel coiled spring located in the center of the wires. The cable terminal ends are 63.5 mm wide and have integral stiffener ribs on the far side of and perpendicular to the contact surface and four slotted holes for 1/2 inch fasteners. The terminal end electrical contact surfaces are coated with Cool Amp³ silver plating powder. Coolant is contained in the jumper by a 3.2 mm wall thickness reinforced styrenebutadiene rubber (SBR) hose clamped onto the terminals at each end with 201 stainless steel Band It⁴ hose clamps.

To obtain the desired stiffness Los Alamos modified the cable with the addition of a 63.5 mm ID by 2.4 mm wall thickness by 203 mm long 6061T6 aluminum three layer stiffener tube rolled from 0.8 mm thick sheet, Fig. 2. The stiffener tube is assembled to the jumper in the following manner. The SBR hose is removed from the cable and a single layer of polyester thermal shrink tape (General Electric no. 76850 25.4 mm wide by 0.05 mm thick) is applied over the cable wires. Then three layers of self fusing silicone rubber tape (Scotch⁵ no. 70 25.4 mm wide by 0.3 mm thick) are applied. These tapes provide a soft highly elastic layer that distributes loading and allows movement between the aluminum stiffening tube and the cable wires. All surfaces of the three layer wound aluminum tube are then coated with epoxy resin (Epocast⁶ resin no. 202A with 10% no. 951 hardener) and the tube is expanded and slipped over the terminals and onto the taped cable wires. The aluminum tube is then wrapped with two layers of epoxy coated fiberglass tape (Fusa-Fab⁷ no. 76576 203 mm wide by 0.6 mm thick). This tape was then wrapped with two layers of the polyester thermal shrink tape mentioned above, these last two tape layers provide a compressive force on the whole assembly as the epoxy in the assembly is cured in an oven (135 C for 30 minutes, followed by 160 C for 30 minutes).

¹ H. Frank W. Young, Formulas for Stress and Strain, 5th Ed., McGraw-Hill, New York, pg. 127, tables for cable data.

² Wateredge Uniflex is a registered trademark of Wateredge Uniflex.

³ Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof.

⁴ Cool Amp is a registered trademark of the Cool Amp Corp., Ltd. Ltd.

⁵ Band It is a registered trademark of the Band It Corp., Ltd.

⁶ Scotch is a registered trademark of the 3M Co.

⁷ Epocast is a registered trademark of HWA Corp., Inc.

⁸ Fusa-Fab is a registered trademark of the Fusa-Fab Corp.

The SBR hose is then installed over the cable and secured with hose clamps while axially compressing the jumper 3.2 mm. Figure 3 shows the lateral stiffness of the cable before and after the stiffness modification.

Fig. 2. Stiffened jumper cable

Fig. 3. Jumper cable stiffness

III. Life Cycle Test

The complicated geometry and loading of the twisted and banded wire strands of a current carrying cable insulated for high voltage (25 kV) and located in an intense magnetic field preclude a sufficiently accurate analytical or finite element method solution to the questions of stiffness, mechanical fatigue life and heat transfer under operational conditions. Therefore to prove the suitability of the modified cable in terms of performance and reliability it was necessary to perform a life cycle test under operational conditions. Operational conditions were produced by mounting the 514 mm long jumper between the poles of a C-shaped electromagnet which produced a field of 100 gauss. The jumper was placed in the center of the magnet. The jumper was then subjected to a current of 100 A for 10 minutes. The cable

was fastened by one terminal end to a fixed copper block and the other end was fastened to a copper block mounted on linear bearings that allowed the block to be moved by an compressed air powered actuator. The fasteners used were 316 stainless steel bolts and nuts with Belleville washers included in the fastener grip. The copper blocks had fastener hole patterns and electrical contact surfaces identical to those found on the OH coil leads and on the OH bus work. Also these blocks were water cooled in a manner similar to that which will be used on the ZTH machine. The copper blocks were connected to a power supply/switching system that sent a current pulse through the cable. The cable and copper blocks were connected to the cooling water source and then they were insulated to withstand 25 kV with three layers of self fusing semi conducting tape (Scotch no. 13 19 mm wide by 0.76 mm thick). Figure 4 shows the cable between the poles of the electromagnet and attached to the copper blocks prior to installation of water cooling hoses and electrical insulation tape.

Fig. 4. Jumper cable mounted in test apparatus

Actual cable test conditions were as follows. The cable and the attached copper blocks were cooled by chilled (7.2 C) water. The cooling water flow rate through the cable was 1.5 l/min. A steady state transverse magnetic field of 1.05 T was generated across the cable. The end of cable fastened to the movable copper block was deflected laterally (downward in Fig. 4) 1.5 mm and stretched axially to the left in Fig. 4) 0.3 mm and held in this strained position by the actuator at the start of each test cycle. The test current waveform was a pulse that ramped to 50 kA in 1.2 seconds and then remained steady at 50 kA for 1.6 seconds for a 4.8 second pulse width. Power supply limitations prevented jumper testing at a current level of 60 kA. Therefore the current pulse length and maximum field strength used were selected in order to duplicate the heating and magnetic loading of the cable that would be found at an operating condition of 60 kA and 6000 kA/s. When the current pulse was terminated the actuator retracted and the movable end of the cable returned to its original position. The test cycle was exactly repeated every four minutes, with the exception of a few cycles that were between 2.5 and 5 minutes in length that were used to check cable thermal recovery to equilibrium temperatures and to simulate power supply thermal limitations. The surface temperatures of the cable terminal ends and the copper blocks were measured and monitored throughout the testing through the use

of Type K thermocouples. Resistance across the cable and across both bolted joints was also measured and monitored through out the testing by using a bridge type micro ohmmeter.

IV. Results

A life cycle test of 1015 cycles was completed and the results were as follows. During the current pulse the jumper temperature would rise 11°C and then it would cool exponentially between current pulses to original steady state values. The jumper resistance fluctuated from 6 to 7 $\mu\Omega$. The initial jumper resistance was 6 $\mu\Omega$ and its final resistance was 6.5 $\mu\Omega$. The resistances of both bolted electrical joints fluctuated between 2 and 4 $\mu\Omega$ with the initial value being 2 $\mu\Omega$ and the final being 3 $\mu\Omega$. The tightening torque values of the bolted joint fasteners after the test were 80 to 90% of initial values. The cable was disassembled and inspected after the test. The contact surfaces of the bolted joints appeared to be unchanged; there were no indications of arcing or slipping present. The cable hose and hose clamp bands showed no damage and there were no water leaks. The stiffener tube's layers were still bonded and there was no evidence of cracking or plastic deformation. The cable terminal ends showed no indication of overheating or mechanical damage. Approximately fifty wires (individual strands) adjacent to one of the terminal ends were broken and showed evidence of a sharp corner of the stiffening tube gouging into them. There was no other evidence of wire breakage due to tension or fatigue banding.

V. Conclusions

The stiffened cable survived the life cycle test and met all operational requirements. The water cooled 2000 MCM cable proved to be a reliable link capable of carrying 60 kA current pulses with more than adequate thermal recovery and very low peak temperatures. The stiffener tube carried the lateral magnetic load to the terminal ends to minimize tension in the cable's wires and terminal ends. The bolted joints with slotted holes did not loosen and bolted joint contact pressure was maintained by a combination of bolt tension and Belleville washer force. The bolted joint fasteners and the cable terminal showed no mechanical or electrical arc damage. A few cable wires were cut by a sharp stiffener tube corner but this damage can probably be eliminated or greatly reduced by rounding off the sharp corner. There was no mechanical, electrical or thermal damage to the cable's electrical insulation.