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COAXIAL TEST FIXTURE AND PULSED POWER SUPPLY FOR CONTACT-MATERIAL SCREENING TESTS[a]

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ABSTRACT

A coaxial test fixture and a pulsed power supply have been built to conduct high-current screening tests on candidate materials for contacts to be used in first wall connectors on fusion devices, particularly tokamaks. The fixture was operated with half-sine-wave pulses of ≤ 300 kA; it is designed for carrying currents of up to 600 kA for approximately 300 ms at a repetition rate of 1 pulse every 5 minutes. The fixture is built as a vacuum vessel and capable of testing specimens in an ambient temperature of 300°C. Instrumentation is provided to measure the current pulse, contact voltage drop, contact pressure, the strain caused by contact pressure, and the operating temperature. The test fixture, its power supply and possible future upgrades are described.

INTRODUCTION

One of the many problems to be overcome in fusion reactors is that of providing reliable electrical contacts between first wall segments. An easily separable connector that can handle large currents requires contact surfaces that tolerate much abuse. The amount of current they can safely carry depends on certain physical characteristics. The size of the contacts, the force at which they are pressed together and their physical properties (conductivity, melting point, oxidation resistance, etc.) are of interest. The nature of the applied current (transient vs steady state, pulse ramp-up-time, etc.) will also greatly influence the choice of material. For the experimental evaluation of candidate contact material alloys a test fixture was developed and built by a collaboration of Argonne National Laboratory and McDonnell Douglas Astronautics Co. The objective was to determine the current density and pulse that a particular material can absorb without sticking (welding), melting, or jumping apart. A coaxial test fixture design was chosen. It provides the following features.

1. Test samples are part of the inner cylinder of the fixture made from two coaxially arranged cylinders.
2. Magnetic forces keep the current distribution in the cylinders symmetrical with respect to the cylinder axis.
3. There are no external magnetic forces produced by the coaxial cylinders.
4. The fixture has a relatively small inductance.
5. The fixture can be built as a vacuum vessel; the vacuum is adjustable down to 2×10^{-2} Pa.
6. Contact pressure is adjustable up to 2.07 MPa.
7. Contact area of test samples can be as large as 50 cm^2.

A transformer coupled high voltage (HV) capacitor discharge circuit provides a half sine wave current pulse adjustable from 0 to 300 kA peak.

The parameters measured as a function of current, contact pressure, and specimen shape are:

- voltage drop across specimen junctions during current pulse,
- temperature rise of specimen during current pulse, and
- specimen strain during pulse.

This paper will describe the test fixture, the pulsed power supply, and the instrumentation. Test results are reported in a separate paper.[1] Figure 1 shows the experimental setup.

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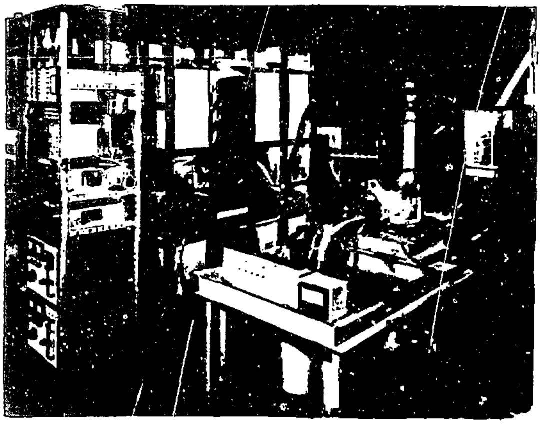

Fig. 1. Contact Material Screening Test Facility.

COAXIAL TEST FIXTURE ASSEMBLY

A cross section of the coaxial test fixture is shown in Fig. 2. The test specimens are part of the inner cylinder. The magnetic field produced by the current flowing through the coaxial cylinders will act upon the current itself. These magnetic forces will exert pressure on the outside of the test samples, tending to shrink them, and pressure on the inside of the outer cylinder, tending to expand it. These forces will keep the current distribution in the cylinders symmetrical around the cylinder axis.

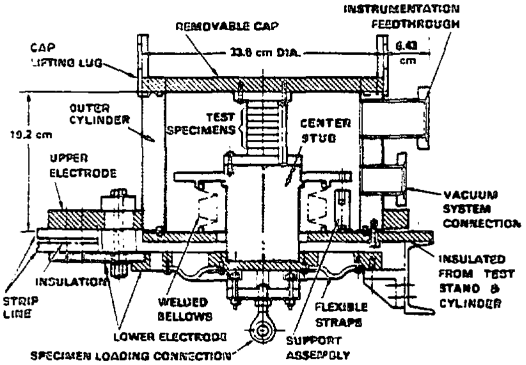

Fig. 2. Cross Section of Coaxial Test Fixture Assembly.

The coaxial test fixture is mounted on a portable test stand together with the hydraulic loading system and the vacuum system required to provide appropriate conditions for tests. The test stand is portable to permit use of the fixture with power supplies that have differing capabilities.

The test fixture consists of a cylindrical copper vacuum chamber 33.6 cm in diameter and 19.2 cm high mounted on top of the test stand structure as shown in Fig. 1. Two vacuum feed throughs are installed in the chamber sidewall, one to the vacuum system and one for instrumentation connections. Access is provided to the interior through a removable copper cap plate 1.9 cm thick.

The design of the test fixture passes the current from the strip line through the lower electrode to the center stub, through the specimen contacts, out through the removable cap, down the outer cylindrical sidewall and out through the upper electrode back to the strip line.

The test chamber can contain up to eight test specimens, each 0.95 cm thick. These specimens rest on an adapter plate between three Vespel guideposts. Different adapter plates and guideposts are used for different diameter specimens. The adapter plate is bolted to the floating center stub of the lower electrode assembly. This stub has been designed to allow regulation of the direction and magnitude of the compressive force exerted on the specimens by the atmosphere and the hydraulic loading system. The direction is varied only to assure that the contact surface parallelism tolerances for the specimens are compensated and the force remains normal to the surface of the specimens. To gain this flexibility, a stainless steel welded bellows is used as part of the lower vacuum wall and a flexible strap connection exists between the stub and the fixed part of the lower electrode.

The upper part of the specimen stack is butted against an upper adapter plate bolted to the chamber cap. Access to the chamber is made by removal of the bolts which attach the chamber cap to the sidewalls and then lifting off the cap. If necessary, access to the bellows and supports is accomplished by removal of the chamber cylindrical sidewall and upper electrode assembly from the bottom plate to which the bellows are welded. The support assemblies are used to tie down the bellows and stub during transportation and, with long close-tolerance-bolts as guide pins, they keep the floating stub centered in the chamber during operation.

The test chamber is grounded at the sidewall near the vacuum port. The chamber sidewall is insulated from the mounting plate and lower electrode at its juncture with the mounting plate by a 0.25 cm thick glass reinforced teflon gasket. The vacuum seals across this insulation are two Viton "O" rings, one on each side of the insulation. The mounting plate is also insulated from the test stand to assure that all of the current passes through the specimens. The vacuum seal between the removable cap and the chamber sidewall is a Viton "O" ring. Twenty-four bolts are used to attach the cap to the sidewall so that sufficient pressure exists to assure good electrical contact and to resist the upward force of the contact specimen stack.

The upper and lower electrodes are designed to distribute the current uniformly around the circumference of the coaxial cylinders. Figure 3 is a top view of the test fixture which illustrates the upper electrode configuration.

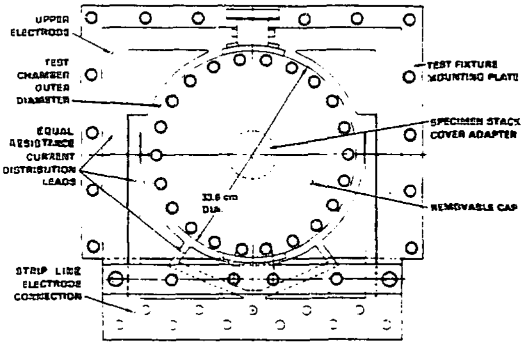

Fig. 3. Coaxial Test Fixture Assembly (Top View).

This electrode has six distribution leads of equal resistance. The lower electrode configuration is similar.

SPECIMEN PRESSURE

The contact pressure on the specimens is adjustable from near zero to a maximum pressure of 2.07 MPa. These pressures are attained by use of a system which adjusts the load on the base of the floating center stub and the direction of application of this load. For contact pressures less than approximately 1.38 MPa, a downward or negative compression load must be applied to overcome air pressure on the floating stub. Above these pressures an upward or positive load is required. The loading system consists, therefore, of a double acting cylinder operated by a hand hydraulic pump with valving that provides for application of the loads in either direction. A bleed valve for fine adjustment of the loading pressure is also provided. The pressure adjustment is roughly made by use of a standard 0-1500 psi hydraulic pressure gauge and a 454 kg rated capacity load cell. The load cell is mounted between the hydraulic cylinder and the floating stub. The final adjustment utilizes strain gauges mounted on the specimen stack. The directional adjustment of the pressure on the specimen stack is accomplished by lateral motion of the bottom of the floating stub. The top of this stub is held in place by guide pins which allow vertical motion but not lateral motion. A set of three turnbuckles is used to provide the force needed for lateral motion of the floating stub and the directional control of this force. These turnbuckles are mounted at 120° angles around the stub and are attached to the test stand. They exert a force normal to the load axis of the stub and load cell. Turnbuckles are required because the current requirements necessitate use of a large copper cross section in the flexible straps which makes them quite stiff; therefore, a moderately large force is required to deflect the floating stub.

VACUUM

The vacuum pumping system uses a compressed air aspirator to bring the vacuum to about 6670 Pa and then dual Varian Vacsorb LN_2 pumps are opened to the system to achieve a vacuum pressure as low as 2×10^{-2} Pa. This pressure is measured by a cold cathode vacuum gauge mounted at the vacuum feed through. For the purpose of the tests, a pressure on the order of 1.3×10^{-1} Pa is desired. The vacuum pumps are connected directly to the side of the test chamber through two shutoff valves and a 45.72 cm long, 3.81 cm diameter flexible line. The aspirator pump and the cold cathode gauge are connected directly to the feed through in the chamber wall. A Bourdon gauge gives rough vacuum pressures during aspiration. The chamber requires approximately 15 minutes to pump down to the operating level of 1.3×10^{-1} Pa. All connections in the vacuum system use copper conflat seals and stainless steel flanges, fittings, and lines.

INSTRUMENTATION

All instrumentation installed within the test chamber is brought out through a hermetically sealed 37 pin Deutsch connector. The connector is mounted at the end of a tube through the test chamber wall as shown in Fig. 2. This design locates all of the instrumentation leads, soldered to the connector, outside of the current carrying wall. This technique, together with the use of twisted leads in shielded cable, nearly eliminates the influence of the internal magnetic field noise on the intrumentation signal.

Each specimen stack is instrumented with voltage taps across the contact surface for each pair of specimens, with a chromel alumel thermocouple mounted halfway between contact surfaces in the side of one specimen of each pair, and with strain gauges to read the strain caused by the contact pressure. A small Rogowski belt is placed around the top specimen in the stack to measure current through the stack.

The strain gauges employ three arrays mounted on the periphery of a 1.9 cm thick copper slug which takes the place of one set of specimens at the bottom of the specimen stack. These are separated at 120° angles around the copper slug periphery. Each strain gauge array is made up of two 90° gauge rosettes wired as a half Weatstone bridge for maximum sensitivity.

Each specimen stack is wired and calibrated as a unit with the wires connected in the female coupling of the Deutsch connector. This unit is installed and connected by shielded cables to the readout instruments. The contact voltage drop and current readings are taken during each pulse by taking oscilloscope pictures. All other data is taken before and after each pulse. More details of the instrumentation are found in Ref. 1.

FUTURE UPGRADE

For future testing the coaxial test chamber has been designed to allow the specimens to be heated to 300°C before the current pulse is discharged. Some modification in selection of the vacuum seal material is required, and heaters must be added, but all other components will withstand this temperature. Also, for future testing, the chamber will accommodate specimen diameters to approximately 8.5 cm, if required, at currents of 600 kA with a 50 V drop across the test chamber. The maximum diameter being tested at the present time is 4.13 cm.

PULSED POWER SUPPLY

Alternating half cycle sine wave current pulses are applied to the coaxial test fixture by the capacitor discharge circuit of Fig. 4.

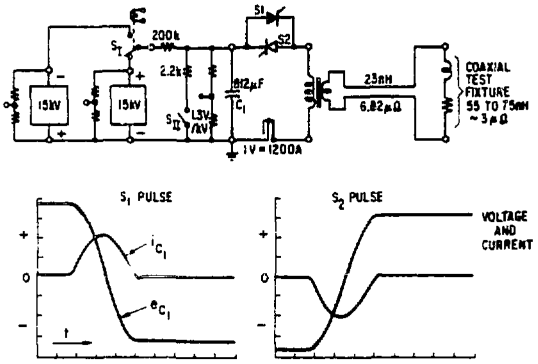

Fig. 4. Bipolar Capacitor Discharge Circuit.

The 812 μF capacitor bank C_1 is slowly charged through a 200 kΩ resistor($RC = 162$ s). To prevent saturation of the transformer iron the capacitor charge is reversed after every discharge. For example with the polarity reversing switch S_I in the position shown in Fig. 4 the capacitor bank is charged positive with respect to ground. A positive current pulse is initiated by turning on thyristor S_1 as soon as the capacitor bank has reached a preset voltage. The current pulse, via logic circuits, initiates transfer of switch S_I from the positive to the negative HV power supply. At the end of the positive current pulse the capacitor voltage has reversed as illustrated in Fig. 4. Circuit losses are being made up by the negative power supply which charges the capacitor bank to the same but negative HV as was used for the positive pulse. The charge time is approximately 5 minutes; it is adjustable to some degree by setting the variable voltage level (0-15 kV) to a value larger than what is set on the voltage reference (e.g., for a 6 kV capacitor voltage reference the HV power supply may be set at 10 kV). The next current pulse is negative, initiated when thyristor S_2 is being turned on. The thyristor assemblies are rated 10 kV and 1 kA rms; the half sine wave current pulse has been less than 2.3 kA peak with a pulse duration of < 15 ms.

The pulse shape is a function of the impedance reflected to the transformer primary. Depending on the geometry of the test samples (diameter and length) the inductance of the coaxial test fixture varies. The transformer has a single turn secondary made up from 16 copper sheets 0.159 cm thick. These sheets are 45.6 cm wide where they form a 1 m long strip line separated by 0.3 cm and are cut back to a width of 20 cm where they enclose the transformer core. To reduce eddy current losses, the sheets are insulated from each other with sheets of mylar 0.0076 cm thick. The transformer primary has 308 turns with taps at 225 and at 150 turns. Since the secondary impedance is reflected to the primary by a factor equal to the square of the turns ratio the impedance of a given stack of test samples can be varied by factors of 2.25 × 10^4, 5.06 × 10^4, or 9.49 × 10^4 depending on the turns ratio selected. Of course the turns ratio and the peak voltage on the capacitor must not exceed the volt-second rating of the transformer.

The resonant frequency of the circuit is:

$$f = \frac{1}{2\pi}\left(\frac{1}{LC_1} - \frac{R^2}{4L^2}\right)^{1/2} \tag{1}$$

the current at any time is given by:

$$i = \frac{E_{C_1}}{L}\,\frac{1}{\left(\frac{1}{LC_1} - \frac{R^2}{4L^2}\right)^{1/2}}\,\epsilon^{-\frac{Rt}{2L}}\,\sin\left(\frac{1}{LC_1} - \frac{R^2}{4L^2}\right)^{1/2} t \tag{2}$$

the time t_p at which the current reaches its peak is:

$$t_p = \frac{1}{\left(\frac{1}{LC_1} - \frac{R^2}{4L^2}\right)^{1/2}}\tan^{-1}\frac{\left(\frac{1}{LC_1} - \frac{R^2}{4L^2}\right)^{1/2}}{\frac{R}{2L}} \tag{3}$$

where:

L = total circuit inductance reflected to the transformer primary in henries.

R = total circuit resistance reflected to the transformer primary in ohms.

The capacitor discharge current is measured by a coaxial shunt rated 1 V at 1200 A. The current in the coaxial test fixture is measured by a Rogowski belt placed around the specimen stack. It consists of 100 turns of #30 AWG wire wrapped around the core of an RG 58/U cable.

POWER SUPPLY UPGRADES

Two upgrades to the power supply are being considered:

1. Pulse shaping by means of a passive crowbar.

The half sinusoidal current pulse generated by the circuit of Fig. 4 can be extended if we crowbar the capacitor when the current is at its peak (after a quarter sine wave). Figure 5a shows the necessary modifications to the existing capacitor discharge circuit. Figure 5b shows the exponential current decay produced by the crowbar. Thyristor S_3 acts as a crowbar for a positive current pulse (the pulse being initiated by thyristor S_1). Thyristor S_4 is the crowbar for a negative current pulse (initiated by thyristor S_2). A crowbar thyristor receives a gate signal approximately 0.2 ms before the capacitor voltage crosses zero. The gate signal is maintained for a few ms in order that the high di/dt rating of the thyristor can be realized. A saturable reactor L gives a ~20 μs time delay to allow the thyristor junction to be fully turned on before it has to carry the full crowbar current (approximatley 1.33 kA for 300 kA through the test samples with a 225:1 transformer turns ratio).

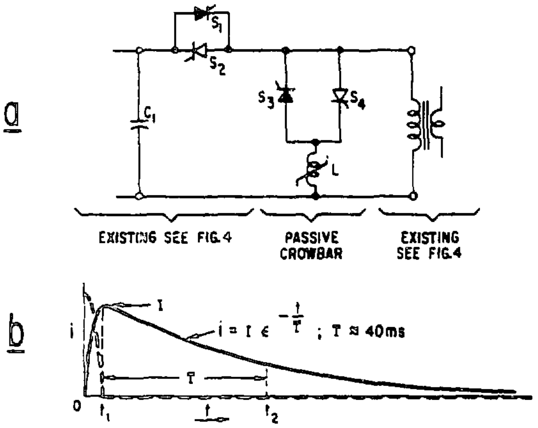

Fig. 5. Pulse Shaping with Passive Crowbar.

2. Pulse shaping with an active crowbar.

By adding electrolytic capacitor banks C_2 and C_3, bypass diodes D_1 and D_2, and low voltage power supplies P_1 and P_2 in series with the crowbar thyristors mentioned above, we can maintain the current pulse for a longer time. Figure 6a illustrates the circuit; Figure 6b shows the current shape. Referring to Fig. 6b and with capacitor banks C_1 and C_2 charged to their respective positive voltages with respect to ground, the time sequence of events is as follows:

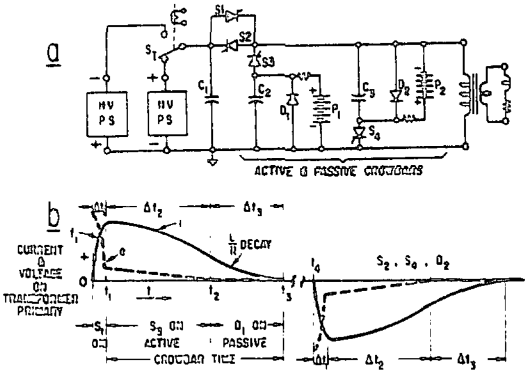

Fig. 6. Pulse Shaping with Active and Passive Crowbar.

<u>At $t = t_0$</u> — Thyristor S_1 is turned on. A sinusoidal current of frequency f_1 rises to its peak value.

<u>At $t = t_1 - 200\ \mu s$</u> — A 2 ms gate signal is applied to crowbar thyristor S_3.

<u>For $(t_1 + 100\ \mu s) < t < t_2$</u> -- The active crowbar carries the primary current. The decay of this current is delayed (as compared to the sinusoidal decay without a crowbar) while the voltage on capacitor C_2 decays nearly linearly.

<u>At $t = t_2$</u> — Capacitor C_2 is discharged; the primary crowbar current commutates from capacitor C_2 to diode D_1.

<u>For $t_2 < t < t_3$</u> -- The current decays exponentially through the now passive crowbar until all the inductively stored energy has been dissipated.

<u>At $t = t_4$</u> -- A negative pulse of similar shape is initiated by turning on thyristor S_2.

The desired peak current and the duration and shape of the current for time intervals Δt_1, Δt_2, and Δt_3 will determine the design of the capacitor banks and of the transformer.

REFERENCES

1. D. C. BANKER, "Selection of High Current Contact Materials for Tokamak Devices," McDonnell Douglas Astronautics Company, Presented at the Fifth Topical Meeting on the Technology of Fusion Energy (April 26–28, 1983).

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