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**Breakdown Voltage at the Electric
Terminals of GCFR-Core Flow Test
Loop Fuel Rod Simulators in
Helium and Air**

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MASTER

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**BREAKDOWN VOLTAGE AT THE ELECTRIC TERMINALS OF GCFR-CORE
FLOW TEST LOOP FUEL ROD SIMULATORS IN HELIUM AND AIR**

W. R. Huntley T. B. Conley

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ABSTRACT

Tests were performed to determine the ac and dc breakdown voltage at the terminal ends of a fuel rod simulator (FRS) in helium and air atmospheres. The tests were performed at low pressures (1 to 2 atm) and at temperatures from 20 to 350°C (68 to 660°F). The area of concern was the 0.64-mm (0.025-in.) gap between the coaxial conductor of the FRS and the sheaths of the four internal thermocouples as they exit the FRS. The tests were performed to ensure a sufficient safety margin during Core Flow Test Loop (CFTL) operations that require potentials up to 350 V ac at the FRS terminals.

The primary conclusion from the test results is that the CFTL cannot be operated safely if the terminal ends of the FRSs are surrounded by a helium atmosphere but can be operated safely in air.

INTRODUCTION

The GCFR-Core Flow Test Loop (CFTL) is being designed and constructed to accept test bundles of electrically heated rods which simulate portions of GCFR helium-cooled fuel and control rod assemblies and full-sized GCFR blanket assemblies. In the CFTL, the bundles are to be subjected to the steady-state and the upset, emergency, and faulted conditions anticipated with the Gas-Cooled Fast Breeder Reactor (GCFR).

A conceptual bundle design study was done in which the triangular pitch of the fuel rod simulators (FRSs) was varied between 11.2 and 9.8 mm (0.441 and 0.389 in.). The 9.8-mm (0.389-in.) pitch led to consideration of a bundle configuration in which gas pressure would be nearly equalized across the FRS cladding and the tube sheet into which the FRSs are welded. This is in contradistinction to the traditional bundle design in which gas pressure is exerted on both the external surface of the cladding and the internal surface of the tube sheet, which is part of the system pressure boundary. Thus, the pressure-equalized design permits the use of a relatively thin tube sheet, which, in turn,

reduces the heat removal problem associated with electrical losses in the FRS conductors where the conductors penetrate the tube sheet.

One problem perceived for the pressure-equalized concept is electrical arcing in the gap between the coaxial conductor and the sheaths of the four internal thermocouples where all emerge from the open end of the FRS into a helium atmosphere. The CFTL voltage at the FRS terminals will range from 350 V ac at helium pressures of 9.0 MPa (1300 psia) and temperatures of 350°C (660°F) to 78 V at ambient pressure. Operation at 350 V will simulate full power operation of a gas-cooled reactor, while the 88-V operation will simulate 5% reactor decay heat during the evaluation of design basis depressurization accidents. Voltage breakdown is not anticipated when the FRS terminals are operated in atmospheric air; however, helium is known to have lower breakdown voltage characteristics than air.

The relatively low voltage breakdown potentials of noble gases have been known for many years.¹⁻³ According to Paschen's law, breakdown voltage varies directly with absolute pressure and inversely with absolute temperature at conditions above the minimum, or "critical," breakdown pressure. However, Paschen's law fails gradually at high pressures; Cohen⁴ observed the loss of linearity of breakdown potential with increasing pressure above 2 MPa (290 psia) for air in a uniform field. Clark⁵ reports that in nonuniform electric fields air departs from Paschen's law at about 1.1 MPa (160 psia) (at room temperature), while such departure in helium occurs at about 3 MPa (440 psia). The configuration of the arc gap in a CFTL FRS creates a nonuniform electric field; therefore, nonuniform field data would appear more applicable to the CFTL situation. No recent references were found for breakdown voltage in high-pressure or high-temperature helium. A computer-assisted literature search was made using keywords on the RECON data systems, which generally include this type of technical data from the mid-1960s to the present, but no pertinent data were located in this manner.

Experimental data can vary widely because the breakdown voltage is affected by a host of variables such as electrode size, shape, material, surface finish, arc conditioning of the electrode, field uniformity, gas purity, gas stagnation, and the type of applied voltage. Experimental

work in 1960 for gas-cooled reactors produced helium breakdown data for the terminals of electric tubular heaters;⁶ these tests were of interest because of the similarity between the heater geometry and the open ends of the CFTL FRSs. These helium breakdown data included helium pressures to 0.6 MPa (85 psia) and temperatures up to 480°C (900°F). For example, Olson's data in Ref. 6 gave a helium breakdown voltage of about 575 V ac for a 2.5-mm (0.1-in.) gap at 25°C (75°F) and 0.15 MPa (22 psia). This is about one-half the breakdown voltage indicated for helium under uniform field conditions in Fig. 4-59 of Ref. 2. Olson tested at pressures up to 7 MPa (1000 psia) but did not obtain voltage breakdown at pressures above 0.6 MPa (85 psia) because of limited voltage supply. H. C. Shaw performed room temperature voltage breakdown testing with helium of about 20 ppm total impurities, both with and without ionizing radiation.⁷ In Fig. 7 of Ref. 7, data taken in the absence of ionizing radiation showed wide scatter using a 0.25-mm (0.010-in.) gap at 13°C (55°F) at pressures ranging up to 2.2 MPa (320 psia) using a pointed electrode opposite a flat plate. The breakdown voltage was repeatable and was lower by about a factor of 2 when ionizing radiation was present. Shaw's data also show higher breakdown voltage than comparable Oak Ridge National Laboratory (ORNL) experimental data contained in Ref. 6. The large uncertainty in extrapolating other helium breakdown data to specific CFTL geometries and test conditions led us to conduct a new series of helium breakdown tests.

Breakdown voltage characteristics of a prototypic CFTL FRS were measured with helium because of interest in the pressure-equalized concept. These measurements were made in air to confirm these characteristics with the pressurized bundle concept in which the gap is located in ambient air. Thus, two separate series of tests are described. In series I, most of the testing was done in helium at 2 atm to simulate CFTL operation during depressurization tests (worst case); in series II, the tests were run in air at 1 atm, and these data were compared with duplicate tests made in helium.

DESCRIPTION OF SCREENING TESTS AND SERIES I VOLTAGE BREAKDOWN TESTS

Measurements of breakdown voltage were made in two different types of test apparatus. A screening test was first run at atmospheric pressure in existing equipment used previously to determine compacted boron nitride (BN) powder electrical resistance values. The modified FRS available in this apparatus, not being equipped with internal thermocouples, had an arc gap of 1.1 mm (0.045 in.), or about twice the gap in an FRS with internal thermocouples. Breakdown occurred at 250 V dc in helium at 315°C (600°F) and atmospheric pressure. The helium was supplied from an available, unanalyzed bottle. The observed breakdown voltage in helium was lower than that indicated by early reference documents. Therefore, definitive bench tests with the specific FRS geometry, utilizing analyzed helium, were run to simulate more nearly the CFTL operation during depressurization tests.

The series I bench tests used an available swaged FRS, GLR-L-7P, which had been operated previously in other tests. The four internal thermocouples were not operable because they were broken off where they emerged from the FRS cladding. However, the gap for arc testing was considered typical — about 0.64 mm (0.025 in.). The test facility was modified (as shown schematically in Fig. 1) so that the open end of the FRS could be operated in vacuum or in helium at pressures to 0.2 MPa (29 psia), the design limit of the existing test vessel. An electric heater and thermocouples were located on the pressure boundary surrounding the upper end of the FRS to help control the temperature of the arc gap between the coaxial conductor and sheathed thermocouples. The FRS cladding was isolated by electric insulators so that leakage currents to the cladding from an arc or through the BN insulation could be measured outside the test vessel by observing the voltage drop across a known resistance in a grounded circuit attached to the cladding. A type K thermocouple was temporarily located on the coaxial conductor to monitor operating temperature adjacent to the arc gap. This thermocouple was disconnected whenever positive potential was applied to the conductor. A type S thermocouple, which was electrically isolated from ground, and an

Fig. 1. Helium ionization test apparatus schematic — series I tests.

optical pyrometer were used to measure the cladding temperature along the normally heated portion of the FRS.

The helium for all tests of FRS GLR-L-7P came from a single bottle of specially conditioned, high-purity helium; an analysis of this helium is shown in the first column of Table 1. This high-purity helium was chosen because it approximated the impurity levels expected at the outlet of the CFTL purification system, as shown in Table 1. The maximum expected CFTL impurity levels during operation and in as-received helium are also shown for information.

The system was evacuated with a mechanical roughing pump while heating the upper portion of the FRS to off-gas the metal surfaces and remove water vapor from exposed BN at the open end of the FRS. The test vessel was then filled with helium to the desired pressure. During operation, a constant flow rate of 200 standard cm³/min (12.2 in.³/min) of helium was maintained downward through the 67-mm-ID (2.64-in.) by 400-mm-long (15.75-in.) tube, which contained the upper portion of the FRS, to better ensure that the helium in the region of the arc did not become laden with off-gassing constituents from the FRS materials or other metal surfaces.

Table 1. Comparison of helium impurity levels in CFTL and breakdown voltage tests (ppm)

Impurity	Used in voltage breakdown tests	Leaving CFTL purification system	Maximum level in CFTL	As-received from CFTL truck trailer supply
H ₂ O	1.6	<1	96	3 ^a
H ₂	0.03	3	960	1
CO		3	12	<i>b</i>
CO ₂	0.06	<1	1.2	<i>b</i>
Ne	0.87	23	23	23
CH ₄	<0.005	<1	2.3	<i>b</i>
N ₂	0.07	<1	12 ^c	5
O ₂	0.01	<1	2.3	3
A	<0.005			

^aEight if in bottles.

^bAll carbon-bearing gases total 1 ppm.

^cN₂ levels may be as high as 10% for depressurization tests.

Initial voltage breakdown testing was done using a low-amperage dc power supply to preclude damage to the terminal end of the FRS during arcing. This power supply had a maximum 500-V potential and produced less current than the 1000-V unit used in the screening test mentioned earlier. Final testing was done using a prototype of the CFTL ac power system with a protective "crowbar" circuit to limit damage during arcing. Both power systems are shown schematically in Figs. 2 and 3.

Fig. 2. dc power supply — series I tests.

Fig. 3. ac power supply — series I tests.

DESCRIPTION OF SERIES II VOLTAGE BREAKDOWN TESTS

This series of tests was performed on short sections of three available FRSs: GLR-L-10P, GNR-L-11P, and GNR-L-12P. FRS 10P was swaged, and FRSs 11P and 12P were nonswaged. The terms "swaged" and "nonswaged" refer to two different techniques of fabricating the FRS. Tests were conducted on both swaged and nonswaged FRSs because both were being considered for use in the CFTL at the time. However, the nonswaged FRS has since been selected as the reference design for use in the CFTL test bundles. The series II tests were performed for two reasons: (1) to confirm the belief that the CFTL could be operated with a sufficient safety margin against voltage breakdown in air at atmospheric pressure and (2) to confirm the results of the series I tests in helium, particularly with a nonswaged FRS. Note that there is a difference in the arc gap between the swaged and nonswaged FRSs. The arc gap in the swaged FRS is ~ 0.64 mm (0.025 in.), as stated earlier in the report; the arc gap in the nonswaged FRS is smaller: ~ 0.56 mm (0.022 in.).

The FRS test sections were prepared by cutting 305 mm (12 in.) off the upper end of each FRS. The FRS sheath was then peeled from both ends, leaving a 102-mm (4-in.) section with the coaxial conductor and the thermocouples emerging intact from both ends. This operation was performed to provide a short specimen for installation in the test furnace, as well as to expose the internal thermocouples and yield a symmetric test piece (see Fig. 4). The thermocouples were bent back to ensure the formation of a uniform gap at the expected point of voltage breakdown (Fig. 5). A type K thermocouple was mounted on the edge of the sheath to monitor the temperature near the expected point of breakdown. The thin layer of BN electrical insulation was removed from both ends of the FRS around the coaxial conductor to ensure a typical gas gap between the internal thermocouples and the conductor; also, the conductor was cleaned with emory cloth to remove any BN and oxides that might have been on the surface. A jet of air was then passed over the ends to remove the loose BN and other particles.

Breakdown voltages were highly sensitive to moisture in the BN insulation; therefore, each segment of FRS was baked in a tubular oven at

Fig. 4. Typical series II test piece in tube oven.

$\sim 230^{\circ}\text{C}$ (450°F) to drive out this moisture. To protect the FRS segment from mishandling during the test and to electrically isolate it from the tubular oven, the segment was placed within an open-ended 25.4-mm-ID (1-in.) quartz tube. This arrangement appears in Fig. 4. After 3 or 4 hr at 230°C , the temperature was increased to about 340°C (650°F), and the resistance was measured at 340°C using a General Radio, 1644-A Megohm Bridge (Fig. 6) at an applied voltage of 500 V in air. The BN resistance measurements were taken to ensure that the BN was adequately dry and also to indicate that no short circuits existed in the experimental wiring system.

The resistance of the BN was also measured with the FRS in a helium atmosphere to compare with the data taken in air. During these tests,

Fig. 5. Close-up of the open end of an FRS as used in series II tests.

the ends of the quartz tube were sealed so that the FRS could be blanketed with helium that flowed through the tube at atmospheric pressure. During such testing in helium, the voltage on the Megohm Bridge had to be reduced from 500 to 200 V to prevent arcing caused by the helium atmosphere.

Fig. 6. Test apparatus — series II tests.

To determine the breakdown potential for dc and ac voltages in air, a Slaughter Company "Hi-Pot" Tester, Model 103/105-5CE, was utilized (Fig. 6). This model is equipped with an audio-signaling device that informs the operator when an arc occurs. The output from the audio-signaling device was used as the criterion for determining the breakdown voltage. In all tests with 10P and 12P, a visible arc coincided with the audio signal; there was no apparent arcing within the body of the BN-filled FRS. A second set of voltage breakdown tests was done in helium with the power supply shown in Fig. 7. The same purity helium used in the series tests (Table I) was passed through the quartz tube at a flow rate of 470 cm³/min (28.68 in.³/min).

DISCUSSION OF TEST DATA

Series I Data

The data for dc breakdown voltage in helium at the upper or terminal end of FRS GLR-L-7P ranged from 200 to 340 V at 0.2 MPa (29 psia), as shown in Fig. 8. These data indicate lower breakdown voltages than would be inferred from Refs. 1, 2, and 7. The first test indicated dc breakdown voltages of about 320 V which were relatively constant at test temperatures from 38 to 370°C (100 to 700°F). Subsequent dc tests showed a lowered breakdown voltage of about 220 V. In all cases, the data show very little temperature dependence. This does not agree with Paschen's law and is not understood. Tests with the prototypic CFTL ac power supply were conducted at 426°C (800°F), and a comparable breakdown voltage of about 170 V was found.

Note that the breakdown voltage of 250 V dc at 315°C (600°F) in the screening test with a 1.1-mm (0.043-in.) gap was in the same range as those found for a 0.64-mm (0.025-in.) gap in the series I bench tests at comparable temperature and pressure. The reason for this apparent contradiction is not definitely known. However, several differences in the tests were obvious, such as gap configuration, surface conditions, and different helium supplies, any of which could account for the variances in breakdown voltage.

Fig. 7. ac power supply used in helium tests — series II.

Fig. 8. FRS GLR-L-7P, helium breakdown voltage data — series I tests.

Posttest examination of the arc gap of FRS GLR-L-7P, the series I test piece, showed that one of the four thermocouple sheaths was damaged by repeated arcing from the surface of the coaxial conductor. The surface of the BN insulation was darkened near this thermocouple, and the inner surface of the FRS cladding was covered with fine particles adjacent to the thermocouple. About half the thermocouple sheath was disintegrated by the arcing in the region facing the conductor. The MgO insulation within the thermocouple sheath was intact. The speculation is that the arcing damage observed may be the reason for the change in breakdown voltage from about 320 to 220 V during the early testing.

Series II Data

The FRS GNR-L-11P was used primarily to determine the proper experimental technique. The most significant fact learned from 11P was the high sensitivity of breakdown voltage to moisture in the BN. Even at 340°C (650°F) in air, the potential required for breakdown within the BN was quite low (400 to 500 V ac, 500 to 700 V dc) if the FRS was not properly dried out (see Table 2). Such arcs were not visible but were detected by the audio-signaling device on the Hi-Pot Tester mentioned

Table 2. Effects of preheating to remove moisture on BN resistance and breakdown voltage in nonswaged FRS in air

Rod No.	Rod temperature (°C)	Approximate resistance (Ω)	Breakdown voltage (V ac)
GNR-L-11P, nonpreheated	340	8.4×10^6	400
	200	8.5×10^6	450
	25	6.5×10^7	500
GNR-L-12P, preheated at 230°C for 4 hr	345	2.6×10^{11}	950
	220	4.8×10^{12}	1100
	30	4.5×10^{12}	1550

earlier. The potential was increased beyond the breakdown point in an attempt to produce visible arcing. The attempt failed and produced current leakage through the BN, ending the test of FRS GNR-L-11P. Therefore, it is emphasized that the CFTL should be brought to full power slowly to drive out the moisture trapped within the BN. This result has been confirmed by other experimenters using similar FRSs.

Initially, two sets of air tests were done on both FRS GLR-L-10P and GNR-L-12P. The scatter of the data was no greater than was anticipated in an experiment subject to so many loosely controlled variables. Figures 9 and 10 present both the ac and dc data for FRSs 10P and 12P, respectively. Some of the dc voltage breakdowns occurred beyond the measurement capability of our equipment because, initially, the maximum available readable voltage was 2500 V (in later tests, the maximum available voltage was increased to 5000 V). Swaged FRS 10P achieved higher ac breakdown voltages than the nonswaged 12P (see Fig. 11 for easy comparison). Part of this difference may have been caused by the smaller gap between the thermocouples and the coaxial conductor in a nonswaged FRS (0.56 vs 0.64 mm). At temperatures of $\sim 340^\circ\text{C}$ (650°F), the breakdown voltage was between 900 and 1000 V ac for the reference design nonswaged FRS, 12P. This is substantially higher than the maximum projected CFTL operating voltage of 350 V ac.

The potentials required for breakdown in helium were too low to be measured on our Hi-Pot Tester; therefore, a new ac voltage source, mentioned previously and shown in Fig. 7, was built to obtain data between

Fig. 9. FRS GLR-L-10P, air breakdown voltage data - series II tests.

Fig. 10. FRS GNR-L-12P, air breakdown voltage data - series II tests.

Fig. 11. Summary of ac air breakdown voltage data — series II tests.

0 and 460 V. The breakdown voltages ranged from 215 to 280 V ac for swaged FRS 10P and from 200 to 240 V ac for nonswaged FRS 12P (Fig. 12). Results of the series I tests were plotted with the results of the series II tests in Fig. 13. Caution should be exercised when interpreting this figure because the data for FRS 7P are for dc voltages, while the data for FRSs 10P and 12P are for ac voltages. The general agreement between the two completely different experiments indicates that breakdown voltage in helium is indeed low and that there may be a very small margin between the potential applied to FRS electrical terminals during normal operation and the breakdown voltage when the terminals are operated in helium.

To confirm that FRSs 10P and 12P were not altered or damaged during the helium tests, the FRSs were retested in air. These data appear in Figs. 14 and 15. When compared with earlier air data in Figs. 9 and 10,

Fig. 12. Summary of ac helium breakdown voltage data — series II tests.

Fig. 13. Helium breakdown voltage data — series I vs series II tests.

Fig. 14. Damage check, FRS GLR-L-10P, air breakdown voltage data - series II tests.

the final breakdown voltages are seen to be comparable, and a reasonable assumption is that the FRSs were not altered by testing. After the completion of all testing, the ends of the test piece were examined under a microscope. No arc damage was seen on the thermocouples or the coaxial conductor. Also, no discoloration of the BN surface was apparent. This leads to the conclusion that the only difference between observed breakdown voltage in the air tests and the helium tests is the dielectric strength of the gases in the gap. Examination of the data indicates that

Fig. 15. Damage check, FRS GNR-L-12P, air breakdown voltage data — series II tests.

the air data are ~ 7.5 times higher than the helium data for rod 10P and 6.5 times higher for rod 12P. This ratio is in agreement with the dielectric ratio of air to helium, which is ~ 7 .

Although the operation of the FRS terminals in helium at the CFTL pressures and voltages would not be expected to result in arcing based on our tests, the margin of safety would be very small compared with design practices for electrical systems. For example, the National Electric Safety Code, ANSI-C2 (1977), specifies capability for 350-V ceramic insulators to sustain a minimum potential of about 2200 V before dry flash-over. Manufacturers of other types of electrical equipment usually design for a standard potential test at twice rated voltage plus 1000 V applied for 1 min. Arcing occurred at the FRS terminals in low-pressure helium at 200 to 320 V, which is far below normal margins of safety.

CONCLUSIONS

The main conclusions derived from the results of these tests are as follows.

1. Helium is not recommended for blanketing the electric terminals of the FRSs because of its lower breakdown voltage characteristic compared with air.

2. The resistance of BN drops markedly with moisture content. This can be seen when the data from a preheated run are compared with those from a nonpreheated run (Table 2).

3. The CFTL FRSs should be heated gradually during loop start-up by gradual voltage application to slowly drive moisture from the BN and thus reduce the probability of arcing within the electrical insulation.

4. The low breakdown potential of helium was confirmed by the general agreement of the data from three completely different experiments, that is, the original screening, series I, and series II tests.

5. The series II experiments, which were most closely controlled, demonstrate that breakdown voltage for helium at standard temperature and pressure is one-sixth to one-eighth that of air and, at 350°C and atmospheric pressure, is one-fifth to one-sixth that of air.

6. If the evolution of test bundle design requires reconsideration of using helium in the region of the FRS terminals, then further testing at higher pressures is necessary to define the minimum pressure level that would provide the required margin of safety against voltage breakdown.

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