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Investigations of Techniques for Reducing Breakdown Voltage in Lightning Arrestor Connectors

Ralston W. Barnard

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INVESTIGATIONS OF TECHNIQUES FOR REDUCING BREAKDOWN VOLTAGE IN LIGHTNING ARRESTOR CONNECTORS

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ABSTRACT

The success of the MC2796 and MC2797 lightning arrestor connectors (LACs) in providing lightning protection for several weapon systems has resulted in requests for other LACs with other protection capabilities. Among these has been the request for lower breakdown voltage. This paper describes some of the initial work on techniques for achieving this goal. Techniques investigated included modifications to the electrode geometry, the use of rare gas at reduced pressures surrounding the electrodes, and radioactive ionization of the gas. Tests with LACs included controlled electrical breakdown with slow-rising and fast-rising waveforms. From tests at SLA and General Electric Company, an optimum configuration was chosen. The final configuration, which achieved 30 to 50% lower average breakdown than original LACs, used a modified web and argon gas. This design was implemented in the MC3114 low breakdown voltage LAC.

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I. INTRODUCTION

The lightning arrestor connector (LAC) was developed several years ago to reduce the vulnerability of nuclear warheads to lightning strikes. The probability of a lightning strike introducing damaging energy into a warhead through a cable is significantly reduced by the presence of the LAC, which shunts energy to ground (or to the warhead external shell).

The principle of the LAC protection is dielectric stimulated arc breakdown,[1] in which voltages above a breakdown threshold cause an arc to form between the cable conductors (the LAC pins) and the ground plane (the LAC web). Lightning energy is then dissipated in the arc, rather than in components downstream from the LAC.

The original LACs (MC2796 and MC2797) had breakdown voltages of not more than 2000 V when exposed to a fast-rising, lightning-like pulse. Some applications such as the W79, however, required a guaranteed breakdown voltage of about 1200 V.

This report discusses the investigations which led to the design of a low-voltage LAC whose design goals included the above guaranteed breakdown voltage.

The design features of the LAC have been discussed elsewhere.[1,2] Figure 1 shows an illustration of a LAC, indicating the pin and web electrodes, the dielectric sleeve, and the breakdown chamber.

II. THEORETICAL BASIS

Development of the low breakdown-voltage configuration for the LAC involved four aspects. Investigations included the electrode gap spacing, electrode configuration, gas type and pressure in the breakdown chamber, and stimulative environments such as are caused by radioactive emissions.

Electrode Gap and Breakdown Chamber Gas

The Paschen curve describes a relationship between breakdown-starting voltage and the product of gas pressure and electrode gap for flat-plate electrodes in various

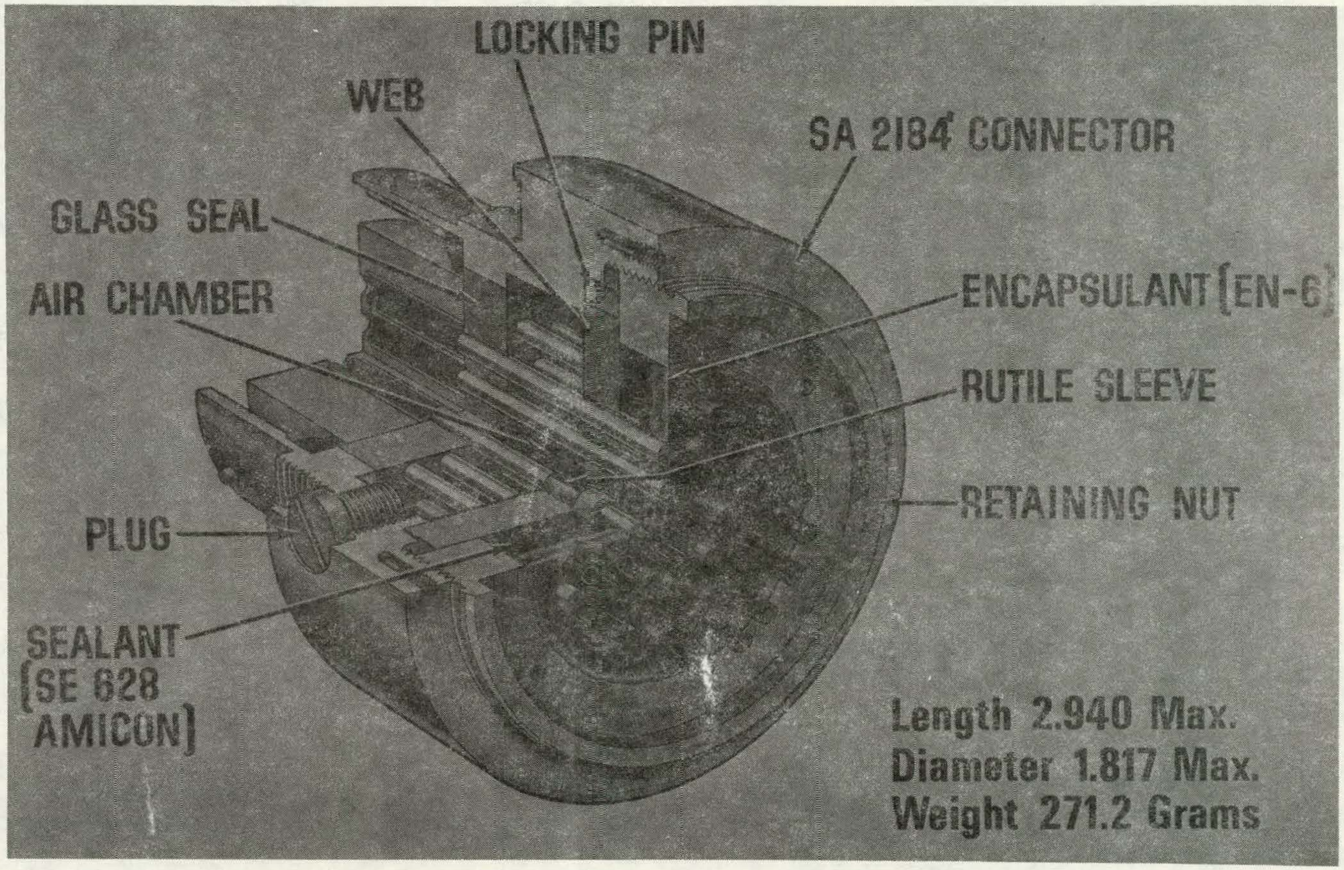


Figure 1. MC2797 Lightning Arrestor Connector

types of gas. Figure 2 shows examples of Paschen curves for various gases. The LAC is operating on the "high pressure" side of the Paschen curve, so a decrease in pressure causes a decrease in breakdown voltage. Although the exact value of pressure and gap spacing (pd value) for the desired LAC breakdown voltage cannot be read directly from the graph, it can be seen that a 25-50 percent decrease from the air curve can be obtained by reducing the pd value and by changing to a different gas, such as argon or neon.

The pin-web gap spacing on present LACs is 0.25 mm. A reduction of the gap is possible, but the amount of reduction must be balanced with increased difficulty in preventing pin-web shorts in the assembled connectors. For a given gap spacing, the gas type and pressure will influence the final breakdown value. Design goals were to use a gas (probably different from air) at approximately atmospheric pressure, in order to simplify manufacture of the L-V LAC and maximize reliability.

Electrode Configuration

Given the restraint of 0.25 mm rutile sleeve wall thickness, a narrower pin-web spacing can be achieved by shaping the web at one edge and allowing the sleeve to rest against it. This is illustrated in Figure 3. Webs were constructed with a lip, which resulted in holes at one end of the web being smaller in diameter than the 2.3 mm holes which contained the rutile sleeves. Various sized lips were used. The size which gave the best tradeoff between reduced electrode gap and ease of assembly (pin-web shorts were frequent with holes which were too small) was about 2.1 mm.

Various shapes of the lip were investigated by means of the computer code FFEARS,[3] which computed fields and potentials for various electrode shapes. Some plots are shown in Figures 4 through 6.

The FFEARS calculations showed that considerable field concentration was achieved with the pointed lips on the ends of the web. Configurations were tried with tips cut inward toward the sleeves and outward away from the sleeves. Figures 5 and 6 illustrate these geometries. Various sizes of air gaps between the rutile sleeve and metal electrodes were tried. Both fields and gradients were plotted. Field compression was higher along the front surface of the rutile sleeve near the web with configuration of Figure 5 than with the configurations of Figure 4 or Figure 6. Consequently, the configuration of Figure 5 was chosen as the design to be used in experiments.

A comparison between the standard configuration (Figure 4) and the low-voltage configuration (Figure 5) shows the latter to have considerably more field stress around the electrodes and the rutile sleeve.

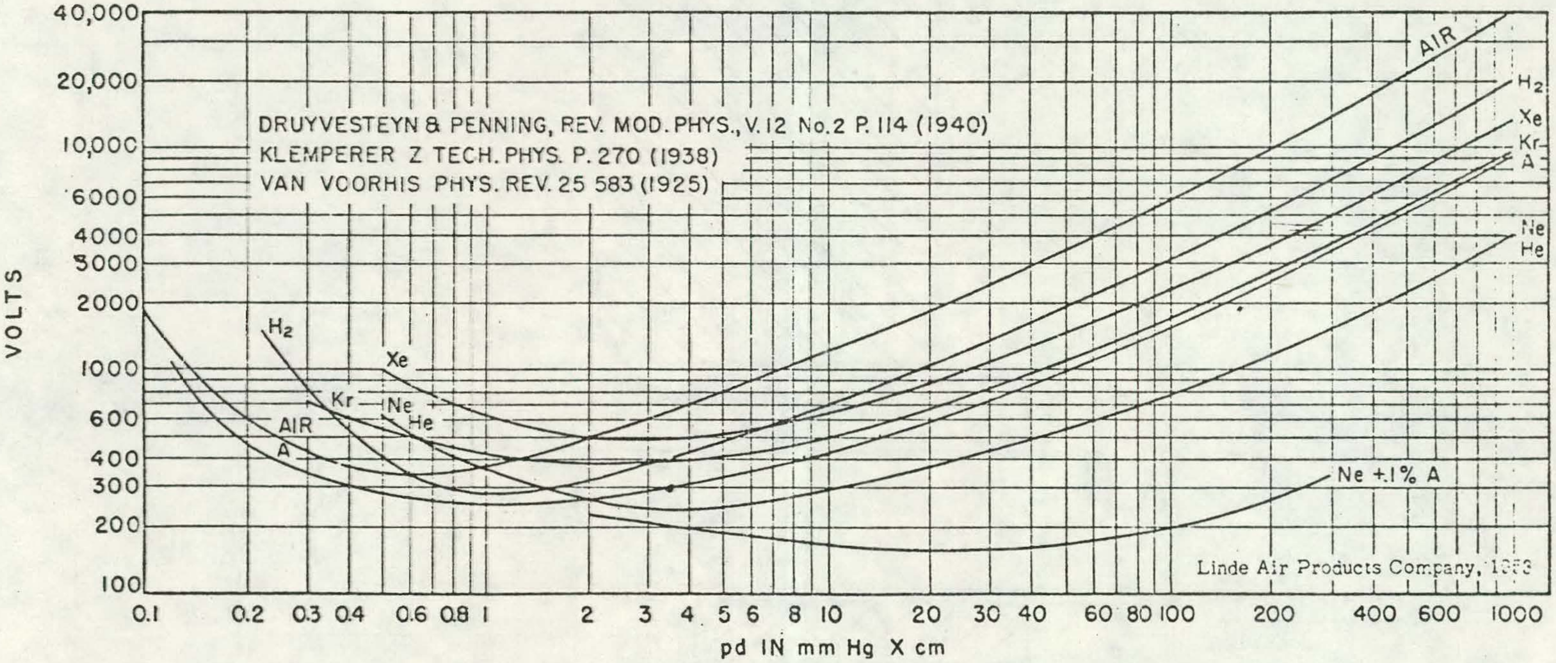


Figure 2. Arc starting voltages vs pressure x gap space (pd) for various gases (the Paschen Curve).

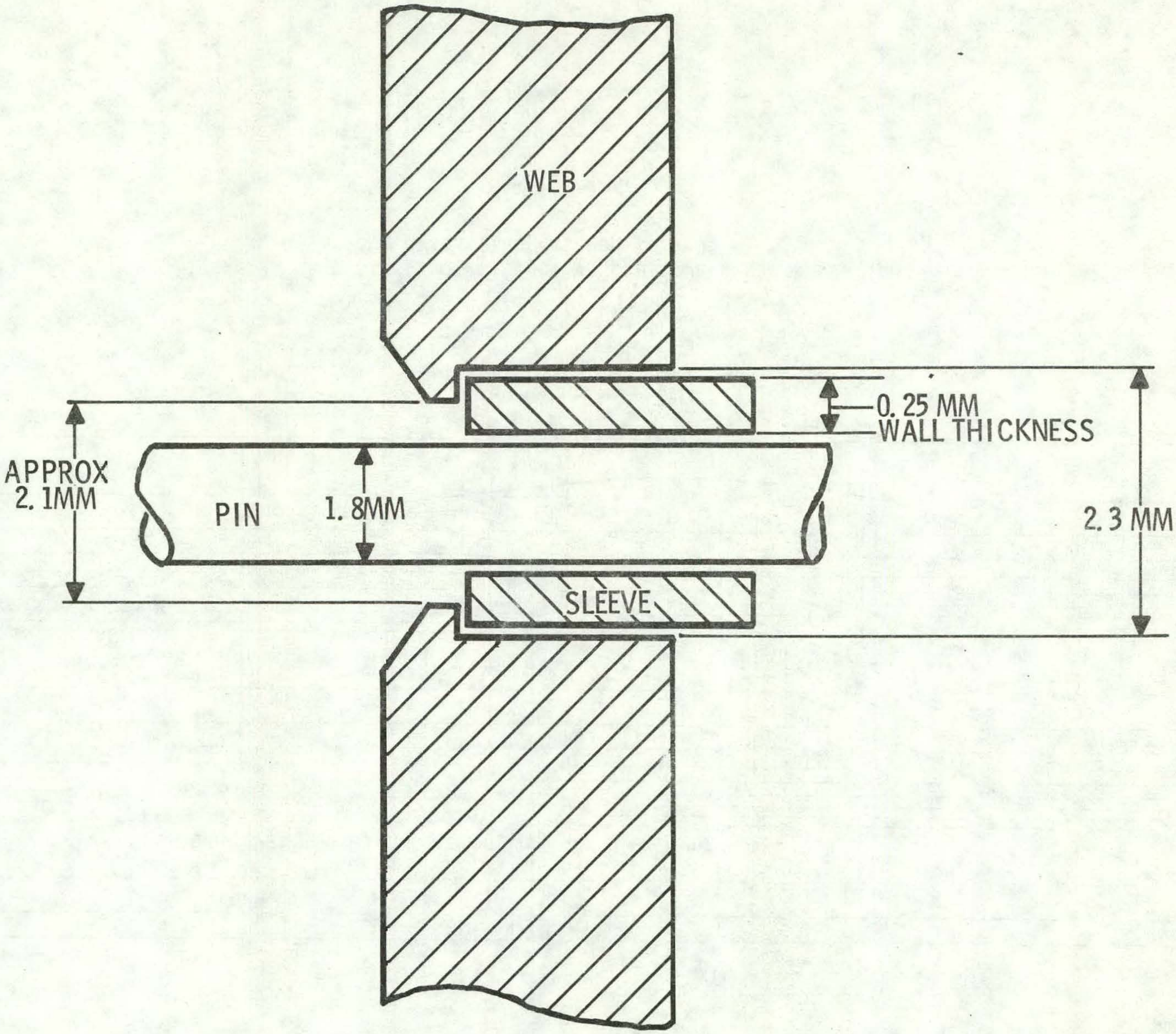


Figure 3. Schematic of modified pin-web geometry.

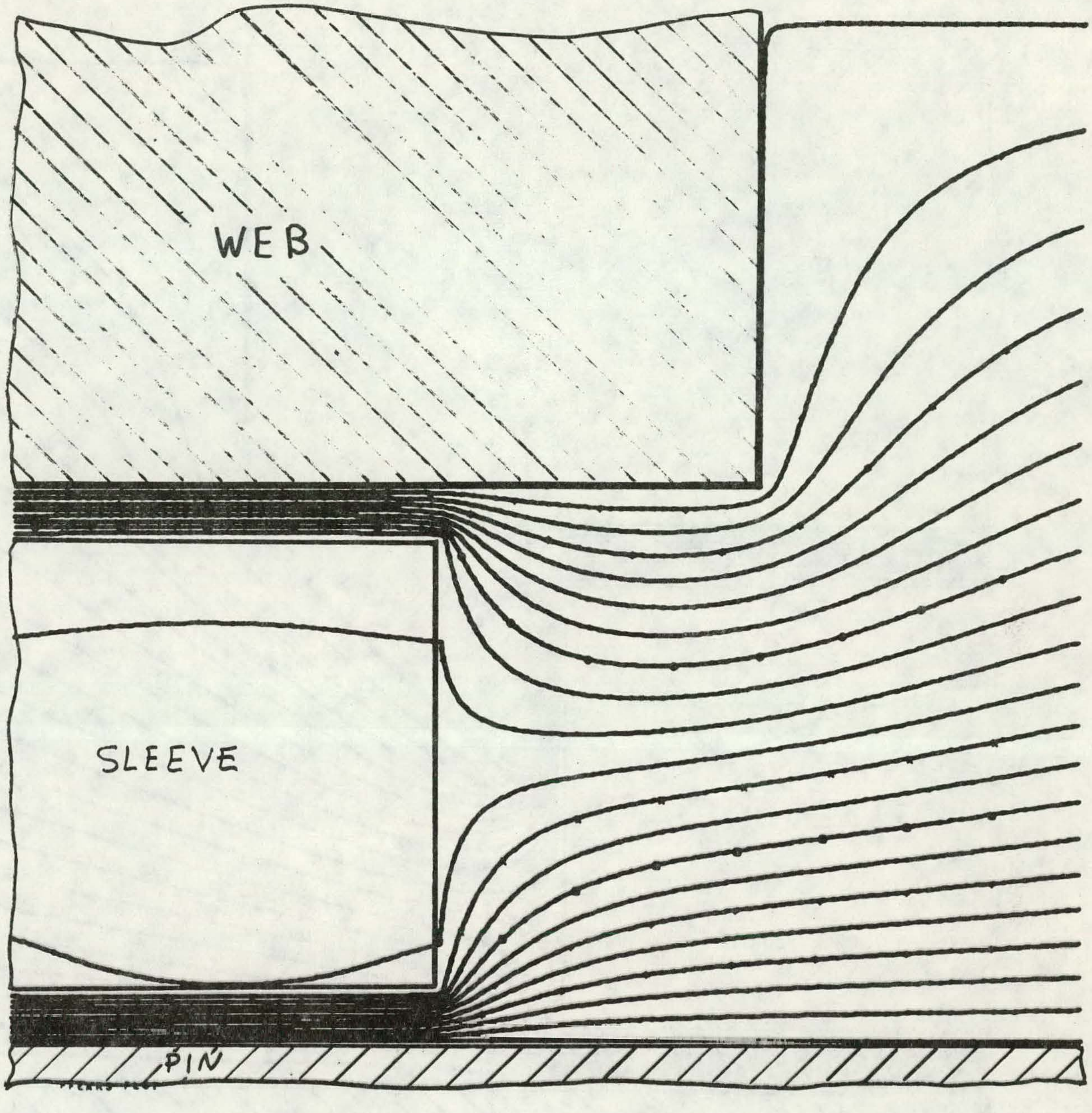


Figure 4. Equipotential plot - standard LAC pin-web configuration.

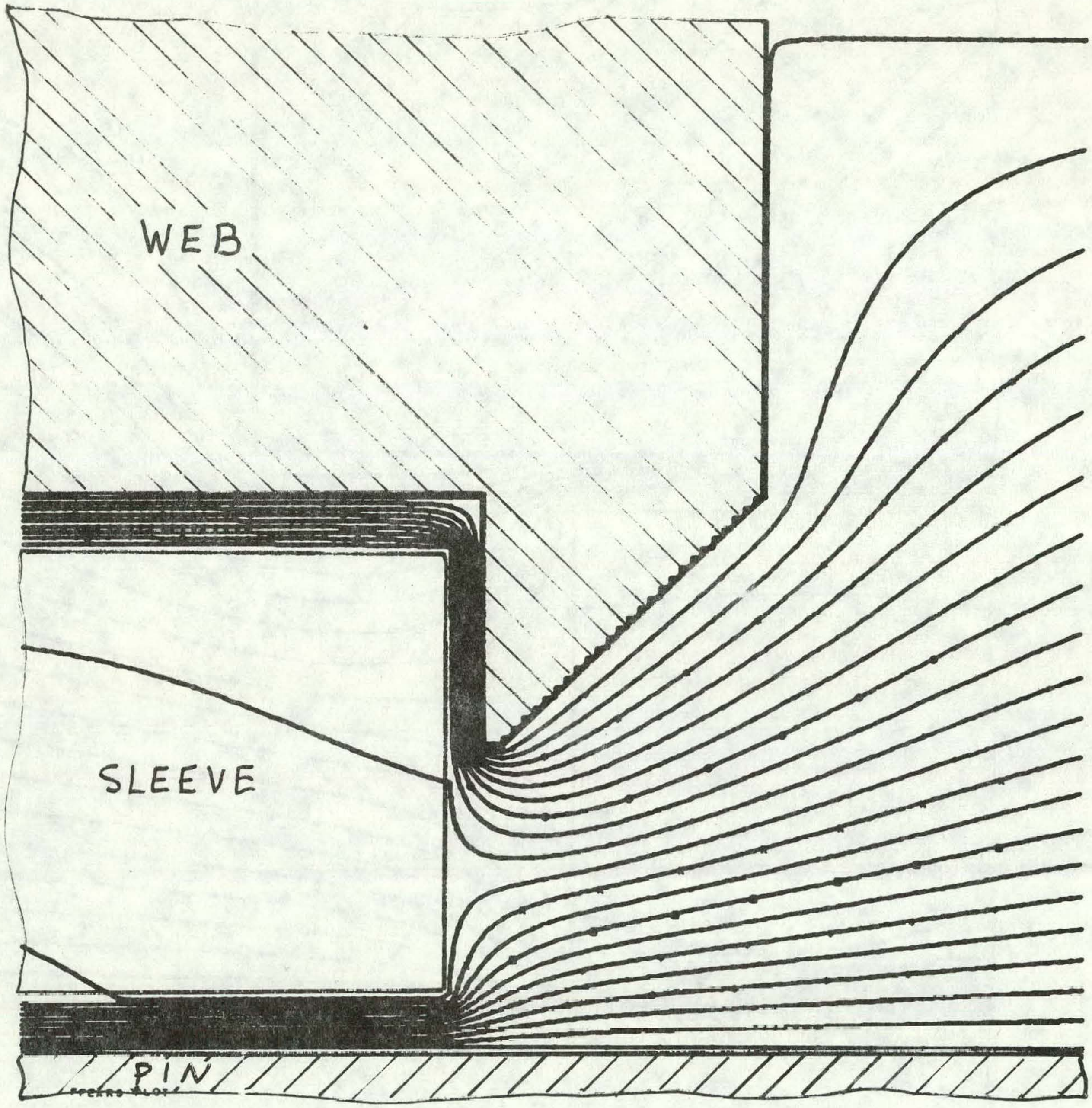


Figure 5. Equipotential plot - modified web with tips cut inward.

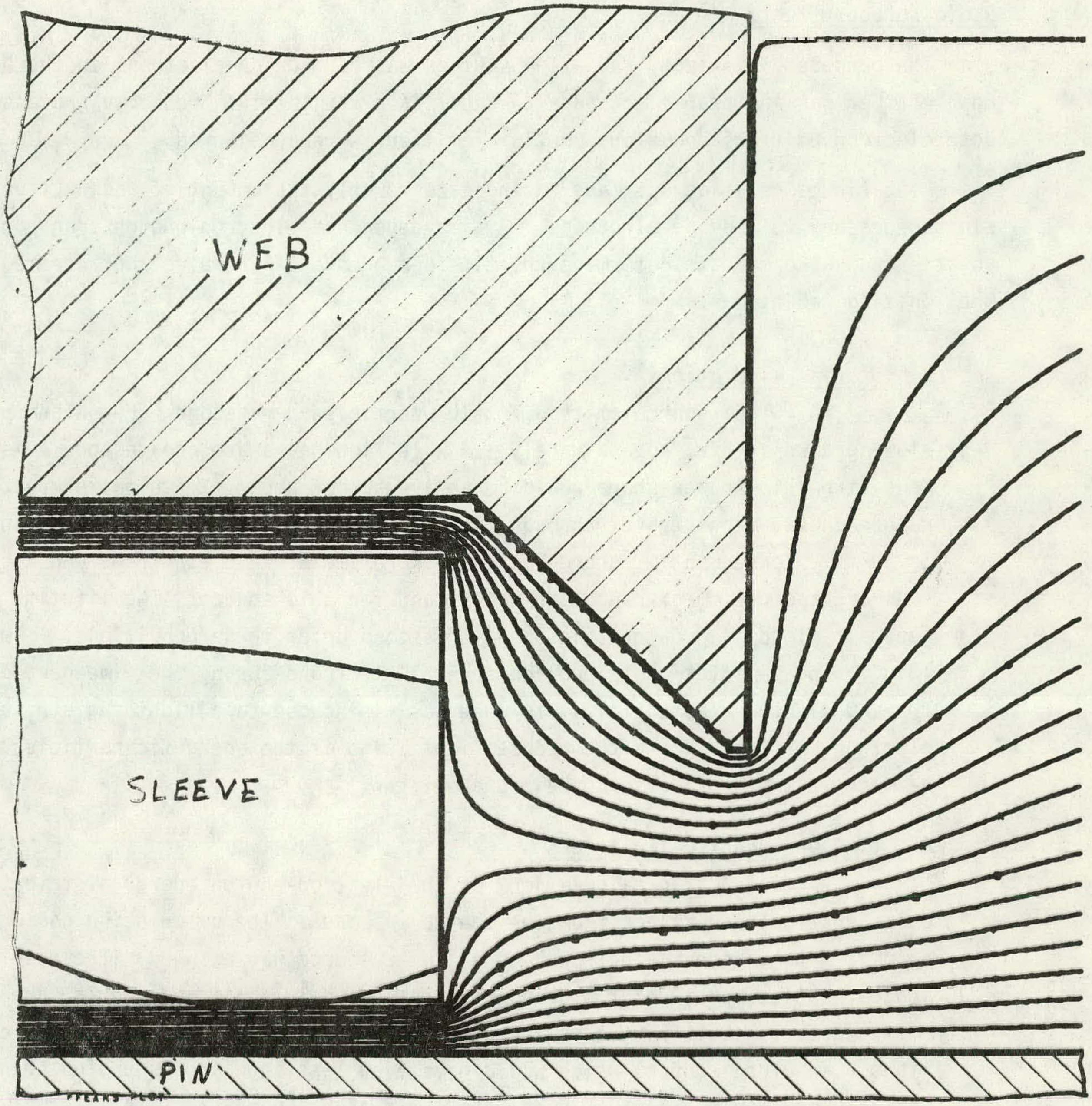


Figure 6. Equipotential plot - modified web with tips cut outward.

Radioisotope Effects

The purpose of ionizing radiation sources was to provide electrons in the breakdown chamber gas and near electrodes to facilitate the initial breakdown process. Both electron emitters and alpha particle emitters were considered.

A static calculation was made to indicate roughly the amount of radioactive emissions necessary to provide electrons. A time-dependent electron-photon transport calculation was also made to determine the time dependence of the electrons created by the ionizing radiations.

A. Static Calculations

A 10 μCi source emits 3.7×10^5 particles per second. For alpha particles slowing down in air, approximately 1.4×10^5 ion pairs are created per emission.[4] Thus, for this source there would be an average of about 52 ion pairs created per nanosecond of alpha travel through the air. The range of 3.5 MeV alphas in air is 20 mm. Consequently, there would be approximately 2.6 electrons and 2.6 positive ions created per mm of range per nanosecond for this source. The lifetime of the ion pair cloud is greater than one microsecond under these conditions.[4] Thus, a 10 μCi alpha emitter would provide several electrons during the time period when the LAC electrode potential difference was rising due to a lightning strike. An electron emitter, due to the reduced ionization of the energetic particles, would be much less effective than the alpha emitter.

B. Time-Dependent Calculations

A Monte Carlo calculation[5] of the electron-photon energy distributions as a function of distance from the source was made. The calculation could only be made with incident electrons, so a ^{63}Ni-β source was assumed. The results indicated that for a point source of radiation, only a limited angular area was affected by the beta particles throughout the time period followed in the calculations. An alpha source, which would have even less angular dispersion than a beta source, would affect an even more limited area over the time interval.

A ring source around the circumference of the LAC pins would provide a uniform radiation flux. An alpha source of 25 μCi/cm^2 would provide 120 μCi of alpha particles from a circumferential strip of 0.76 x 6.28 cm. Such a source would provide an electron flux sufficient to ionize the gas around the LAC pins. The continuous ionization of the gas might affect the insulation resistance capabilities of some of the pins, however.

III. EXPERIMENTAL STUDIES

The test program for development of low-voltage LACs consisted of the following:

1. Tests of modified MC2797 (32 pin) connectors on the PT-1471 "DC" breakdown tester at SLA.
2. Radioisotope and gas tests on the PT-3042 fast-rise tester at GEND.
3. Tests using modified webs in SA2183 (18 pin) connectors using the PT-3123 fast-rise tester at SLA.
4. Complete "design qualification" tests with modified webs and various types and pressures of gases using the PT-3123 tester at GEND.

DC Breakdown

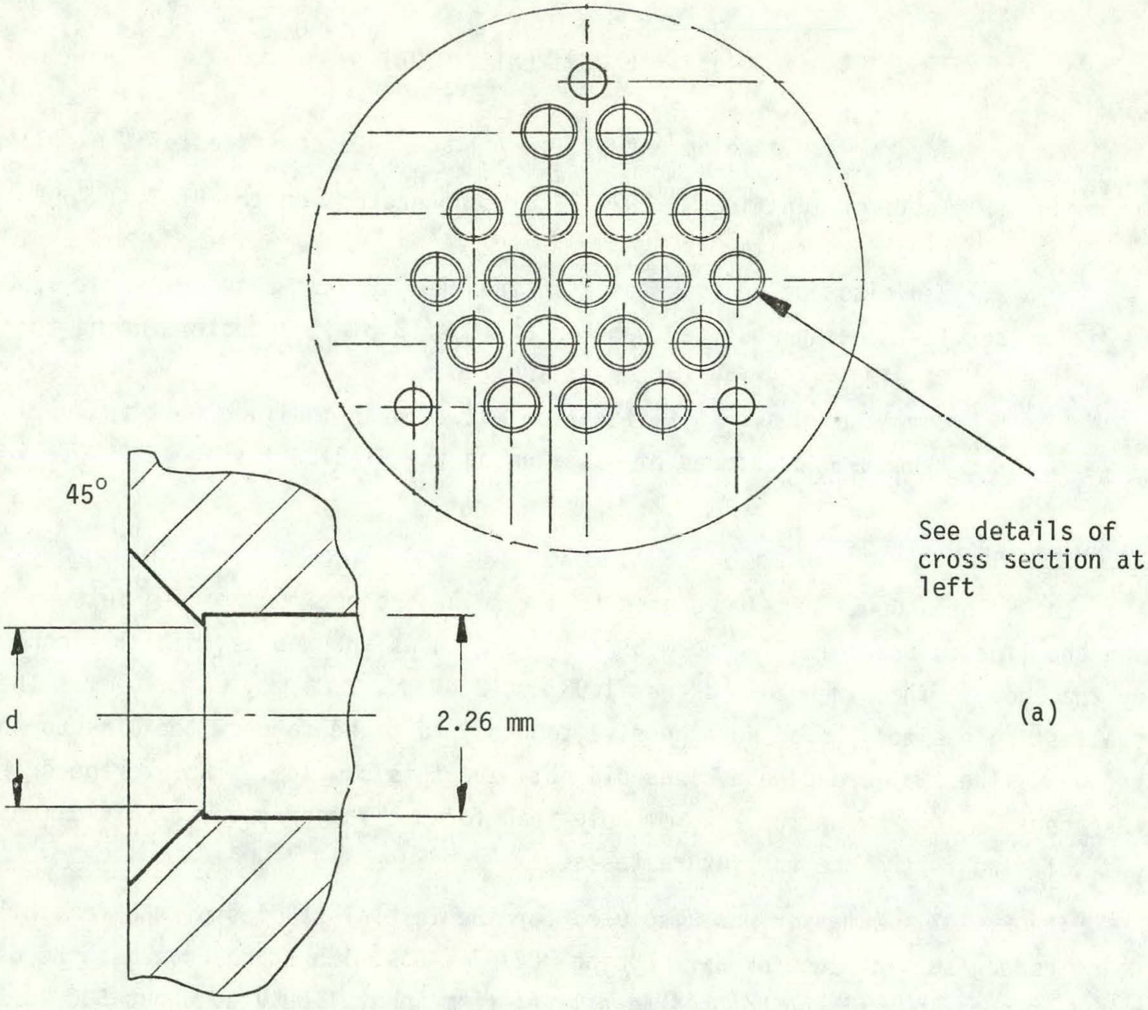
The dc breakdown tests were used to determine the optimum spacing between the pins and the lips on the holes in the web. Figure 7 shows the web as initially constructed by the shops. The dimension "d" was 1.93 mm, 2.01 mm, 2.08 mm, or 2.16 mm. The two smallest hole sizes showed an excessive tendency to cause some of the pins to short to the web. The two larger hole sizes did not have this problem. The average dc breakdown was about 5% lower with the 2.08 mm hole than for the larger one, so this dimension was selected as the one for future tests.

The PT-1471 dc tester was also used for the initial studies of the feasibility of using rare gases in place of air. Using MC2797 LAC's with standard webs, the use of argon or neon lowered the dc breakdown level from about 1100 V to about 500 V.

Radioisotope and Gas Tests

In February 1975, several modified MC2797s were tested at General Electric Company, Neutron Devices Department, St. Petersburg, Florida (GEND), using the PT-3042 fast-rise tester. The LAC modifications consisted of having GEND build two of the connectors with one of the side plugs fitted with a 10 μCi ^{241}Am source. The emitted alpha particles had an energy of 4.7 MeV. In place of the other side plug, a pinch-off tube was attached. These LACs were then backfilled with neon or argon. Two other LACs were fitted with two each radioactive side plugs; one had 10 μCi ^{241}Am sources with alpha energy of 3.5 MeV. The other had 100 μCi ^{63}Ni, with beta energy of 670 keV. An additional group of connectors had no radioactivity but were filled with argon or neon to 101 and 84 kPa. Table 1 shows the results of the tests.

It can be seen that the use of rare gases reduced the average breakdown voltage by 20-30% from the standard configuration (101 kPa air). Reducing the gas pressure to 84 kPa reduced the breakdown voltage levels by about 10% from the 101 kPa levels.



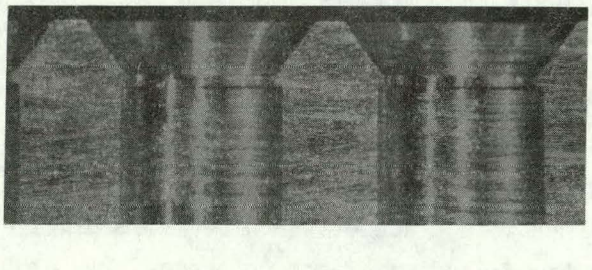


Figure 7

(a) Schematic of modified web.

(b) Cross section of actual web.

Table 1. Results of Radioisotope and Gas Tests

Connector Configuration		Avg. Breakdown (V)	Std. Dev. (V)	V_{Max}	Δ%*
101 kPa air	2 - 3.5 MeV α plugs	1187	92	1565	-
101 kPa air	2 - 4.7 MeV α plugs	1221	93	1535	+3
101 kPa air	2 - .67 MeV β plugs	1218	138	1650	+3
101 kPa air	1 - 4.7 MeV α plug	1173	102	1603	-1
101 kPa Ar	1 - 4.7 MeV α plug	783	172	1301	-34
101 kPa Ne	1 - 4.7 MeV α plug	923	181	1554	-22
101 kPa air	No radioactivity	1195	121	1828	-
101 kPa Ar	No radioactivity	941	172	1477	-21
101 kPa Ne	No radioactivity	908	141	1545	-24
84 kPa Ar	No radioactivity	809	169	1466	-32
84 kPa Ne	No radioactivity	855	93	1128	-28

*This is the percent reduction in average breakdown from the standard configurations (101 kPa air).

The radioisotopes did not have as dramatic an effect. There were conflicting indications of the effect of the radioactivity for the Ar and Ne results. For neon, the difference in means was within the measurement uncertainty of the tester (±7%), so the radioactivity could be considered to have no effect. For argon, the difference was greater than the measurement uncertainty and was statistically significant. The failure of these radioactive sources to significantly aid the breakdown process (either by reducing the average breakdown value or the spread of values), combined with the potential reduction in insulation resistance of the connector due to the ionized gas in the LAC chamber, suggested that methods other than radioisotopes be pursued for achieving lower voltage breakdown.

Modified Web Tests

The tests of modified webs consisted of an extensive series of fast-rise time breakdown tests using the PT-3123 tester at SLA. Ten SA2183 (18-pin) connectors were used with 30 webs fabricated with the reduced-diameter lips. The webs had 2.08 mm reduced diameter holes and were made in the SLA machine shop. Of the 300 combinations of webs and connectors, 125 configurations were used such that no connector-web combination was tested more than once. The fast-rise breakdown test was performed on each connector-web combination, and the breakdown voltages for each pin were recorded. Rutile sleeve insulators were used for all tests; approximately 400 sleeves were available for use, and the ones assembled into connectors were randomly selected from the available supply. Because the connectors were not sealed, the breakdown chamber was assumed to contain 84 kPa dry air. Normal cleanliness was maintained, but no special cleaning procedures were followed prior to the tests.

Breakdown values for the approximately 2250 pins tested were pooled to yield an average breakdown value of 870 V.[6] The maximum observed voltage was 1268 V. The 870 V average compares with a value of 1065 V for LACs with standard components tested in Albuquerque air. The distribution of values was sufficiently normal that a projection of 1200 V for the +3σ (99.6%) level was made. Since the term "guaranteed" breakdown was interpreted as one failure in 10^6, further refinements of the configuration were required to meet this criterion.

<u>GEND Web-Gas Tests</u>

For this phase, tests were performed at GEND, under the supervision of I. L. Levine, using connectors with modified webs and various gases at different pressures. The gases used were air, argon, neon, and 0.1% Ar-Ne mixture. The latter is called a "Penning Mixture," and has low-breakdown values over a wide range of pressures (see Figure 1).

Five gas pressures were used: 13.3 kPa, 26.7 kPa, 66.7 kPa, 101 kPa, and 133 kPa. Twenty SA2183 LACs were built by GEND with modified webs and with one side plug equipped with a pinch-off tubulation. An additional eight LACs were built with standard webs to serve as controls. Table 2 shows the fill and test matrices. Each test LAC was filled with a gas to a specified pressure using a gas-handling and evacuation station. The LACs were then tested five times each in a rotating sequence (to eliminate any tester effects). The test LACs were then refilled to a different pressure with the same gases for a subsequent test series similar to the first. Control LACs were filled only once. The test sequence consisted of fast-rise time breakdown, insulation resistance, and dc breakdown tests.

Data were combined for the five tests for each of the two fills to give populations of 180 data points. The means, $\pm 1\sigma$, and $+3\sigma$, points were determined. The skewness of the distributions at each pressure as a function of different functional dependences was evaluated. Generally, the log-normal distribution was the least skewed. The upper one-sided tolerance limits (99.9% of the sample with 95% confidence) were determined from the log-normal distribution and converted back to linear. Results are shown in Figures 8 through 11.

The mean values for breakdown in air increased with increasing pressure, from about 800 V at 13 kPa to 1150 V at 133 kPa (see Figure 8). The maximum observed values were generally well above the 3σ limits, which indicated a divergence from normality. The means increased steeply from 67 kPa to 133 kPa, suggesting relatively large changes in breakdown voltage with change in pressure.

Table 2

Test Matrix for Low-Voltage LAC Gas Tests

Gas	Fill	Pressure (kPa) 13	27	67	101	133	Test Sequence					
AIR	1	A	B	C	D CO-1	E	CO-1 E D C B	A CO-1 E D C	B A CO-1 E D	C B A CO-1 E	D C B A CO-1	E D C B A
ARGON	1	F	G	H	J CO-3	K	CO-3 K J H G	F CO-3 K J H	G F CO-3 K J	H G F CO-3 K	J H G F CO-3	K J H G F
NEON	1	L	M	N	O CO-5	P	CO-5 P O N M	L CO-5 P O N	M L CO-5 P O	N M L CO-5 P	O N M L CO-5	P O N M L
ARGON NEON	1	R	S	T	U CO-7	W	CO-7 W U T S	R CO-7 W U T	S R CO-7 W U	T S R CO-7 W	U T S R CO-7	W U T S R
AIR	2	E	D CO-2	C	B	A	CO-2 E D C B	A CO-2 E D C	B A CO-2 E D	C B A CO-2 E	D C B A CO-2	E D C B A
ARGON	2	K	J CO-4	H	G	F	CO-4 K J H G	F CO-4 K J H	G F CO-4 K J	H G F CO-4 K	J H G F CO-4	K J H G F
NEON	2	P	O CO-6	N	M	L	CO-6 P O N M	L CO-6 P O N	M L CO-6 P O	N M L CO-6 P	O N M L CO-6	P O N M L
ARGON NEON	2	W	U CO-8	T	S	R	CO-8 W U T S	R CO-8 W U T	S R CO-8 W U	T S R CO-8 W	U T S R CO-8	W U T S R

Legend: A, B,...W are test LACs
CO-1...CO-8 are control LACs

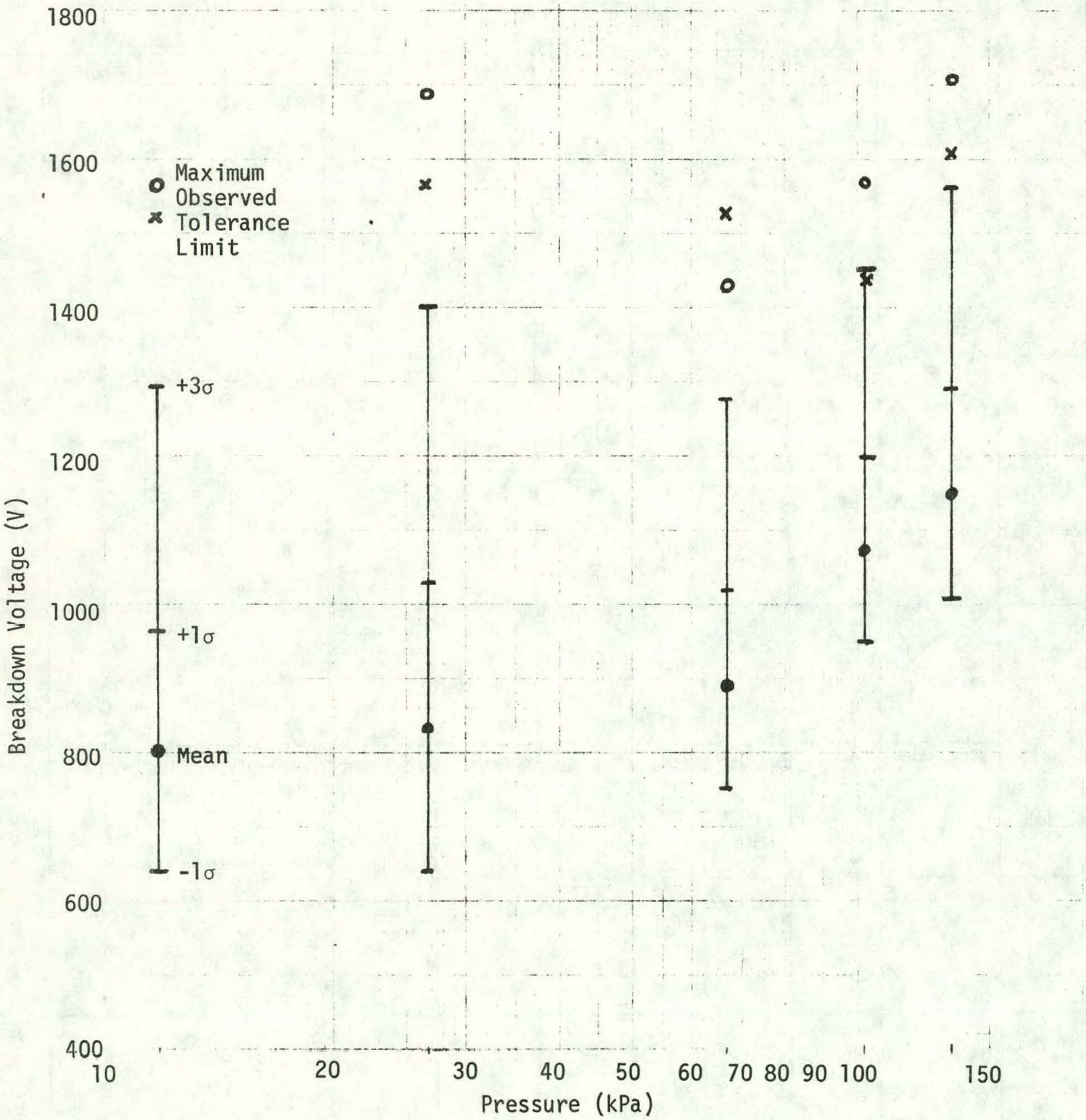


Figure 8. Breakdown voltage vs pressure for GEND gas tests - air-filled LACs.

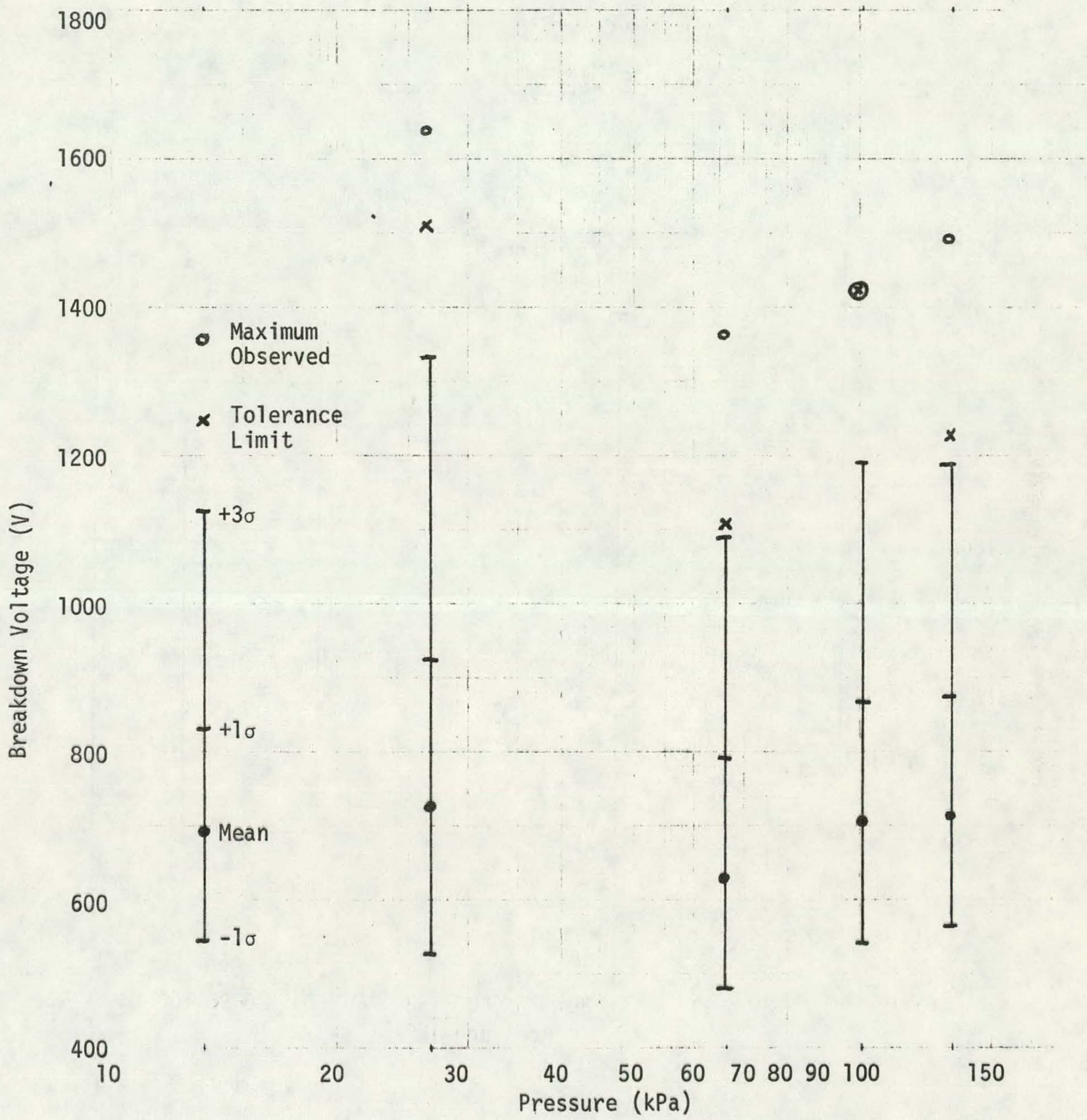


Figure 9. Breakdown voltage vs pressure for GEND gas tests - Argon-filled LACs.

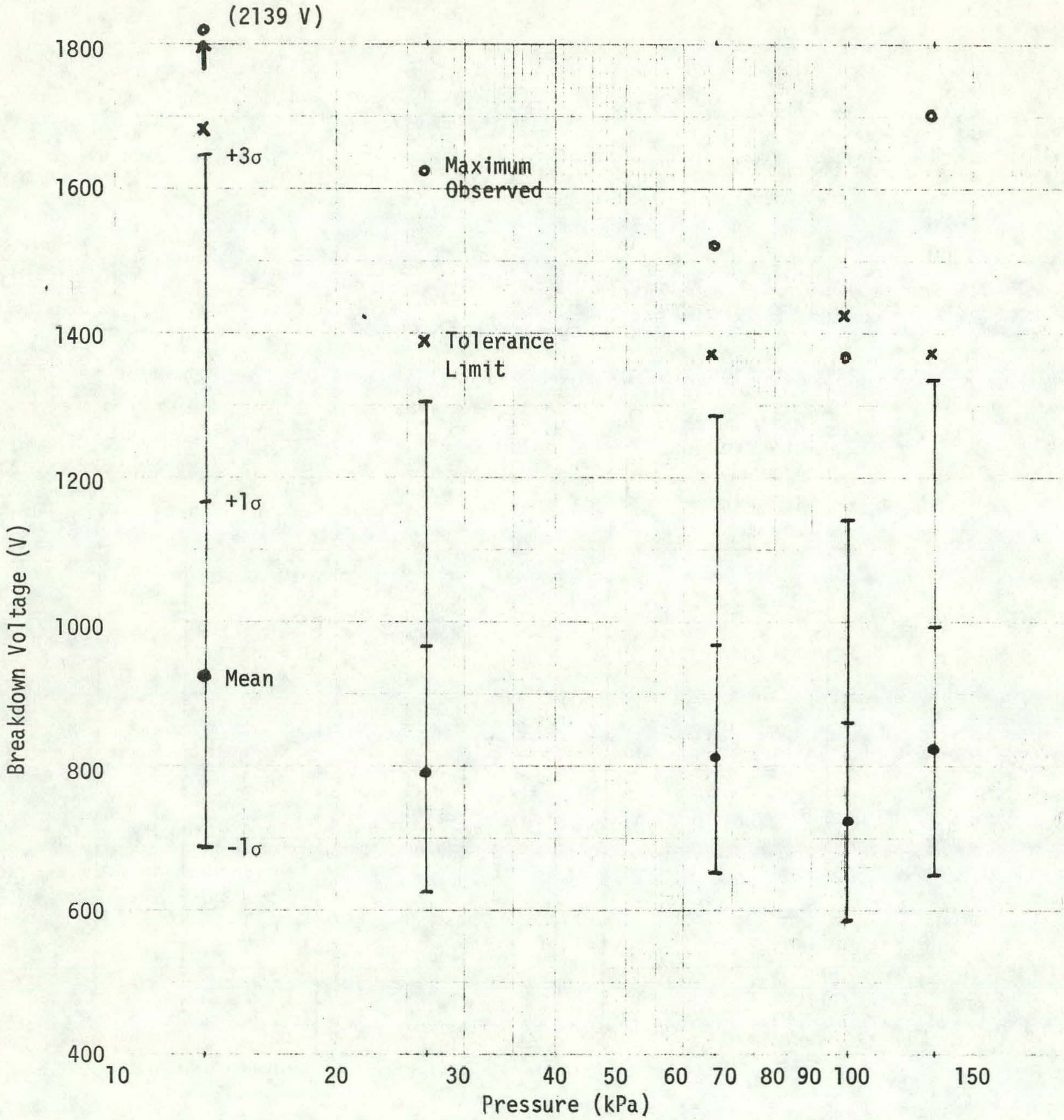


Figure 10. Breakdown voltage vs pressure for GEND gas tests - Neon-filled Lacs

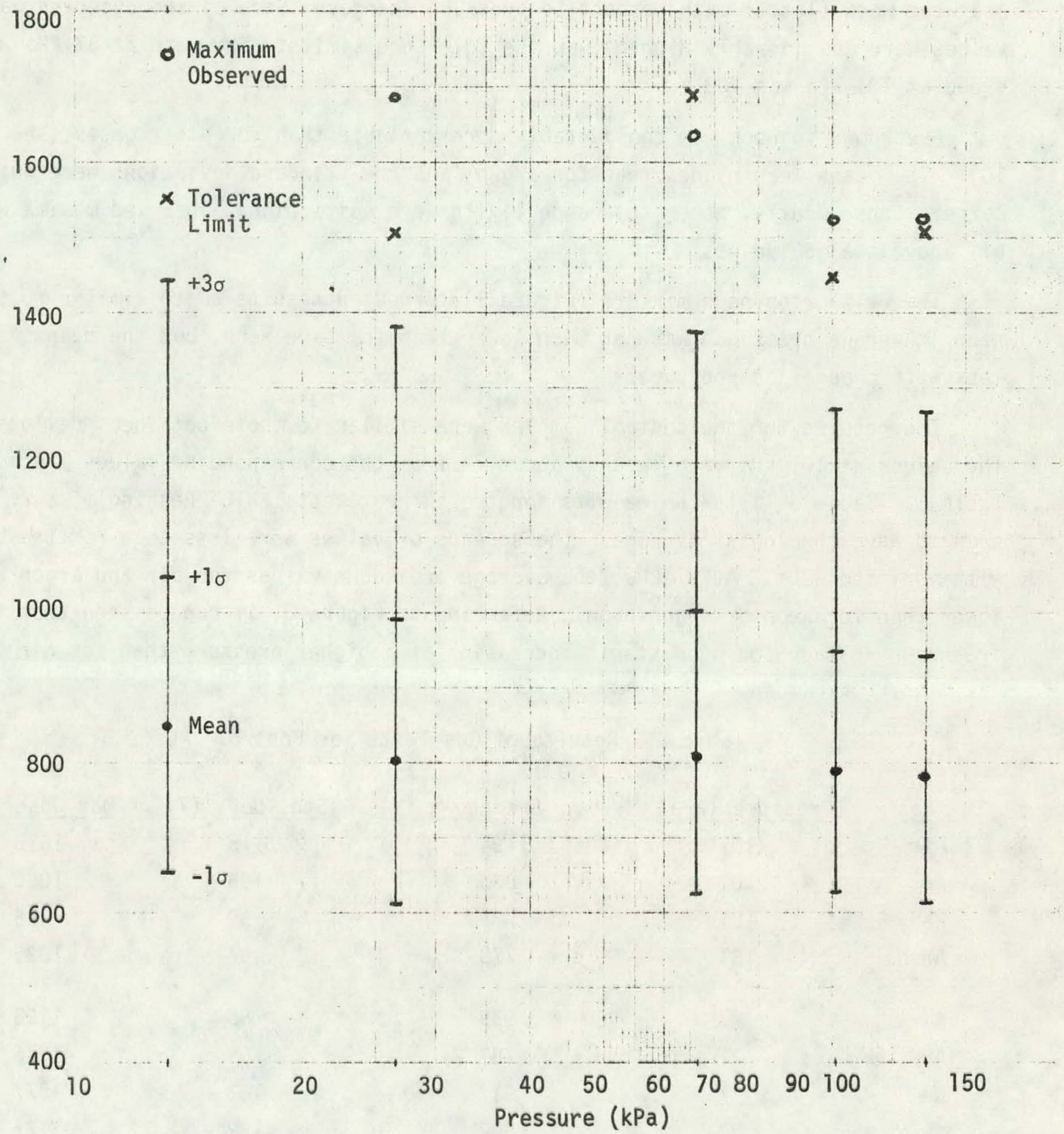


Figure 11. Breakdown voltage vs pressure for GEND gas tests - Argon-Neon-filled LACs.

The results for argon (Figure 9) showed that the means were lower than for air and were much flatter with respect to pressure changes. Some of the observed maximum values were considerably higher than the tolerance limits. The mean at 67 kPa was 633 V and at 101 kPa was 703 V.

Breakdown in neon was considerably more variable than for other gases (see Figure 10). The means were higher than for argon, and the standard deviations were quite large. Consequently, upper tolerance limits were quite high. Observed maxima were all above the $+3\sigma$ points.

The 0.1% argon-neon mixture (Figure 11) produced results quite similar to the pure neon. Average breakdown was not much lower than for pure neon, but the means varied less with changes in pressure.

The results for the control samples were similar to those obtained previously. The values at 101 kPa were less by about 7% from the corresponding values listed in Table 1. Table 3 lists the results for the current tests. The Penning mixture can be seen to have the lowest average. The spreads of values were less than for the LACs with modified webs. At 27 kPa, the average breakdown values for air and argon are lower than for neon or argon-neon. Referring to Figure 2, it can be seen that the breakdown voltage for neon starts increasing at a higher pressure than for air or argon.

Table 3. Results of Gas Tests for Control LACs

Gas	Pressure (kPa)	Avg. Breakdown (V)	Std. Dev. (V)	Max Observed
Air	101	1194	115	1613
Ar	101	823	105	1085
Ne	101	789	69	955
Ar-Ne	101	770	97	1025
Air	27	939	86	1185
Ar	27	787	109	1076
Ne	27	917	163	1377
Ar-Ne	27	832	152	1177

Table 4 summarizes the effects of all the parameter changes; since the test LACs did not perform the same as production LACs, the table also lists expected performance of production low-voltage LACs for various gas-pressure combinations based on these projections. These expected performance values were obtained by starting with the average breakdown values of production LACs (1200 V) and applying the reduction factors listed in the table.

Table 4 - Changes in Breakdown Voltage vs LAC Configuration Changes

Parameter Change*	Response
Modified web vs. normal web	18% reduction
101 kPa Ar vs. 101 kPa air	28% reduction
101 kPa Ne vs. 101 kPa air	24% reduction
84 kPa Ar vs. 101 kPa Ar	24% reduction
84 kPa Ne vs. 101 kPa Ne	20% reduction
67 kPa Ar vs. 101 kPa Ar	12% reduction
84 kPa air vs. 101 kPa air	11% reduction
84 kPa Ar vs. 101 kPa Ar	6% reduction
84 kPa Ne vs. 101 kPa Ne	7% reduction

*All parameters not specified were held at "standard" values; i.e., 101 kPa air, or standard web.

Configuration	Projected Breakdown (V)	
	Average	Avg. +3σ
101 kPa air, modified web	980	1300
101 kPa Ar, modified web	730	1050
84 kPa air, modified web	870	1200
84 kPa Ar, modified web	700	1100
67 kPa Ar, modified web	650	1000

From these tests, it was projected that a low breakdown voltage LAC could be made using a modified web and a gas filling of argon at either 67 or 101 kPa. (The lower pressure would be used if the lowest breakdown voltage was desired, but the higher pressure represented an acceptable tradeoff to reduce manufacturing difficulties.) The requirement of a "guaranteed" breakdown voltage of 1200 V was not met in the tests; however, such a failure could probably be overcome by further refinements of web manufacturing and connector assembly techniques, as was illustrated by the control samples.

IV. DESIGN IMPLEMENTATION

The system for which a low breakdown voltage LAC was originally designed was the W79 8" AFAP. The initial uses were for a LAC for the W79 and a similar one for the associated Nonviolent Explosive Destruction System. The primary features which made this low-voltage LAC (the MC3114) different from previous LACs was the modified web and rare gas filling and the decision to make the breakdown chamber hermetically sealed. This was done because previous work[7] indicated a relatively rapid rate of permeation of moisture through the epoxy and polyurethane seal on the back of the connector (the seal is indicated in Figure 1). The initial design called for two glass-sealed connector halves to be joined together "back-to-back" by welding. An evacuation tube allowed argon to be introduced into the breakdown chamber, after which the tube could be pinched off to achieve a hermetic seal in the breakdown chamber. Subsequent W79 system requirements eliminated the need for the connectors on both ends, so an assembly with solder cups was substituted for one connector assembly. Figure 12 shows this design.

Electrical continuity between the pins in the back half of the connector and those in the front was achieved by compression springs. The springs also retained the rutile sleeves in the holes in the web. This is detailed in Figure 12.

An initial build of the connector halves was completed and practice assemblies were made. The quality of the connectors was not satisfactory, so meaningful electrical tests could not be made. However, the compression spring concept was shown to be feasible and to not cause too many manufacturing problems.

Subsequent to the author's leaving the project, this concept was abandoned in favor of a traditional connector with the epoxy-sealed solder cup but with the reduced-diameter web and argon gas at atmospheric pressure.

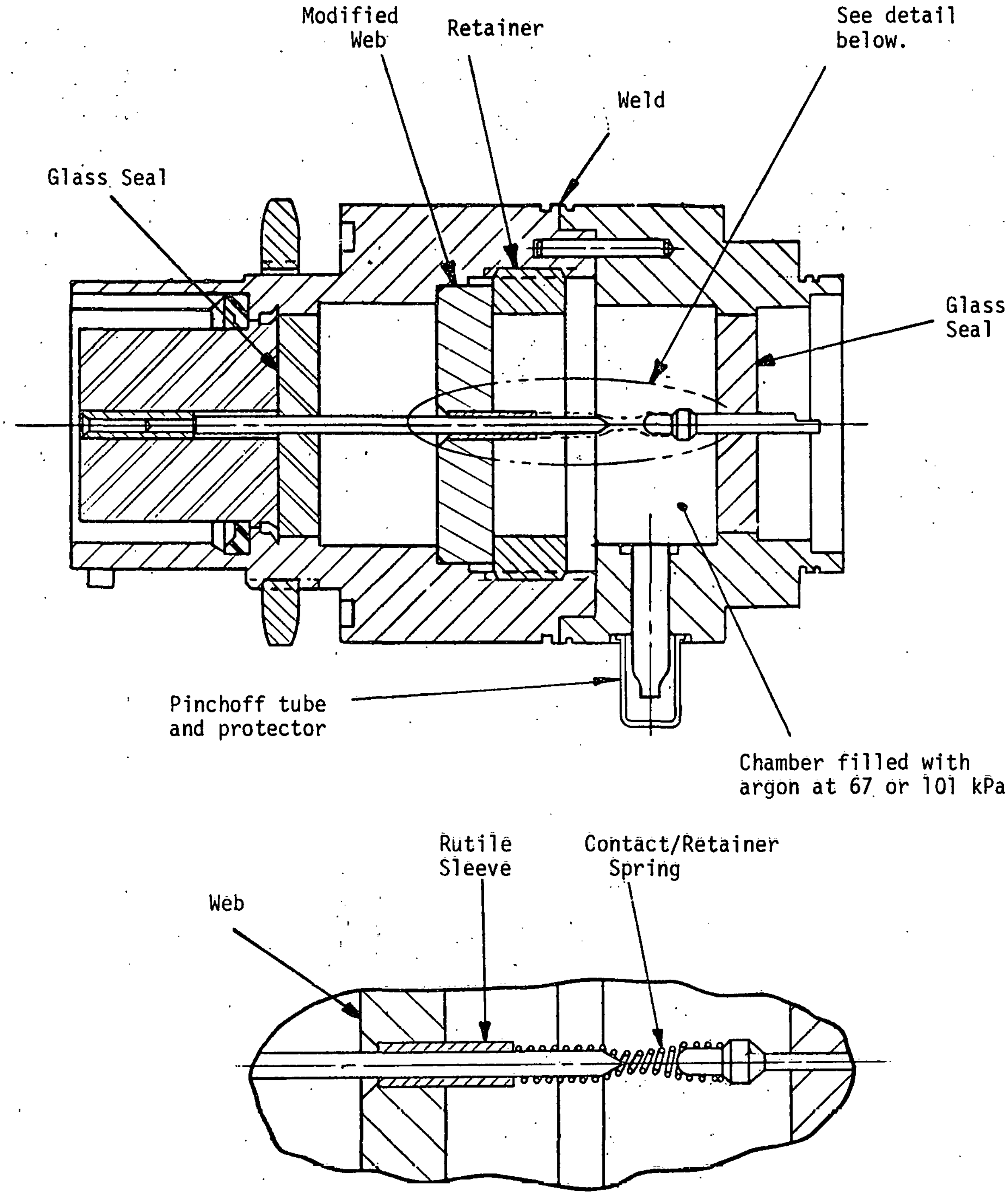


Figure 12. MC3114 Design Features

V. CONCLUSIONS

The exploratory development work on the low breakdown voltage LAC demonstrated that a reduction of 35-50% in the average breakdown value could be achieved by modifications to the electrode geometry and breakdown chamber atmosphere. The goal of a "guaranteed" (i.e., one failure in 10^6) breakdown of less than 1200 V was not achieved, primarily because of a large variation in breakdown voltages. As experience has been gained in the manufacture of the existing LACs (MC2796 and MC2797), the variations in breakdown values have decreased; similar improvement could be expected for a low breakdown voltage LAC.

The unexpectedly poorer performance of LACs filled with neon and neon-argon mixture is surprising in view of the predictions of the Paschen Curve. An explanation for this behavior is that the pin-web-sleeve combinations for the LAC were not optimized. Since this task must be done for the low-voltage LAC regardless of the gas in the breakdown chamber, the effects of the various gases should be reviewed again after the mechanical optimization is done.

ACKNOWLEDGMENT

P. J. Konnick and C. J. Chavez performed most of the breakdown tests done at Sandia Laboratories. They also aided in construction of test apparatus and data reduction. K. F. Moore, General Electric Company, St. Petersburg, Florida, performed most of the MC3114 assembly test.

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ERDA/TIC (25)
(R. P. Campbell, 3172-3)