PRODUCTION ENGINEERING MEASURE

HIGH VOLTAGE SILICON RECTIFIER STACKS

IR INTERNATIONAL RECTIFIER CORPORATION

EL SEGUNDO, CALIFORNIA

TELEPHONE: OREGON 8-6281

PRODUCTION ENGINEERING MEASURE

HIGH VOLTAGE SILICON RECTIFIER STACKS

OBJECTIVE

QUARTERLY PROGRESS REPORT NO. 7

PERIOD COVERED
DECEMBER 25, 1962 TO MARCH 25, 1963

CONTRACT NO.: DA-36-039-SC-85977
CONTRACT DATE: 24 JUNE, 1961
ORDER NO.: 6032-PP-61-81-81

PLACED BY:
U. S. ARMY SIGNAL SUPPLY AGENCY
225 SOUTH 18TH STREET
PHILADELPHIA 3, PENNSYLVANIA

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ABSTRACT

A substantial redesign was made for the sixth set of engineering samples. The redesign was made to eliminate the problems experienced with the insulating fluid at elevated temperatures and to obtain a wider temperature range of operation.

Preliminary tests showed the feasibility of the redesign and design tests on the first completed units showed the design to be successful.

The new design required a reduction in the number of silicon rectifier diodes per stack. This was achieved by going to 1200 volts peak reverse voltage diodes. The 30 KV stack now contains 28 diodes in series and the 40 KV stack has 37 diodes in series. The reduction in the number of diodes together with an increase in the diode shunt resistance facilitates also the thermal problems.

During the quarter the redesign was completed and material for the units procured. The sixth set of engineering samples was manufactured and successfully tested.

PURPOSE

The purpose of this contract is:

1. A Production Engineering Measure (PEM) in accordance with Step I of Signal Corps Industrial Preparedness Procurement Requirements (SCIPPR) No. 15, dated 1 October, 1958 for the following semiconductor devices:

   a. Diode, High Voltage Silicon Rectifier Stack, 30 KV, per Signal Corps Technical Requirement SCS-64 dated 28 September, 1959.

   b. Diode, High Voltage Silicon Rectifier Stack, 40 KV, per Signal Corps Technical Requirement SCS-65 dated 7 October, 1959.

2. Definition of Items la and lb.

3. Design of Items la and lb.

4. Manufacturing of samples according to the design per Item 3.

5. Establish conformance with the specifications by means of tests.

6. Establish a pilot line and perform a pilot run of Items la and lb to demonstrate the capability of said pilot line.

7. Making a study and providing a General Report in accordance with Step II of Signal Corps Industrial Preparedness Procurement Requirements (SCIPPR) No. 15, dated 1 October, 1958 for Items la and lb.

INTRODUCTION

At the beginning of this report, the remaining test results for the fifth set of engineering samples are presented. The remainder of the report is devoted to the sixth set of engineering samples.

During the quarter the redesign for the sixth set of samples was completed. A complete description of the physical structure of the new rectifier stack is part of this report.

The efforts directed to the investigation of insulation materials at elevated temperature were continued and included the solid as well as the liquid dielectric materials.

The results of these tests were incorporated in the design concept for the sixth set of samples. Design tests of these samples demonstrated the success of the new approach.

TIME TABLE OF THE SEVENTH QUARTER

Dec. 28, 1962:	An engineering meeting was held by the Contractor reviewing the latest test results and the status of design and material availability.
Dec. 31, 1962:	Five units of the fifth engineering samples were shipped.
Jan. 3, 1963:	The December Monthly Progress Report was sent to the Contracting Officer.
Jan. 11, 1963:	An engineering meeting was held by the Contractor reviewing the status of the design.
Jan. 23, 1963:	A meeting was held in Ft. Monmouth between T. Krueger and K. H. Fisher of USAELRDL and representatives of the Contractor at which various aspects of the test specifications were discussed.
Jan. 24, 1963:	Draft copies of the Sixth Quarter Report were sent to the Contracting Officer for approval.
Jan. 25, 1963:	The January Monthly Progress Report was sent to the Contracting Officer.
Jan. 31, 1963:	The last unit of the fifth set of engineering samples was shipped.
Febr. 4, 1963:	An engineering meeting was held by the Contractor at which the design and procurement status of the sixth set of engineering samples was reviewed.
Febr. 14, 1963:	A proposed schedule for the balance of the contract was submitted to the Contracting Officer.
Febr. 15, 1963:	A letter outlining the voltage safety factors in the design was sent to T. Krueger, USAELRDL.
Febr. 15, 1963:	A telephone conversation was held between the Contractor and T. Krueger, USAELRDL, about the test specification for the high voltage rectifier stacks.
Febr. 18, 1963:	An engineering meeting was held by the Contractor at which the progress in procurement and the results of design tests were reviewed and the schedule for the preproduction samples was discussed. A request for a supplement to our letter of February 14 was made by telephone by the Contracting Officer.
Febr. 21, 1963:	A supplement to the letter of February 14 was submitted to the Contracting Officer.

Febr. 25, 1963:	The approval of the Sixth Quarterly Report was received.
	A telephone conversation was held between T. Krueger, USAELRDL, and the Contractor about the specifications for subject contract.
Febr. 28, 1963:	The Contractor sent a letter to USAEMA requesting permission to run operating life test (current), operating life test (voltage), and storage life on four tanks each concurrently and submitted proposal test specification for the stacks and diodes.
March 4, 1963:	Received a letter from USAEMA dated February 26 about the extension of the contract delivery schedule.
March 11, 1963:	Received request from USAEMA about distribution of the Sixth Quarterly Report.
March 12, 1963:	The Sixth Quarterly Report was distributed and statement to this effect sent to USAEMA and Tom Krueger at USAELRDL.
March 1-27,1963:	During the month all procurement for the sixth set of engineering samples was completed and four units were built and tested. Design testing of the units was also started.
March 28, 1963:	The sixth set of engineering samples was shipped.

ENGINEERING SAMPLES, FIFTH SET

The last unit of the fifth set of engineering samples was shipped during the quarter.

The unit was tested to the specification given in the Sixth Quarterly Report, pp 46-52.

The test results for the module and column test are given on the next page.

ENGINEERING SAMPLES, FIFTH SET

TEST RESULTS

ITEM 1b   Test Date: January 28, 1963

PART NO. 67-7442-3

COLUMN NO.: 3

Module Test

MODULE NO.	FORWARD VOLTAGE @ 10A	REVERSE CURRENT AC	REVERSE CURRENT DC	MODULE NO.	FORWARD VOLTAGE @ 10A	REVERSE CURRENT AC	REVERSE CURRENT DC
	V dc	ma rms	ma dc		V dc	ma rms	ma dc
1	.95	20	9	29	.95	20	9
2	.95	20	9	30	.95	20	9
3	.95	20	9	31	.95	20	9
4	.95	20.5	9	32	.95	20	9
5	.95	20.5	9	33	.95	20	9
6	.95	20.5	9	34	.95	20	9
7	.95	20	9	35	.95	20	9
8	.95	20	9	36	.95	20	9
9	.95	20	9	37	.95	20	9
10	.95	20	9	38	.95	20	9
11	.95	20	9	39	.95	20	9
12	.95	20	9	40	.95	20	9
13	.95	20	9	41	.95	21	9
14	.95	20	9	42	.95	20	9
15	.95	20	9	43	.95	20	9
16	.95	20	9	44	.95	20	9
17	.95	21	9	45	.95	20	9
18	.95	20	9	46	.95	20	9
19	.95	20	9	47	.95	20	9
20	.95	20	9	48	.95	20	9
21	.95	20	9	49	.95	21	9
22	.95	20	9	50	.95	21	9
23	.95	20	9	51	.95	20	9
24	.95	20	9	52	.95	20	9.2
25	.95	20	9	53	.95	20	9
26	.95	20	9	54	.95	21	9
27	.95	20	9	55	.95	20.5	9
28	.95	20	9	56	.95	20	9

Column Test

Reverse Current @25°C: 7.5 ma Avg. @ 28.3 KV rms.
@85°C: 10.1 mA Avg. @ 28.3 KV rms.
Forward Voltage @25°C: 53 V d-c @ 10 A d-c.

High-Potential Test

Leakage Current @ 25°C: 0.75 mA d-c @ 40 KV dc.

ENGINEERING SAMPLES, FIFTH SET

TEMPERATURE RISE MEASUREMENTS

In order to determine the effect of elimination of the internal corrugation of the tank upon the temperature rise, one unit of the fifth set of engineering samples was modified in such a manner as to remove the internal corrugation of the tank. The unit contained 42 modules with a heat sink as shown by Fig. 32 of the Sixth Quarter Report, page 104.

The unit was operated at a direct forward current giving approximately 300 watts total power dissipation, which is the maximum total power dissipation expected in the sixth set of engineering samples.

Both free convection and forced convection (at 400 LFM air velocity) tests were made. The unit was operating in vertical position and baffled, with the air inlet at the bottom plane of the tank at a temperature between 20°C and 24°C.

The location of the thermocouples is shown in Fig. 1 . The following temperature rises above the ambient air temperature were measured.

- ΔT_1: Pyranol at top of tank
- ΔT_2: Pyranol at bottom of tank
- ΔT_3: Outside tank wall at top of unit
- ΔT_4: Outside tank wall at bottom of unit
- ΔT_5: Corner fin at top of unit
- ΔT_6: Module at second row from top

The results are as follows:

Free Convection in Air:

Operating Time	I	E	P	T_a	ΔT_1	ΔT_2	ΔT_3	ΔT_4	ΔT_5	ΔT_6
Hours	Adc	Vdc	Watts	°C	°C	°C	°C	°C	°C	°C
0.75	9	33	297	24	18	13	11	7	10	24
1.5	9.5	32.5	309	24	27	21	16	11	16	32
2.5	9.5	32	304	23	32	27	21	14	20	38
3.5	9.5	32	304	24	39	32	25	18	23	43
6.5	10	31	310	24	42	36	27	21	26	47
12.5	9.5	31.5	300	22	43	36	28	20	25	47

Forced Convection in Air at 400 LFM:

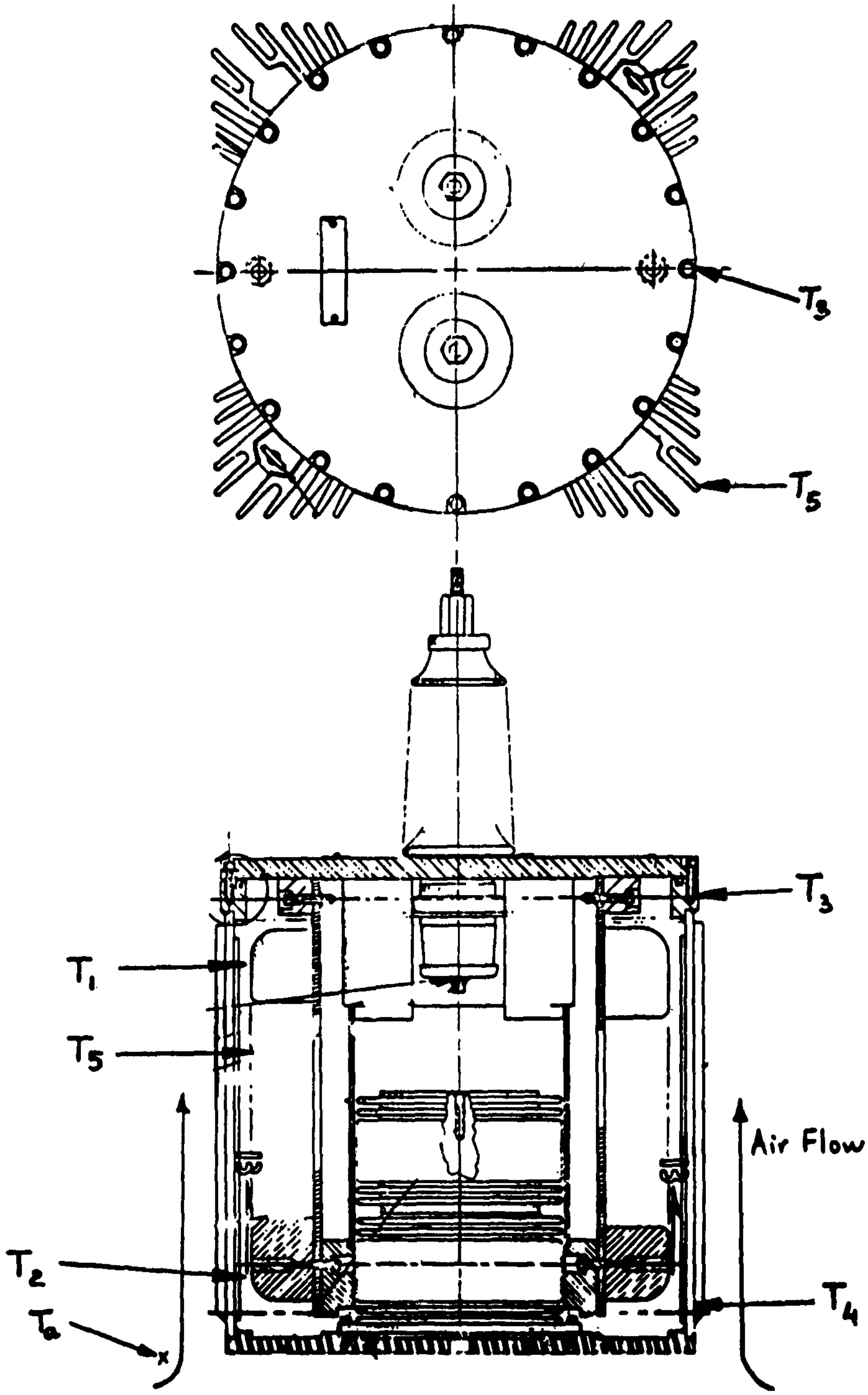
1.5	9.3	32.5	302	20	24	18	10	7	9	28
3	9.5	32.5	308	20	27	19	11	8	9	31
6	9.5	32.5	308	20	28	19	11	8	9	32
24	10	32.5	325	20	29	19	11	8	10	33

The following temperature differences are thus obtained:

Temperature Difference	Free Convection 300 W	Forced Convection 325 W
Module to ambient	47°C	33°C
Pyranol to top to ambient	43°C	29°C
Module to pyranol at top	4°C	4°C
Pyranol top to bottom	7°C	10°C
Outside tank wall at top to ambient	28°C	11°C
Outside tank wall top to bottom	8°C	3°C
Pyranol to outside tank at top	15°C	18°C
Pyranol to outside tank at bottom	16°C	11°C
Outside tank wall to corner fin	3°C	1°C

These results do not show any increase in temperature differences as result of the removal of the internal corrugation when compared to previous temperature rise measurements adjusted to corresponding power dissipation.

Fig. 10



ENGINEERING SAMPLES, SIXTH SET

PHYSICAL STRUCTURE OF THE RECTIFIER

The devices which are to be developed and manufactured under the present contract (No. DA-36-039-SC-85977) and order (No. 6032-PP-61-81-81) have now assumed a shape and dimensions which provide the desired performance characteristics. In order to protect the contracting agency and in keeping with the wording of the contract under:

L. PATENT RIGHTS
(page 18) (ASPR 9-107.2(6) (Jan. 1961),

this structure is described in the following in the form of a "Disclosure of Invention". It will be submitted by the Contractor to the U. S. Patent Office in the form of a patent application.

DISCLOSURE OF INVENTION

IR-1.258

HIGH VOLTAGE RECTIFIER, LIQUID INSULATED IN GROUNDED TANK

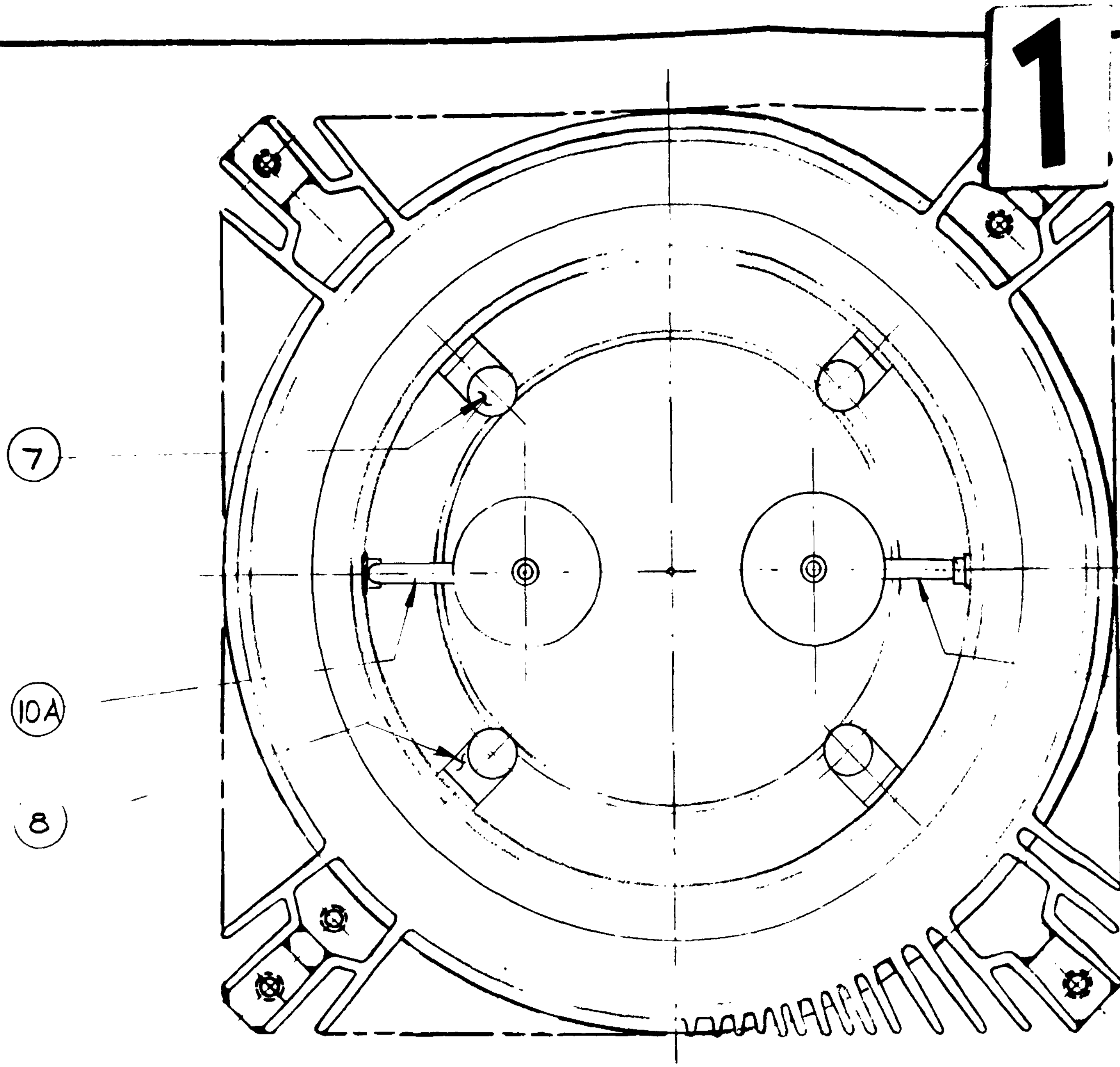
By: E. J. Diebold March 4, 1963

This disclosure pertains to high voltage rectifier assemblies consisting of a multitude of semiconductor devices in series. The entire assembly to have a reverse blocking voltage capability which is far above the one of an individual diode, (e.g. 50,000 volt vs 1000 volt) while carrying only a negligible reverse current (e.g. 5 milliampere). Furthermore, it must be able to carry a substantial current in the forward direction (e.g. 10 ampere) at a relatively low forward voltage drop (e.g. 50 volt). Switching from the forward (low impedance) state to reverse (high impedance) state, and back, to be accomplished in microseconds without perturbations by undesirable oscillations or other side effects.

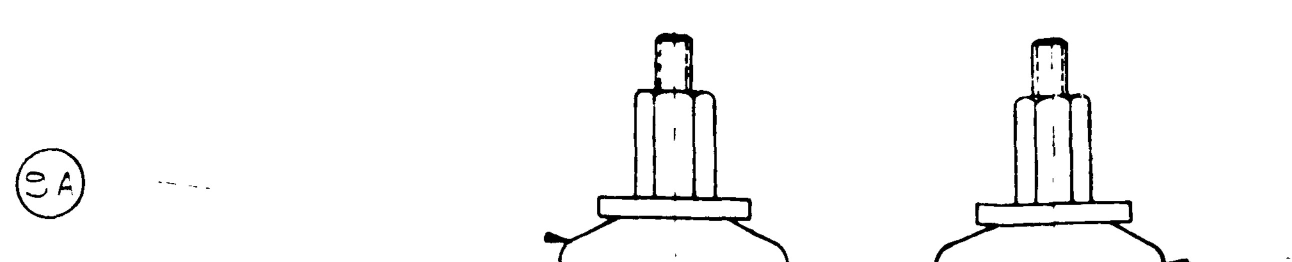
Mounting

One of the purposes of this invention is to support the entire structure on a grounded mounting surface, without accessory insulation. Internally, the assembly must be able to sustain any voltage occurring in practical operation between live parts and ground without conducting an excessive leakage current (more than a few microampere). Particularly, mounting must be permitted in any direction, or position (upright, sideways, upside-down). Operating performance to be unaffected by tilting, vibrations of any kind (straight, circular motion, variable tilt, variable frequency) and shocks. Except for the clearly apparent high voltage terminals, which can be covered by insulating caps fitting over the cable, no electrical flash-over or leakage current to ground should be possible, even when these units are subjected to rough stresses in a situation where loose objects are thrown about.

Electrically, the above objectives require the device to be made with three terminals: ANODE, CATHODE, GROUNDED TANK.



SECTION **A-A**



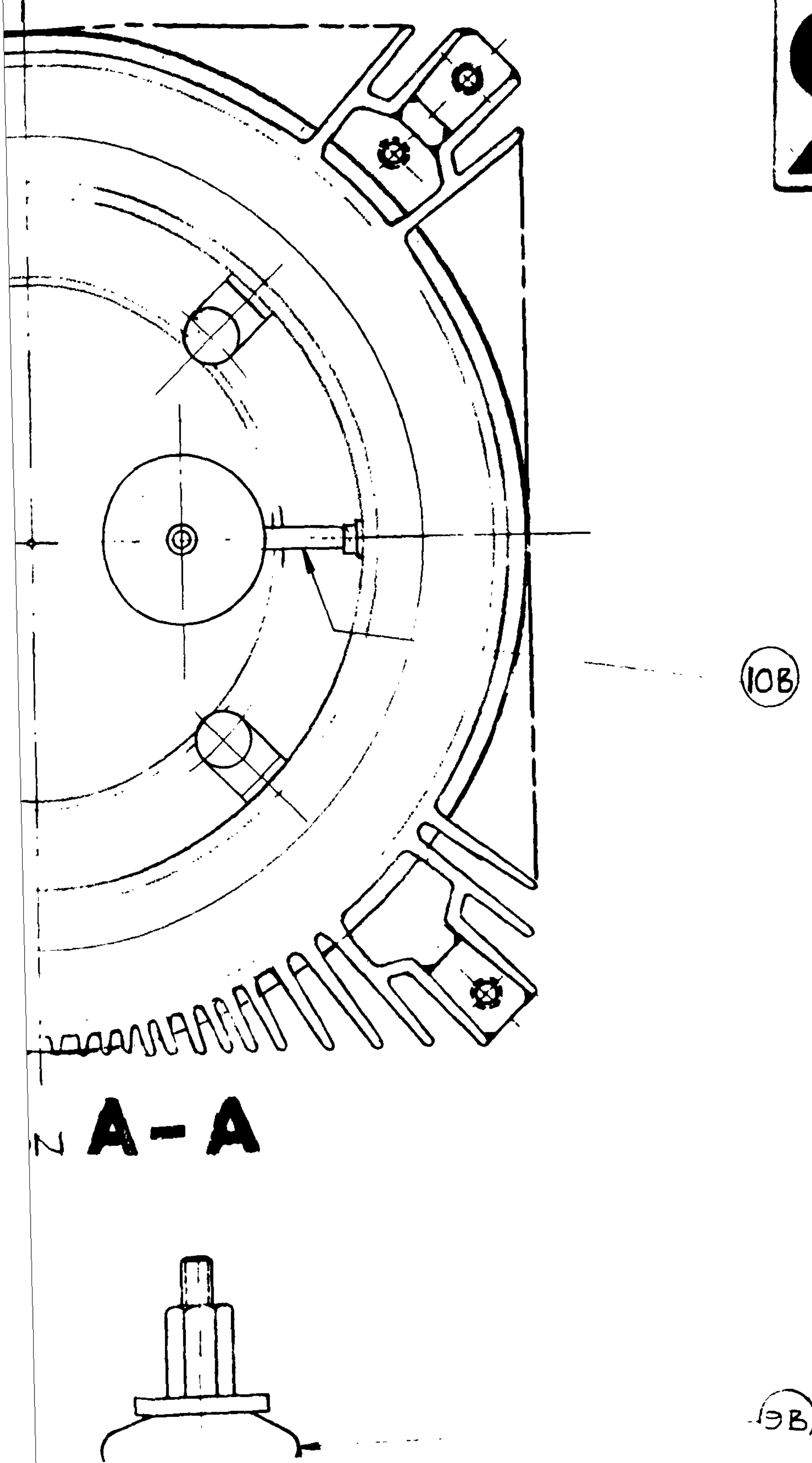


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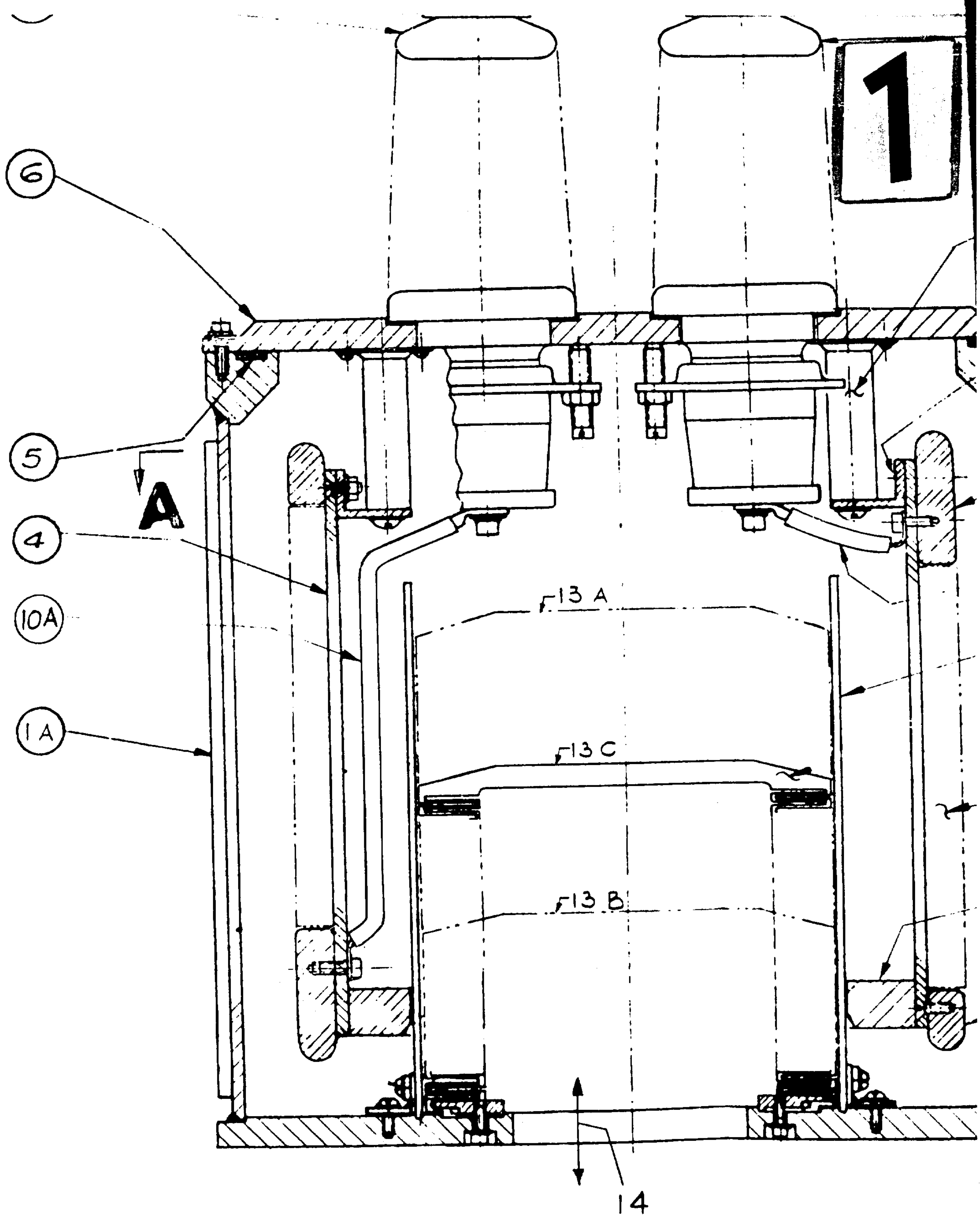
FIGURE 2



1
6
5
A
4
10A
1A
13 A
13 C
13 B
14

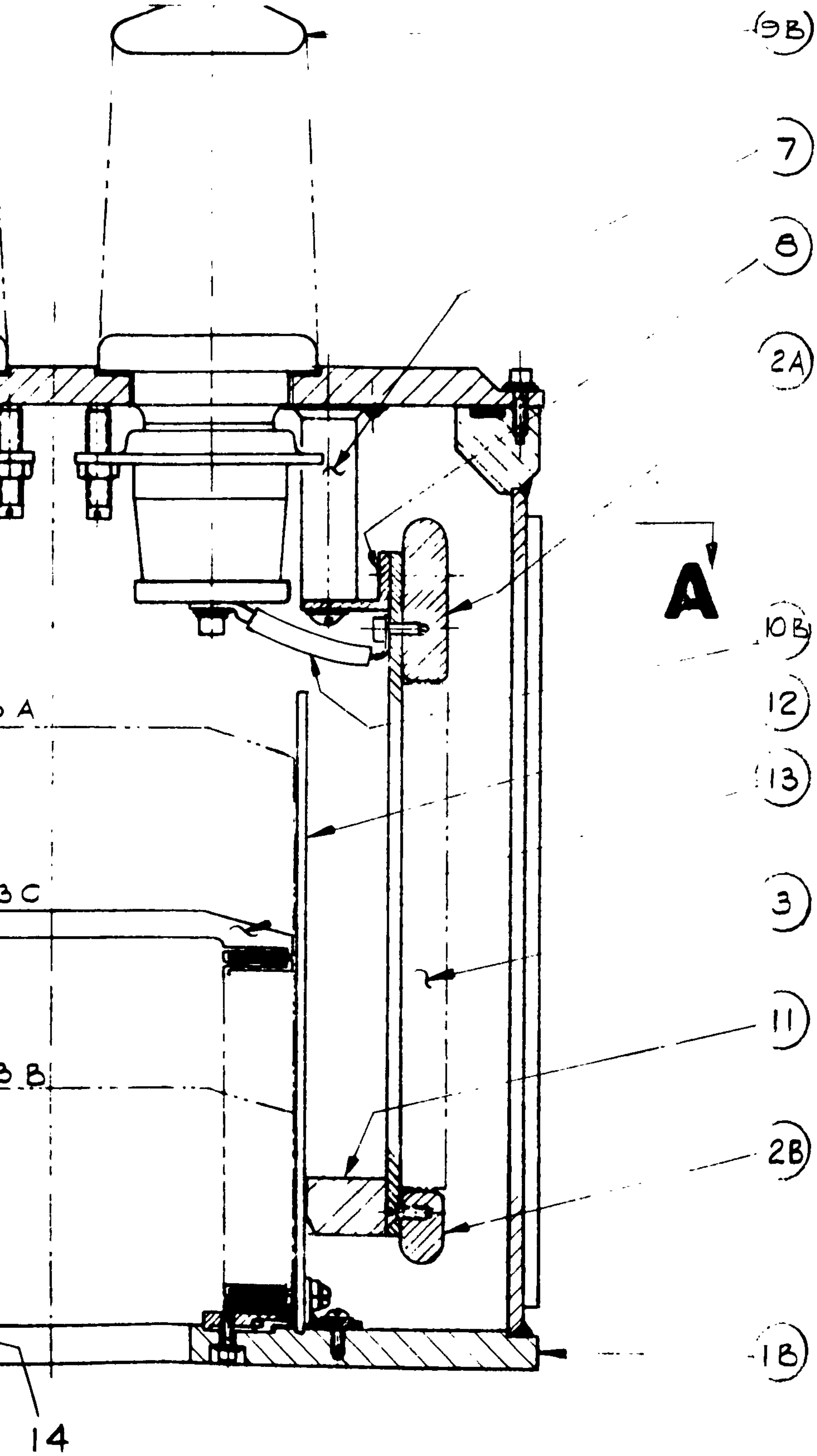


FIGURE 3

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Each of these terminals having its own function of non-negligible importance, particularly the voltage blocking capability and impedance (at various frequencies) between any two of these electrodes must be of specific and controllable magnitude.

Reliability

High voltage rectifiers of the type described in this invention are frequently used in communication equipment which is located on ships, airplanes or in transportable equipment. Other applications are for radio transmitters or other communication gear located in remote areas, such as polar zones, tropical islands, high mountains or other poorly accessible locations. In these applications it is desirable to have high voltage rectifiers which are extremely reliable and not affected by ambient conditions such as extreme temperatures, humidity, fungi, dust, salt spray or any combinations and successions of these unfavorable conditions. Furthermore, the device should be as small as possible, of light weight, rugged and capable of withstanding vibrations and shock.

Another very important requirement is that the device should be able to operate reliably even when partially damaged, failing safe wherever possible and repairable in the field (in case of emergency) by cannibalizing several damaged units to make a good workable unit.

A further requirement is that the protective fluid be non-flammable to avoid a catastrophic fire under conditions of slight field damage, field repairs or other occasions when the fluid comes into contact with the atmosphere.

Controlled Ambiance

High voltage apparatus and devices fail most frequently by voltage breakdown, either between terminals or, more frequently, between the high voltage device and ambient. Accordingly, it is a first objective of this invention to provide a controlled ambient to the live parts of the rectifier, eliminating as much as possible the danger of electrical flash-over between live parts and ambient.

When confronted with the problem of insulating electrical devices, either internally or with respect to ambient, the influence of varying atmospheric conditions or contaminations can be controlled by submerging all the sensitive electrical components in an insulating fluid. The only electrical terminals to ambient are then so-called 'bushings': Ceramic insulators with a conductor through them, providing a hermetic seal between the internal part of the vessel and the outside and providing reliable insulation between their live parts and the grounded vessel. This vessel is a sealed tank, full of fluid and firmly connected to ground potential.

Expansion of Liquid

Whenever an electric device is insulated from ambient by submerging it in a liquid which is contained in a rigid tank, some means must be provided for the expansion of the liquid. This can be made by an external expansion vessel in which the liquid raises and falls, by gravity, depending on its volume which is dictated by temperature. Another method is to fill the tank only partially, providing a gas space above the liquid into which it can expand by compressing the gas. Both of these methods are space-consuming and depend on a liquid level maintained by gravity. For the contemplated use, in which the device is tilted, reversed, laying on its side or subjected to shock and vibration these methods are not acceptable.

For small devices insulated with liquid, a flexible tank can be made by making it with thin walls so that the expansion or contraction of the liquid will collapse or expand the tank walls. In case of a high power device this is not permissible, the tank would be much too fragile to support being man-handled or subjected to heavy external stresses by vibration, shock or acceleration; furthermore, to move the walls of a strong tank required over- and under-pressures which are excessive. Preferably, the tank should be very strong and rigid, although of minimum weight. Furthermore, the walls must be shaped to facilitate heat dissipation. The flexibility must be provided by another means.

Accordingly, another purpose of this invention is to make the tank externally hermetic, rigid and with minimum weight. In addition, it contains a flexible section which provides for expansion and contraction of the fluid. This flexible part is mounted internally, protected from the ambient so that it cannot be damaged by rough handling, distorted by shock, vibration or acceleration, yet moves so freely that no over- or under-pressure between ambient and liquid can occur so that the rigid part of the tank is not unduly stressed by the substantial changes in the liquid volume due to changes in temperature.

Over- or Under-Pressure in the Tank

The separation of flexibility and rigidity is particularly important when the assembly must be used over a wide range of temperature, and additional stresses by liquid expansion or compression are not tolerable because of the requirement for strength of the tank which is needed for other purposes than just to maintain the liquid itself.

The design described by this invention prevents high pressure differentials between the inside and outside of the tank. Thus, the tendency of seals, welds and insulators to leak is not enhanced, because a small leak can be rather harmless if it is not subjected to a high pressure differential, allowing only a small loss of fluid. At low temperature, with a negative pressure differential, atmospheric impurities (air, water, salt) can be sucked into the dielectric fluid. Such liquids have very good electrical properties in their pure state but are very greatly affected by a small amount of contamination (one to ten parts per million).

Insulation to Ground

The insulation to ground in a high voltage rectifier must satisfy several conditions.

1. The insulation between live parts and grounded parts must be sufficient to prevent electric flash-over or electric leakage from the active parts to ground. This insulation must be more than just adequate. In most practical systems the voltage between terminals of component devices is well defined, whereas the voltage between active devices and ground is frequently undefined and subject to variations which are very hard to predict. Accordingly, the insulating level between active parts and ground should be very high, covering direct voltages, low frequency alternating voltages, pulses and high frequency oscillations. Furthermore, under these high voltages the electric discharge effects should be minimized to have no leakage currents, noise currents, arcs or other undesirable current effects between the active parts of the circuit and ground.

Beyond the necessity of holding a high voltage of undefined time variability and withstanding these voltages without carrying an undue current to ground, there is the requirement of limited coupling capacitance between live parts and ground. High voltage rectifiers used as switching diodes or power rectifier diodes are subjected to fast voltage changes. If the live parts of the diode, contained within the grounded tank, have an excessive coupling capacitance to the tank, a displacement current flows through this capacitance, whereby effectively short-circuiting the device. Thus it is desirable to minimize the capacitance between live parts and ground.

The above mentioned requirements of: High voltage blocking capability without arcing or noise effects: High impedance between live parts and ground (low current per unit of applied voltage): High capacitance impedance between these parts and ground are not sufficient. There is the added requirement that these properties must be maintained constant under various unfavorable environmental conditions.

The worst environmental conditions are humidity, contamination, low air pressure, moving objects near the device, temperature extremes, shock, vibration, tilting, etc. A major advance to eliminate these unfavorable environmental effects is to submerge the live parts in non-flammable liquid contained in a strong grounded tank. A further requirement, then, is to maintain this liquid in excellent insulating condition under all the adverse conditions. This is achieved by providing a hermetically sealed tank which eliminates all chemical external influences.

The tank is provided with a flexible member which prevents a voltage gradient being applied to the liquid while a vacuum exists at a low temperature. Such a vacuum would cause bubbles of gas (liberated by the fluid) or, at extremely low temperature, cracking of the congealing fluid, when under vacuum. As the atmospheric pressure is maintained, it prevents bubble formation and forces the soft fluid into the cracks, thus preventing flash-over.

At high temperature, the liquid is maintained under near atmospheric pressure by the flexible member of the tank so that no excessive high pressure effects are encountered. Without this, a "pressure cooker" effect takes place. This dissolves, at high temperature, resins or other insulating materials in the insulating fluid. Returning to lower temperatures and pressure the dissolved substances will be precipated out of the liquid, endangering the performance. It is understood that the actual operating conditions of the devices are not always exactly predictable but the assembly is being built for withstanding a maximum temperature, without open pressure, in the range of 150°C (or possibly higher). In this case, a "pressure cooker" effect would be very dangerous.

Coupling Capacitance to Ground

Holding the coupling capacitance between the totality of live parts and ground to a low value is important for the performance of the rectifier. Beyond this, because the rectifier must block voltages of various magnitudes, the distribution of the coupling capacitance over the series of rectifier devices which are connected together is of even greater importance. It can be shown that the coupling capacitance between individual devices and tank has a fundamental effect on the voltage distribution. It is particularly important that the members of the series string of modules which are connected near the ends (but not directly to the terminals) of the column are not coupled with a higher capacitance to ambient than the members in the center of the string.

On the other hand, a more substantial capacitance between terminals and ambient is of much lesser importance, because these terminals are usually connected to a low impedance circuit (feeding power to the rectifier) so that capacitive displacemen, currents through the terminals to ground are less harmful. Internally in the series string of high quality rectifier devices, when subjected to transient voltages, are coupled together only by the very low reverse leakage current which flows through them. High displacement currents from these devices to ambient must be carried by these devices, which is damaging to them.

This effect can be partially overcome by buffering each individual device, using a capacitor shunted across each device as shown in Figures 4, 5 and 6. To equally divide any unknown shape of applied voltage versus time, it is first mandatory that these shunting capacitances be equal for all the series connected devices and also equally important that the capacitances between devices and ambient be equal for each device. A normal series arrangement does not provide for this because the shape of the field to ambient makes the capacitances to ground to be very unequal, high at the ends, low in the middle. Equalization is achieved by shaping the end shields, indicated by 2A and 2B in Figure 3 in the shape of rings having a helicoidal cut-off on their periphery, matching the helicoidal arrangement of the individual modules as shown in Figure 7.

The coupling capacitance between individual modules and the end

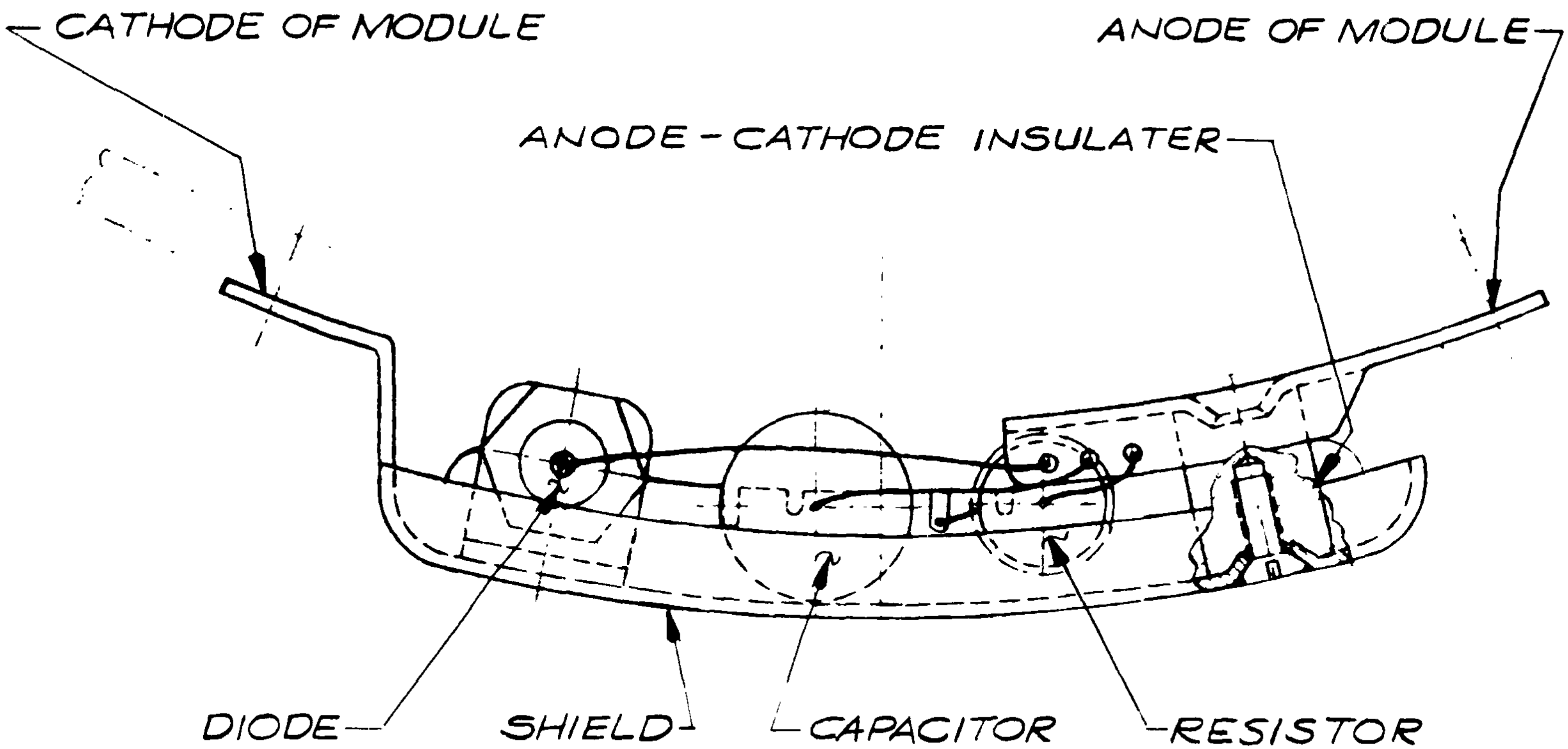
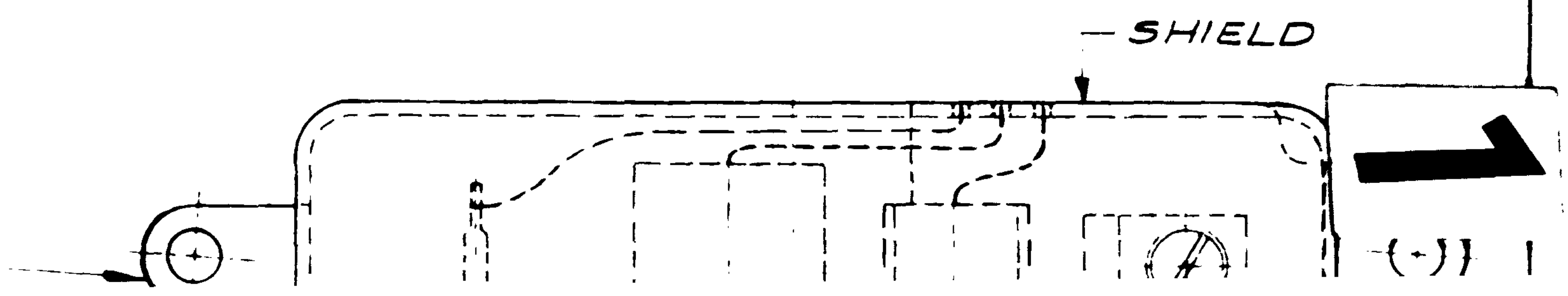

CATHODE OF MODULE
ANODE OF MODULE
ANODE - CATHODE INSULATER
DIODE
SHIELD
CAPACITOR
RESISTOR

FIGURE 4


SHIELD
1
(+)

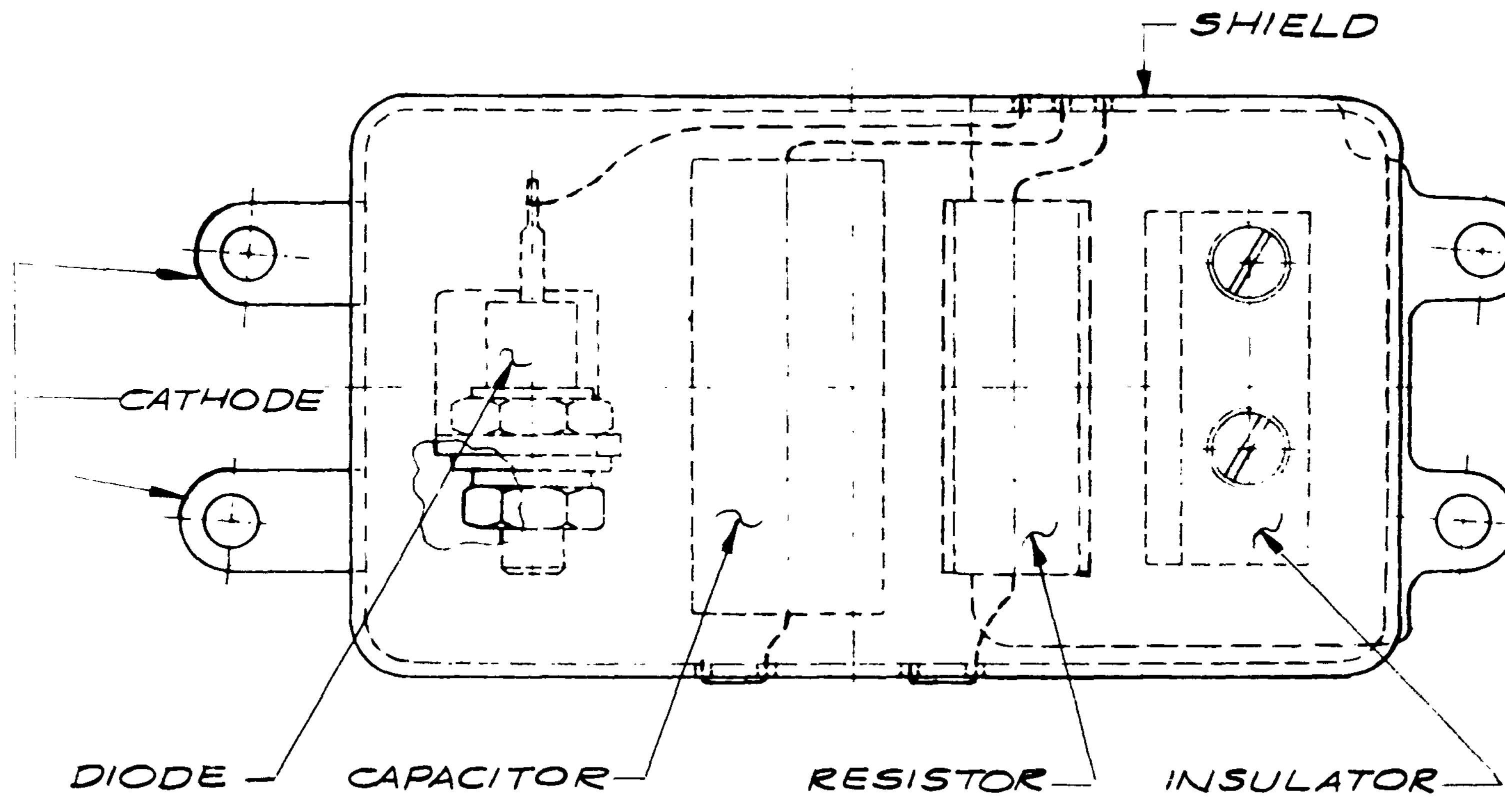


FIGURE 5

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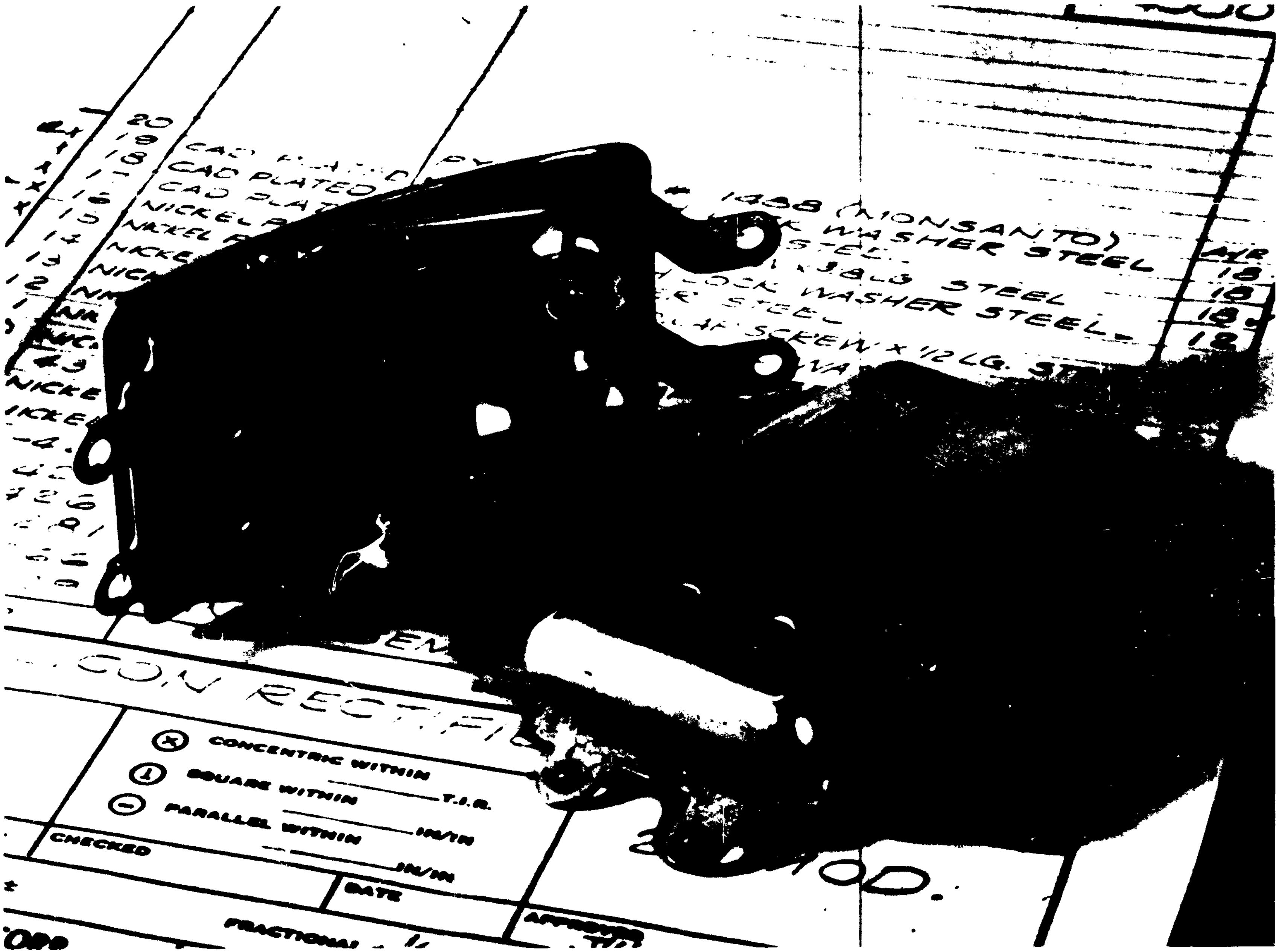


Fig. 6

rings is the same as between any module and its neighbouring modules within the string. Furthermore, the electric field spreading from one individual module near the end of the string is the same as the one of a module in the center because this field is limited by the larger field of the end rings, which are at the same potential as the end of the string. If a high voltage is suddenly applied to the string of devices in series, the driving voltage is first applied to those end rings. If the rate of rise of the voltage applied is so high that the circuit source impedance is relatively high, the capacitance between terminals and ambient will prevent the voltage from rising, thus reducing the voltage stress on the string. Displacement currents which flow through the terminals to the end rings do not have to be carried by any devices and, therefore, are not harmful to the rectifier itself.

Later, as the voltage across the devices and between devices and ground rises, the displacement current to ground must be carried by the string, which is provided by the diode shunting capacitor in each module. On the other hand the major part of the displacement current is still carried through the end shields to ground preventing an excessive current from flowing through the rectifier devices and their buffering capacitors.

Terminal to Terminal Voltage

In order to achieve a good rectifier, able to function under adverse circumstances, the herein described structure must present a low forward impedance, even when a high forward current is forced through the diode. This impedance must be low for the rated current, overload currents and pulse currents. The impedance must be particularly low when the current is applied in short, steep pulses. Accordingly, the forward resistance of the diode must be low; as a counter-electro-motive force opposed by individual devices, as a resistance of accessory hardware (such as wires) and as inductance presented by the string of devices in series.

As shown in Figures 3 and 8, the impedance of the conductors from terminals to active parts is held low by making the leads short and connected as directly as possible to the end shields which act as current distributors. Individual modules are fastened with heavy brackets to end shields and to each other, as shown in Figures 6 and 7. The double brackets are the actual current carrying means, minimizing the conductor-self-inductance. To keep the systematic inductance low, the string of devices is arranged on an open and wide diameter helix in which the terminal conductors are connected inside (Figures 6 and 7). The helix is made with a minimum number of turns. Within the helix the flow of current is straight forward and through heavy conductors. Thus the total inductance of the assembly is minimized, assuring good performance under high frequency.

When the diode is forced to block the flow of current in the reverse direction, it must present a high impedance. This is also necessary under a-c, d-c and pulse operation. Thus the reverse impedance must be high as resistive impedance, and, (to assume voltage division under transient condition) it must essentially be a capacitive

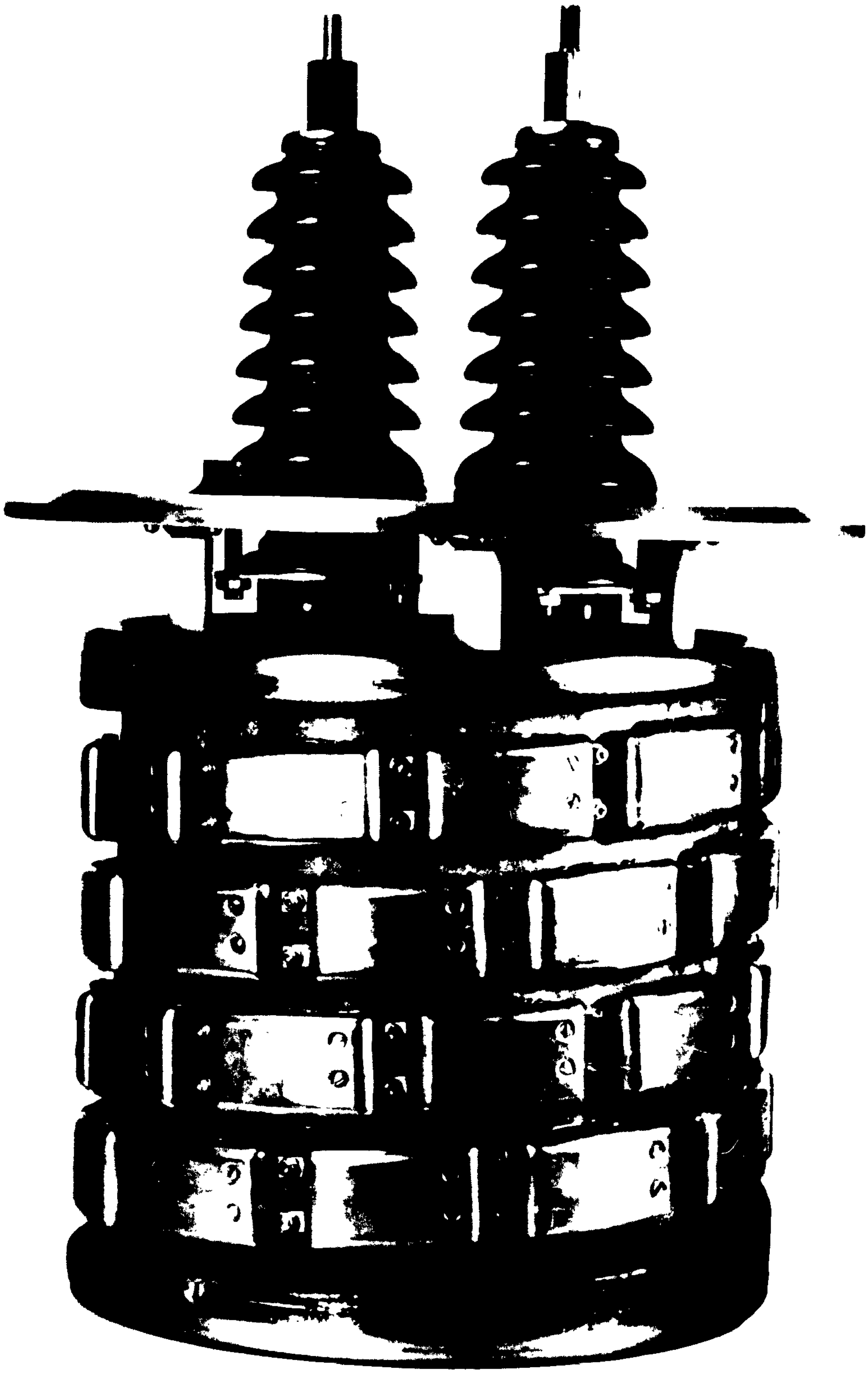


Fig. 7

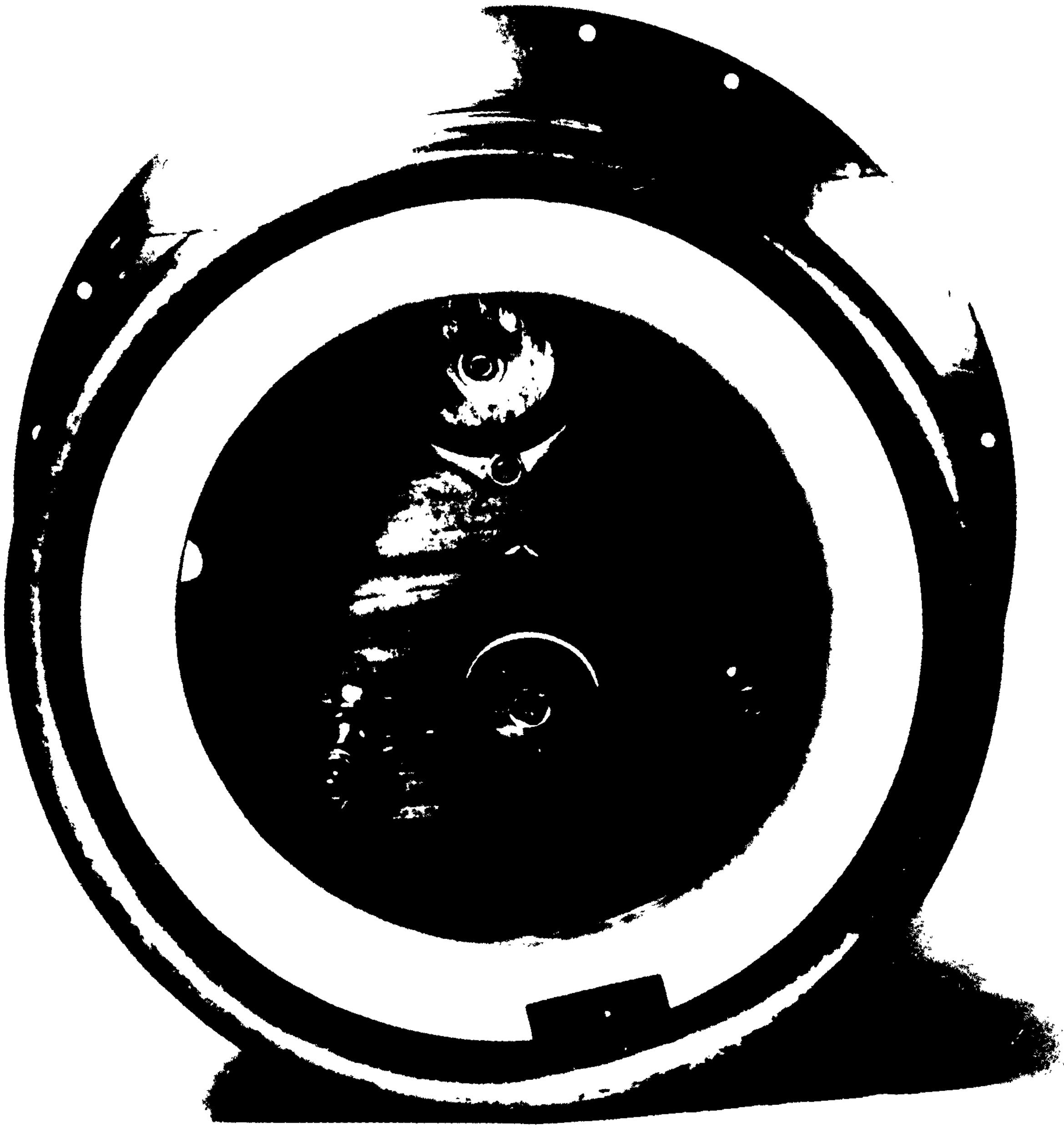


Fig. 8

impedance, without excessive inductance. The low inductance described for the forward impedance is the same in the reverse direction. The capacitive reverse impedance is maintained by buffering capacitors shown in Figures 4, 5 and 6. The resistive reverse impedance is maintained by a resistor shunted across each individual device to present a definite reverse resistance of each module. Thus the entire structure has a definite capacitance and resistance when the diodes are blocking, assuring a high reverse impedance, however of definite magnitude.

The elimination of shunting resistors and capacitors would evidently increase the reverse resistance to allow a lesser reverse current to flow. On the other hand, in this case the reverse impedance of the assembly would be the one of a number of diodes connected in series. Diodes are essentially non-linear devices, having a reverse impedance which is variable. Furthermore, this impedance is a function of temperature. By providing a definite linear reverse impedance the assembly hereby is a defined reverse impedance under any operating condition, which improves the reliability of the assembly. Furthermore, by making the system with very low inductance, the system is self-damping, eliminating the self generated switching oscillations.

Description of the Design

Insulation to Ground

As shown in Figures 2 and 3, the insulating space between live parts and ground is cylindric, of equal thickness and with rounded parts facing each other. Thus the electric field between the live parts and ground is maintained in an almost ideal field condition, between large areas opposing each other across a substantial distance, without corners, points or other sharp protrusions. Thus the electric field is of low gradient, constant gradient and predictable in its configuration. Figure 7 shows also how all the live parts have rounded corners. Figure 9 shows the smooth interior walls of the tank.

Solid insulators required to maintain the live parts within the grounded tank are held outside of the field. Thus the insulators 7 shown in Figures 3 and 7 are ceramic pillars connected to the cover 6 of the tank and fastened by the brackets No. 8 to the insulating cylinder which supports the live parts. The main electric field, however, existing between the rings 2A and 2B and the tank, is not disturbed by these pillars which are outside of the field. Thus the electric stress on these pillars is held very low. On the bottom end of the tank a heavy Teflon ring 11 (also visible in Figure 8) insulates the tube 4 and the tube 12. These two other tubes are insulators, so that the electric field between those parts is always low. Furthermore, the material used for the ring 11 is of the highest quality, although inserted in a location wherein the electric field is low.

Assembly

In order to facilitate the assembly of the rectifier, all the live parts and their supporting members are fastened to the cover of the tank (Figures 7 and 8). This cover No. 6 supports the main rectifier cylinder No. 4 by the pillars No. 7. The lead wires from the bushings to the ends of the string No. 10A and 10B are fastened permanently. The bushings 9A and 9B are also fastened in a hermetic and permanent fashion to the cover.

On the other hand, the flexible bellows No. 13 and its guide tube No. 12 are permanently fastened to the bottom 1B of the tank, as shown on Figures 9 and 10. The ring 11 which is rigidly fastened to the tube 4 slides around the tube 12 when the tank is assembled. In operation, when the temperature of the tank changes because of the heat developed by the electric components, or the ambient temperature is changed, the tank may expand and contract. Under these conditions a slight sliding motion can occur between the ring 11 and the tube 12. However, when lateral shock, tilting or vibration is applied to the tank, the live parts are prevented from oscillating because of the close guiding effect of the ring 11 on the tube 12. Thus the assembly is held rigidly within the tank, without introducing excessive mounting stresses due to a differential in thermal expansion coefficients.

The connections between the live parts and bushings are made with very heavy wires insulated with a thick layer of Teflon, although they are located in a field of low electrical stress. This is provided to minimize the possibility of electrical breakdown, electrical noise or any undesirable effects between the leads and the surrounding electrical parts. It should be noted that the bracket No. 8 in Figure 3 which is located close to the wire 10B is in effect at a much further distance, as shown in Figures 2 and 8. Because all the connecting wires, bushings and associated hardware are permanently connected, their electric performance can be tested before the assembly is closed.

The ceramic bushings are over-sized, with solid internal rods. The ceramic parts of the bushing which go through the cover are metalized to prevent corona between ceramic (of otherwise indeterminate potential) and ground tank. Thus the electric field within the bushing is maintained entirely within the high grade porcelain.

As shown in Figures 4, 9 and 10, a flexible bellows No. 13 is located within the insulating guide tube No. 12 at the interior of the tank. Within the bellows enters the atmosphere through the breathing hole 14. At maximum temperature, the bellows is compressed to the small size 13B because the fluid has expanded to its maximum volume. At minimum temperature, the bellows expands to the dimension 13A, because the fluid has contracted. The bellows are cut or molded from one piece of Teflon, including its top 13C. Thus the bellows is one high grade insulating part which cannot disturb the electric field between live parts and ground. This is particularly important because of the change of dimensions in the bellows which extends within the live parts of the assembly. A non-insulating bellows would change the shape of the dielectric field, which might lead to failures in case of extreme thermal and electric stresses applied simultaneously.

Fig. 9

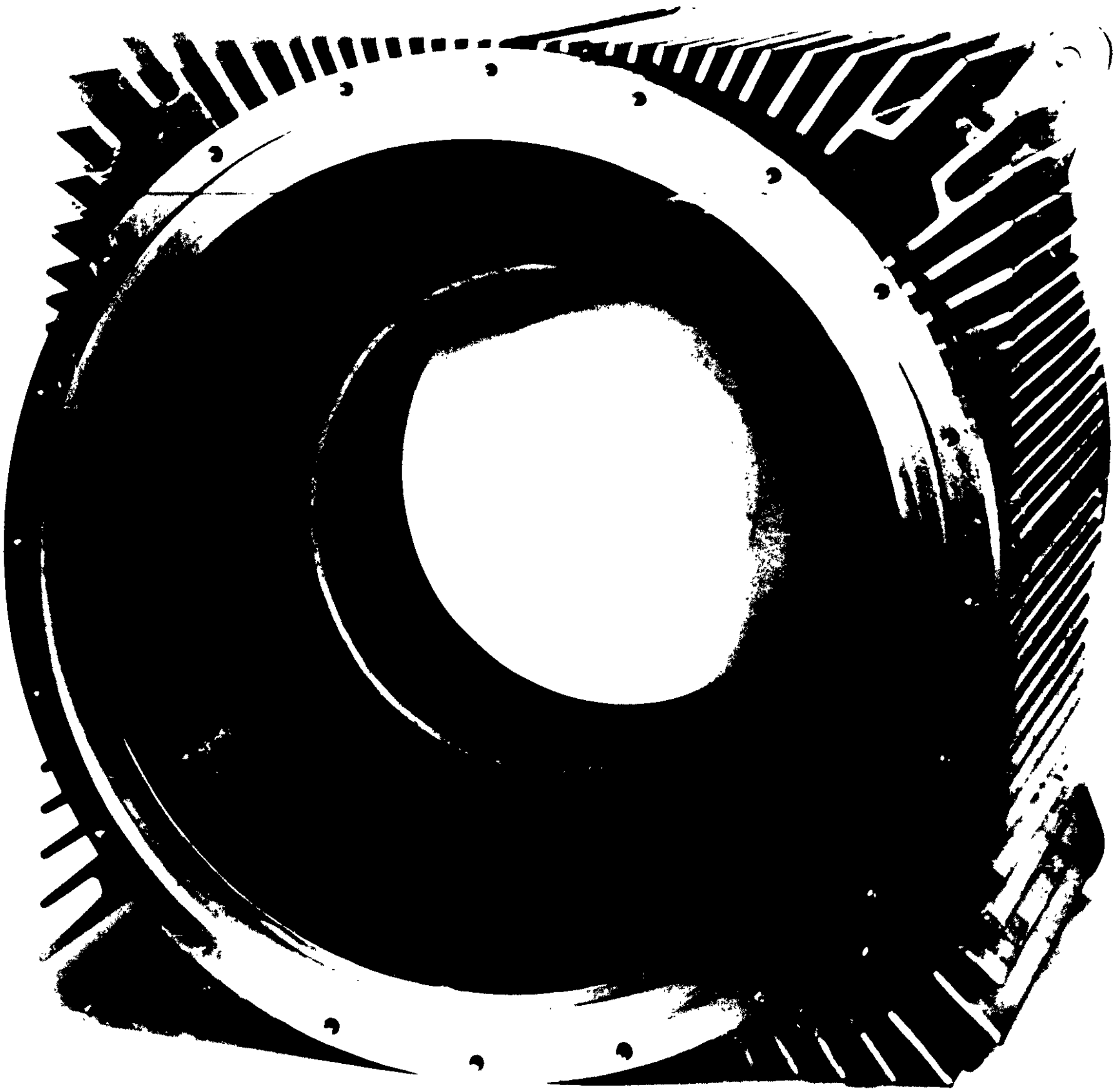


Fig. 10

The bellows is extremely flexible which allows it to move over a wide volume, without causing over-pressure or under-pressure within the tank. On the other hand, by being guided within the tube 12 the bellows is not damaged by laterally applied shock, vibration or tilting. It should be noted that relative motion between bellows and tube 12 or guiding ring 11 and tube 12 is facilitated by the excellent lubricating properties of the insulating fluid.

Terminal to Terminal Insulation

In order to separate the terminal to terminal insulating properties from the terminal to ground properties, the insulating cylinder No. 4 which insulates all the live parts from each other, is not used as the insulator to ground, as seen on Figure 7. Insulation is provided by the pillars No. 7 and the ring No. 11 in conjunction with the tube No. 12. The insulation between live parts is limited by the voltage capabilities and ratings of the semiconductor devices which make the rectifier, whereas the insulation against ground is much less well defined.

The cylinder No. 4 is able to hold a very high voltage because it is subjected to the voltage in gradual steps, between the two end rings 2A and 2B which are at the potential of the two terminals. Within the cylinder 4 the voltage changes gradually from one end ring to the other end ring by step-wise voltage increase from one module to another and between turns of modules in the helix arrangement. As shown on Figures 4, 5 and 6, the voltage across one module appears across the long distance between the two pairs of fastening screws on each end. On the other hand, because the modules are staggered on mounting (as seen on Figure 7), the voltage between rows of modules is distributed over a very wide spacing. Thus the electrical stresses on the cylinder 4 are held at a low fixed values. Because this cylinder is stressed in a direction parallel to its laminations, the configuration of the assembly, by minimizing this stress, allows for a high insulating capability regardless of the properties of the material.

As seen on Figure 7, the coupling capacitance, and module to module impedance is held at equal values by the equal spacing of modules against each other and between modules and the next turn of modules, or the end rings. This allows for an equal and undisturbed voltage distribution between modules, when subjected to a rapid overall voltage change between the terminals of the assembly.

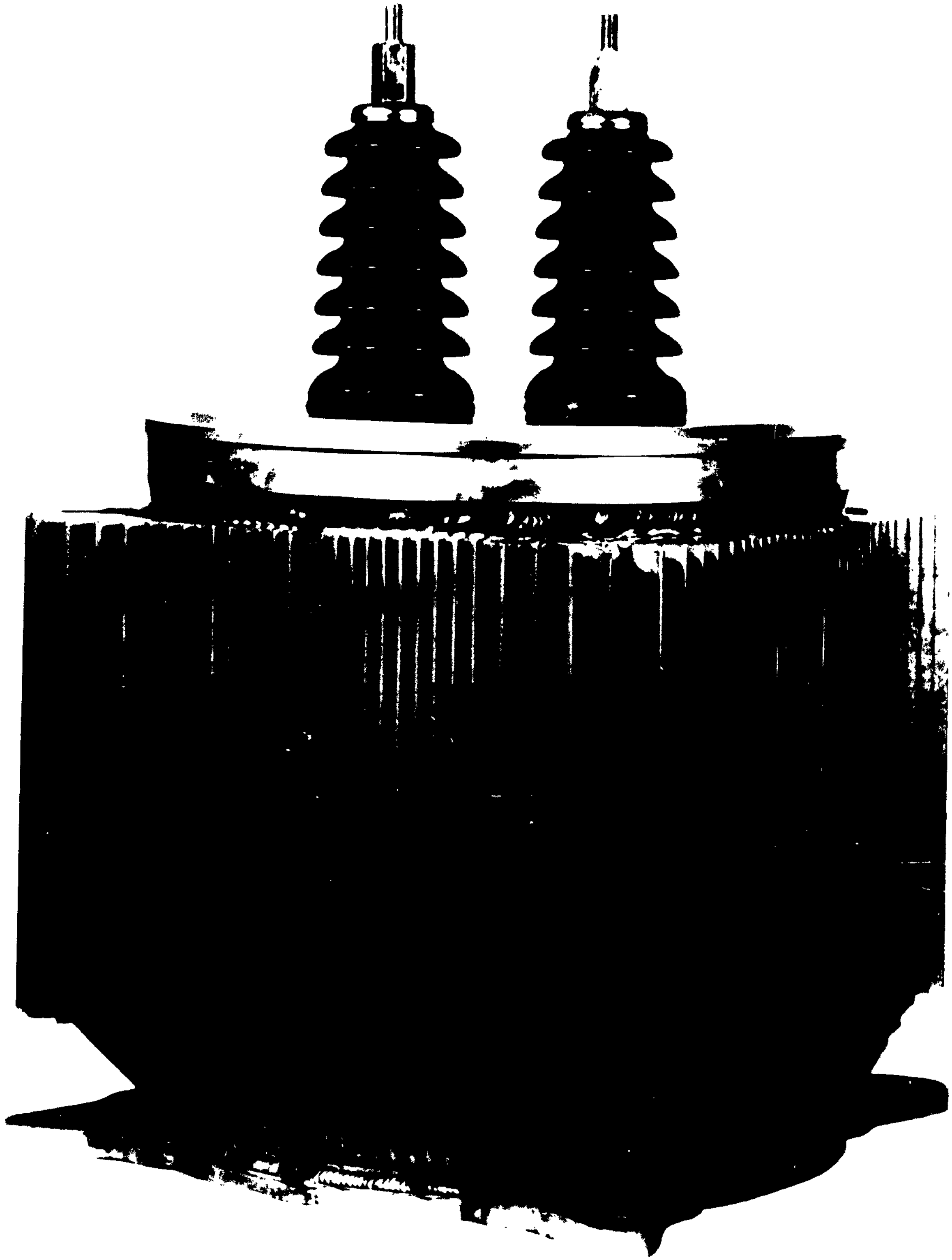


Fig. 11

Fig. 12

ENGINEERING SAMPLES, SIXTH SET

TEST SPECIFICATION

1. TEST FOR SILICON RECTIFIER DIODE, TYPE 16F, PART NUMBER 66-6736

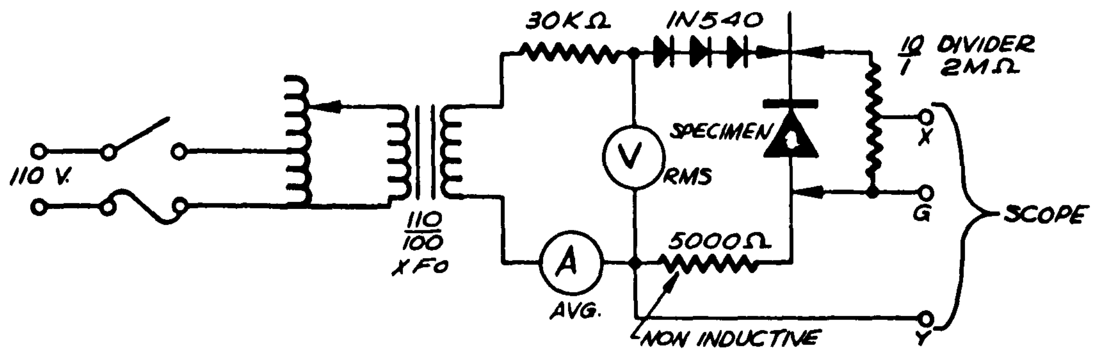
Inspection conditions. Inspection conditions shall be in accordance with the referenced paragraphs.

Ref.	Test	Condition	Sym.	Min.	Max.	Unit
	Group A. Inspection					
1.1	AC Reverse Current	V_R=1400 volt peak T_A=25°C	I_S		50	uA peak
1.2	DC Saturation Current	V_R=1200 volt dc T_A=25°C 125°C	I_R		2 400	uA dc uA dc
1.3	Avg. Forward Voltage	I_F=12 A Avg. T_A=25°C	V_F		0.50	V Avg.
1.4	Surge Test	T_A=25°C Prior I_F=0 i_f(surge)=400 A .			3	Surges

1.1 AC Peak Reverse Voltage Test

Voltage grade of silicon rectifier cell is determined by peak reverse alternating voltage and current observed on oscilloscope.

1.1.1 Test Circuit



1.1.2 Testing

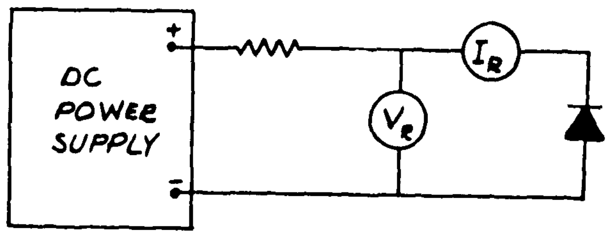
Connect test silicon rectifier cell to test leads, observe trace on oscilloscope while increasing voltage with powerstat. Stop when:

1.1.2.1 Zener point is reached.
1.1.2.2 Hysteresis appears.
1.1.2.3 Instability appears.

1.1.2.4 Breakdown occurs.
1.1.2.5 Maximum allowed saturation current I_s is reached.
1.1.2.6 Maximum allowed reverse current I_R is reached.

1.2 DC Reverse Voltage Test

1.2.1 Test Circuit



1.2.2 Testing

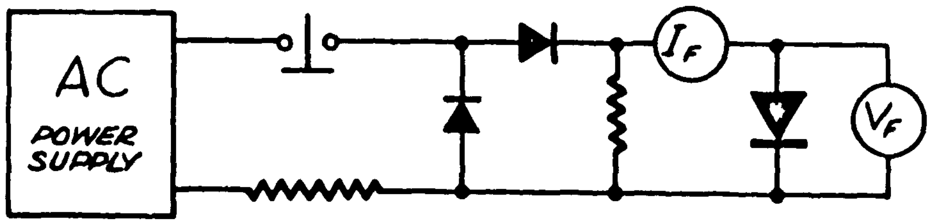
Connect a DC power supply (5% ripple max.) to diode. Increase the voltage to V_R. Observe leakage current for 10 seconds. Reject diode if:

1.2.2.1 Leakage current exceeds the specified value.
1.2.2.2 Leakage current is not stable but increases with time (runaway).

1.3 Average Forward Voltage Test

Forward voltage drop is measured as direct voltage.

1.3.1 Test Circuit:



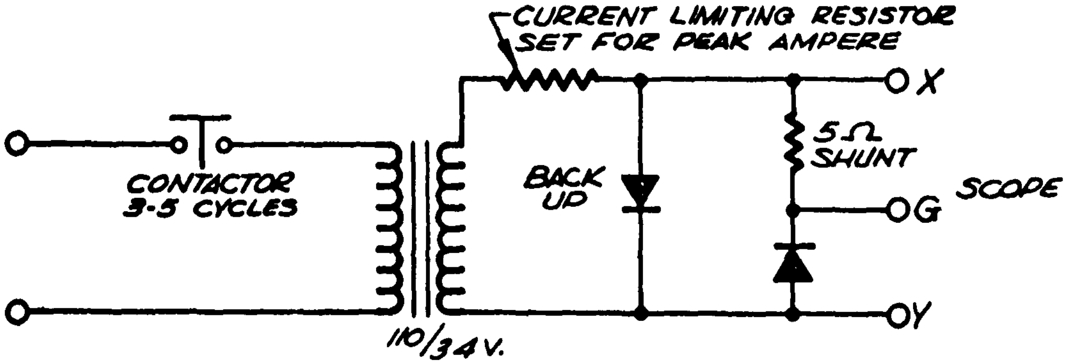
1.3.2 Testing:

Connect test silicon rectifier cell to test jig. Close test switch, increase current I_F to specified value. Release test switch, insert rectifier in test jig, push test button, read forward voltage drop V_F.

1.4 Surge Current Test:

Apply three half cycles of forward current with peak value shown in table below. Observe resulting plot of forward current vs forward voltage drop on calibrated oscilloscope.

1.4.1 Test Circuit:



1.4.2 Oscilloscope Calibration:

Current - Vertical deflection 50 amp/sq.
Voltage - Horizontal deflection 0.2 Volt/sq.

1.4.3 Acceptable Samples:

Forward voltage drop as shown in table:

Forward Voltage Drop V_F		i_f (surge)
Min.	Max.	
Volt	Volt	Amperes
1.5	2.2	400

1.4.4 Reject samples which have voltage drop higher than maximum given in table, and samples which indicate loops on trace larger than 1/16 inch.

2. <u>TEST FOR RECTIFIER MODULE</u>: (Complete Module with Silicon Rectifier Diode, Resistor and Capacitor)

Inspection Conditions: Inspection conditions shall be in accordance with the referenced paragraphs in this document.

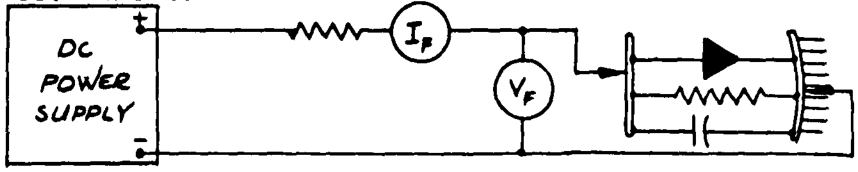
Ref.	Test	Condition	AQL %	Sym.	Min.	Max.	Unit
2.1	Group A Inspection Visual & Mechanical	Major Minor	1.0 2.5				
2.2	Forward Voltage	I_F=10 Adc T_A= 25°C		V_F		0.96	Vdc
2.3	Reverse Current	Direct Voltage, 300 Vdc		I_R	0.57	0.63	mA dc
		Alternating Voltage: 100 V rms. T_A=25°C		I	20.5	23.5	mA rms

2.1 Visual and Mechanical Inspection

Visual inspection, checking all solder joints, connections, and placements of parts.

2.2 Forward Voltage Drop Test

2.2.1 Test Circuit



2.2.2 Testing

2.2.2.1 Connect a dc (maximum 5% ripple) power supply between positive and negative connectors of module.

2.2.2.2 Apply forward current I_F as read on average reading dc meter.

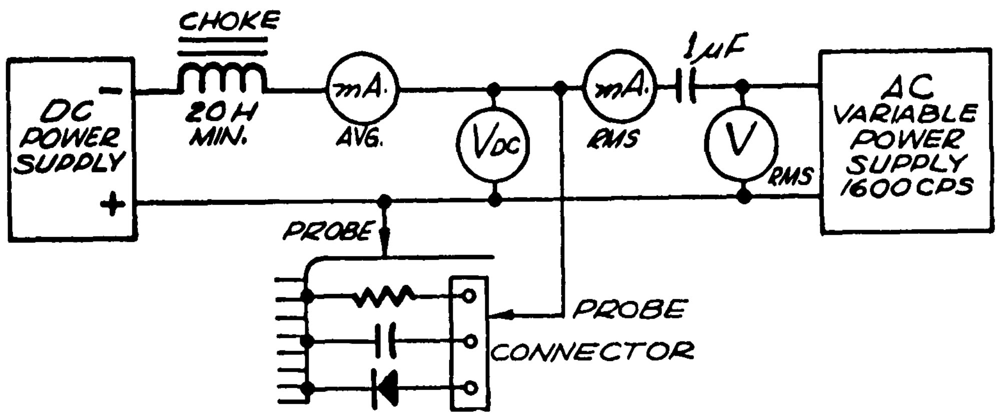
2.2.2.3 Read voltage drop between negative terminal and heat sink of module.
Note: Include voltage drop of all connections.

2.3 Reverse Voltage Test

Test all rectifier modules of one high voltage rectifier column together to include test results in the rectifier column test report.

2.3.1 Test Circuit:

2.3.1. **Test Circuit:**



2.3.2 **Testing**

2.3.2.1 Connect output of AC-DC tester with positive lead to heat sink of module and negative lead to anode connector.

2.3.2.2 Apply specified direct voltage as indicated on the DC voltmeter.

2.3.2.3 Apply specified alternating voltage as indicated on the AC meter by rotating the AC rheostat.

2.3.2.4 Read resulting currents.

2.3.2.5 DC current must be between tabulated limits. Less current means resistance too high; more current means resistance too low and/or diode bad.

2.3.2.6 AC current must be between tabulated limits. Less current means too small capacitance; more current means too high capacitor.

2.3.2.7 Certified test report of rectifier <u>module</u> must be shipped with each high voltage rectifier stack.

3. <u>TEST FOR HIGH VOLTAGE RECTIFIER COLUMN</u>

Inspection Conditions: Inspection conditions shall be in accordance with the referenced paragraphs:

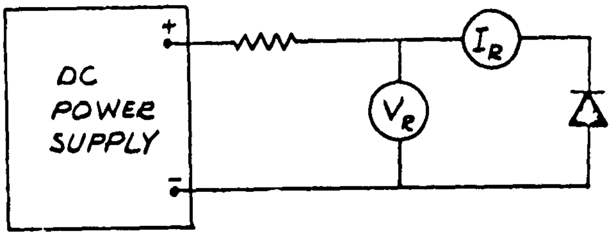
Ref.		Condition	AQL %	Sym.	Min.	Max.	Unit
3.1	Group A Inspection Visual & Mechanical	Major Minor	1.0 2.5				
3.2	DC Reverse Current	Item 1a V_R=30 KV dc T_A=125°C		I_R		10	mA dc
		Item 1b V_R=40 KV dc T_A=125°C		I_R		10	mA dc
3.3	Forward Voltage	Item 1a I_F=10A dc T_A=25°C		V_F		33	V dc
		Item 1b I_F=5A dc T_A=25°C		V_F		45	V dc

3.1 Visual and Mecnanical Inspection

Visual inspection, checking for assembly of parts, polarity, continuity and clearances.

3.2 DC Reverse Voltage Test

3.2.1 Test Circuit



3.2.2 Testing

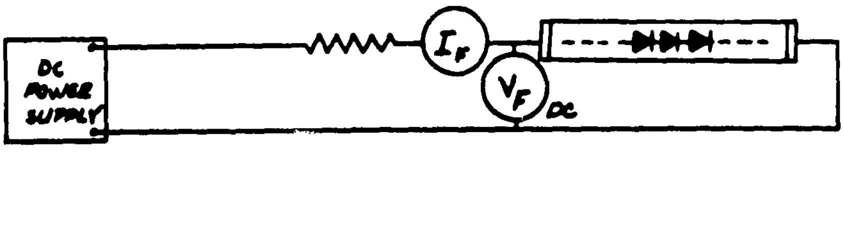
Connect a DC power supply (5% ripple max.) to diode. Increase the voltage to V_R. Observe leakage current for 10 seconds. Reject diode if:

3.2.2.1 Leakage current exceeds the specified value.

3.2.2.2 Leakage current is not stable but increases with time (runaway).

3.3 Forward Voltage Drop

3.3.1 Test Circuit:



3.3.2 Testing:

3.3.2.1 Connect a DC (5% ripple max.) power supply to terminals of the rectifier column.

3.3.2.2 Apply specified forward current I_F as read on average reading DC meter.

3.3.2.3 Read voltage drop across column on DC voltmeter.

4. <u>HI-POT TEST FOR HIGH VOLTAGE RECTIFIER COLUMN</u>

4.1 Elevated Temperature Test at 125°C.

4.1.1 Short terminals together with copper wire.

4.1.2 Connect DC power supply between shorted terminals and tank.

4.1.3 Apply 30 KV for Item 1a - 40 KV for Item 1b - and hold for one minute.

4.1.4 Record leakage current.

4.1.5 Retest per Para. 3.2.

<u>TEST RESULTS</u>

The test results for the module and column tests for the sixth set of engineering samples are given on the following pages.

ENGINEERING SAMPLES, SIXTH SET

TEST RESULTS

ITEM 1a

Test Date: March 27, 1963

PART NO. 67-7501

COLUMN NO. 1

Module Test

MODULE NO.	FORWARD VOLTAGE @ 10A V dc	REVERSE AC ma rms	CURRENT DC ma dc	MODULE NO.	FORWARD VOLTAGE @ 10A V dc	REVERSE AC ma rms	CURRENT DC ma dc
1	.95	21.5	0.6	15	.96	21.5	0.6
2	.95	22	0.6	16	.95	21.5	0.6
3	.95	22	0.6	17	.95	21.5	0.6
4	.95	21.5	0.6	18	.95	22	0.6
5	.95	22	0.6	19	.95	22	0.6
6	.95	22	0.6	20	.96	22	0.6
7	.95	21.5	0.6	21	.95	21.5	0.6
8	.95	22	0.6	22	.95	21.5	0.6
9	.95	21.5	0.6	23	.95	22	0.6
10	.95	21.5	0.6	24	.95	22	0.6
11	.95	21.5	0.6	25	.95	21.5	0.6
12	.96	21.5	0.6	26	.95	21.5	0.6
13	.95	21.5	0.6	27	.96	22	0.6
14	.95	22	0.6	28	.95	22	0.6

Column Test

Reverse Current: 5.7 mA dc at 30 KV dc at 135°C.
Forward Voltage: 24 volt dc at 10A dc at 25°C.

High Potential Test

Leakage Current: 1.10 mA dc at 30 KV dc at 135°C.

ENGINEERING SAMPLES, SIXTH SET

TEST RESULTS

ITEM 1a Test Date: March 28, 1963

PART NO. 67-7501

COLUMN NO. 2

Module Test

MODULE NO.	FORWARD VOLTAGE A 10Adc V dc	REVERSE AC ma rms	CURRENT DC ma dc	MODULE NO.	FORWARD VOLTAGE @ 10Adc V dc	REVERSE AC ma rms	CURRENT DC ma dc
1	.95	21.5	0.6	15	.95	22	0.6
2	.95	22	0.6	16	.95	21.5	0.6
3	.95	21.5	0.6	17	.96	21.5	0.6
4	.96	22	0.6	18	.95	21.5	0.6
5	.95	22	0.6	19	.95	21.5	0.6
6	.95	21	0.6	20	.96	21.5	0.6
7	.95	21	0.6	21	.95	21.5	0.6
8	.95	21.5	0.6	22	.95	21.5	0.6
9	.95	21.5	0.6	23	.95	21.5	0.6
10	.95	21.5	0.6	24	.95	22	0.6
11	.95	21.5	0.6	25	.95	21.5	0.6
12	.95	21	0.6	26	.96	21.5	0.6
13	.95	21.5	0.6	27	.95	21.5	0.6
14	.95	21.5	0.6	28	.96	22	0.6

Column Test

Reverse Current: 3.7 mA dc at 30 KV dc at 125°C.
Forward Voltage: 24.5 volt dc at 10 A dc at 25°C.

High-Potential Test

Leakage Current: 0.40 mA dc at 30 KV dc at 125°C.

ENGINEERING SAMPLES, SIXTH SET

TEST RESULTS

ITEM 1b   Test Date: March 12, 1963

PART NO. 67-7502

COLUMN NO. 1

Module Test

MODULE NO.	FORWARD VOLTAGE A 10A V dc	REVERSE AC ma rms	CURRENT DC ma dc	MODULE NO.	FORWARD VOLTAGE @ 10A V dc	REVERSE AC ma rms	CURRENT DC ma dc
1	.96	21.5	0.6	20	.96	21	0.6
2	.95	21.5	0.6	21	.95	22	0.6
3	.95	21.5	0.6	22	.95	22	0.6
4	.95	21.5	0.6	23	.95	22	0.6
5	.95	21.5	0.6	24	.95	22	0.6
6	.95	22	0.6	25	.95	21.5	0.6
7	.96	21.5	0.6	26	.95	22	0.6
8	.95	21.5	0.6	27	.95	21.5	0.6
9	.95	22	0.6	28	.95	22	0.6
10	.95	22	0.6	29	.95	21.5	0.6
11	.96	22	0.6	30	.95	22	0.6
12	.95	21.5	0.6	31	.95	21.5	0.6
13	.95	22	0.6	32	.96	21.5	0.6
14	.95	21.5	0.6	33	.95	21.	0.6
15	.95	22	0.6	34	.95	22	0.6
16	.95	22	0.6	35	.95	21.5	0.6
17	.95	22	0.6	36	.95	22	0.6
18	.95	21.5	0.6	37	.95	21	0.6
19	.95	21.5	0.6				

Column Test:

Reverse Current: 2.50 mA at 40 KV dc at 125°C.
Forward Voltage: 32.5 V dc at 10 A dc at 25°C.

High-Potential Test

Leakage Current: 0.40 mA dc at 40 KV dc at 125°C.

ENGINEERING SAMPLES, SIXTH SET

TEST RESULTS

ITEM 1b   Test Date: March 27, 1963

PART NO. 67-7502

COLUMN NO. 3

Module Test

MODULE NO.	FORWARD VOLTAGE @ 10Adc V dc	REVERSE AC ma rms	CURRENT DC ma dc	MODULE NO.	FORWARD VOLTAGE @ 10Adc V dc	REVERSE AC ma rms	CURRENT DC ma dc
1	.95	22	0.6	20	.95	21.5	0.6
2	.95	22	0.6	21	.95	22	0.6
3	.96	21.5	0.6	22	.95	22	0.6
4	.96	22	0.6	23	.95	22	0.6
5	.95	22	0.6	24	.95	21.5	0.6
6	.95	22	0.6	25	.95	22	0.6
7	.95	22	0.6	26	.95	21.5	0.6
8	.96	22	0.6	27	.95	21.5	0.6
9	.96	21.5	0.6	28	.96	22	0.6
10	.96	21.5	0.6	29	.95	22	0.6
11	.95	21.5	0.6	30	.95	21.5	0.6
12	.95	21.5	0.6	31	.96	21.5	0.6
13	.95	21.5	0.6	32	.95	21.5	0.6
14	.95	21.5	0.6	33	.95	22	0.6
15	.96	21.5	0.6	34	.95	22	0.6
16	.95	22	0.6	35	.95	22	0.6
17	.95	21.5	0.6	36	.95	21.5	0.6
18	.95	22	0.6	37	.95	21.5	0.6
19	.95	21.5	0.6				

Column Test

Reverse Current: 3.2 mA dc at 40 KV dc at 125°C.
Forward Voltage: 33 volt dc at 10 A dc at 25°C.

High-Potential Test

Leakage Current: 0.31 mA dc at 40 KV dc at 125°C.

ENGINEERING SAMPLES, SIXTH SET

DESIGN TESTING

TESTING OF SOLID INSULATING MATERIALS

Insulation Between High Potential and Ground

The solid insulating material used in the supporting tubes is melamine-glass fiber #G5, of the Taylor Fiber Company. From our previous tests it was understood that this material is needed to support the live parts of the rectifier to withstand vibration and shock. It has good insulating properties at room temnerature, but it was concluded from the test reported in Quarterly Progress Report No. 6, pages 34 through 36, that its properties are greatly reduced at a higher temperature.

Previously observed failures were encountered through the laminated material along the direction of the laminations. This was remedied by increasing the flash-over or puncturing distance which allowed the material to be used at higher temperature and full voltage.

A new series of tests were instigated, using the previously made electrodes for testing both the stresses across the laminations and along the surface of the material. This is shown in the Figures 13 through 18. Figure 13 shows the test of a solid tube, Figure 14 of a smaller section, both using the large electrodes. A new top electrode was made, shown on Figure 15, which has a dimension of 1x1". Figure 16 shows the two metal electrodes, together with five pieces of insulating material, ranging from 2x2" to 4x4" in ½" steps. Figure 17 shows the tester with the small electrode and a small piece of insulating material. Figure 18 shows the tester with a larger piece of insulating material.

It was assumed that these tests would give results of increasing breakdown voltage, when going from a small piece of insulation to a larger piece of insulation, because of the increase in creepage distance between the small top electrode and the large bottom electrode, around the rim of the insulating material.

The tests results were in contradiction to the predicted behavior. It was found, at 125°C, that the insulating material which had a thickness of 3/16" would puncture at voltages ranging from 10 KV dc to 25 KV dc, with a definite correlation between the distance of the electrode from the rim, and the flash-over voltage, as shown in the Figure 19. This behavior of the tested materials is very unusual. As observed and expected: When the creepage distance increases, the breakdown voltage increases. However, inspection of the failed material shows, in every instance, that the breakdown occurred as a direct puncture of the material! There are absolutely no signs of surface creepage or partial surface-and-puncture flash-over. There are also no signs of a flash-over by partial puncture across the laminations and partial internal creepage along the laminations. The behavior cannot be explained. We may assume that a combination of effects caused this, for example: First dc creepage

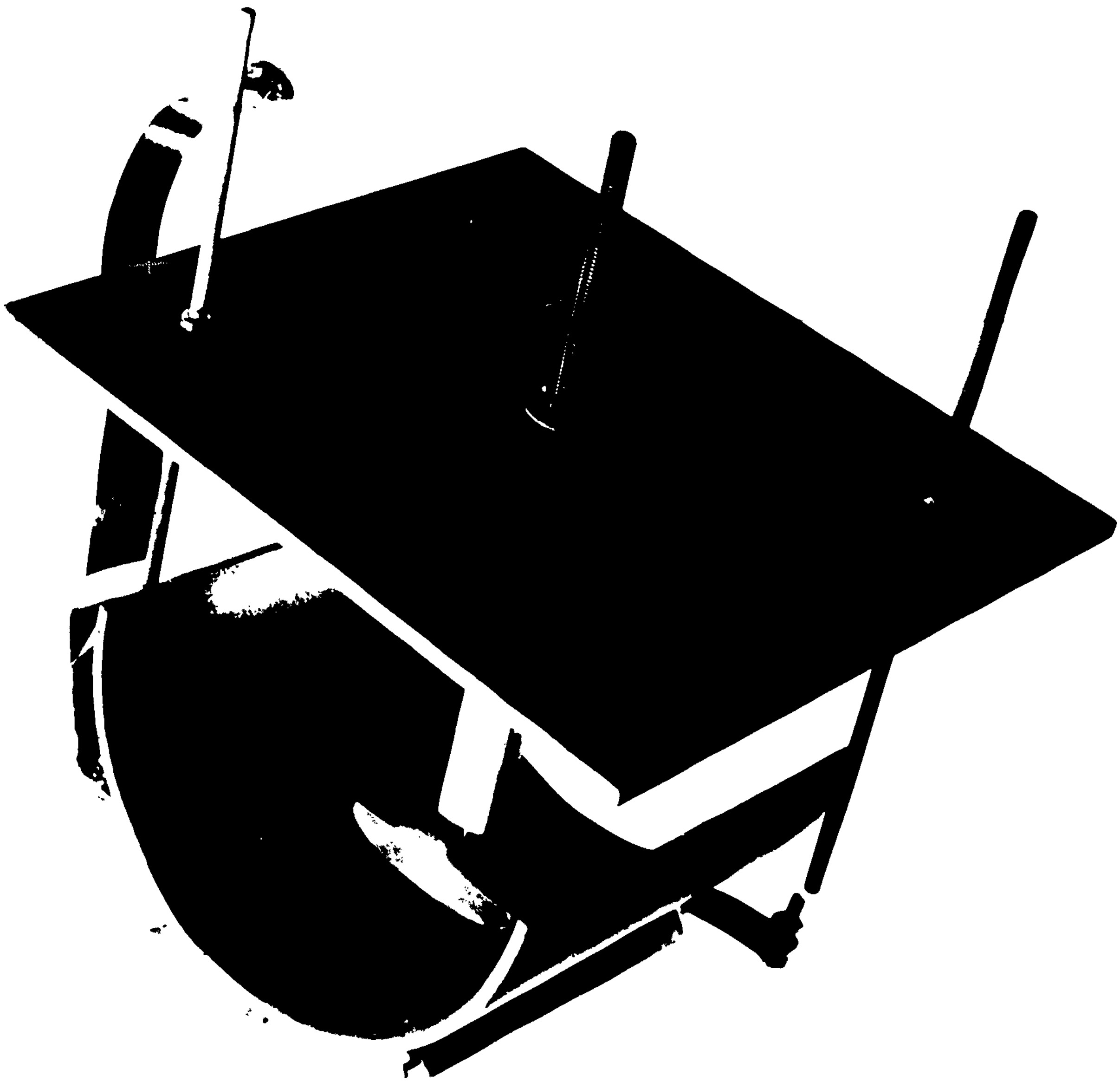


Fig. 13

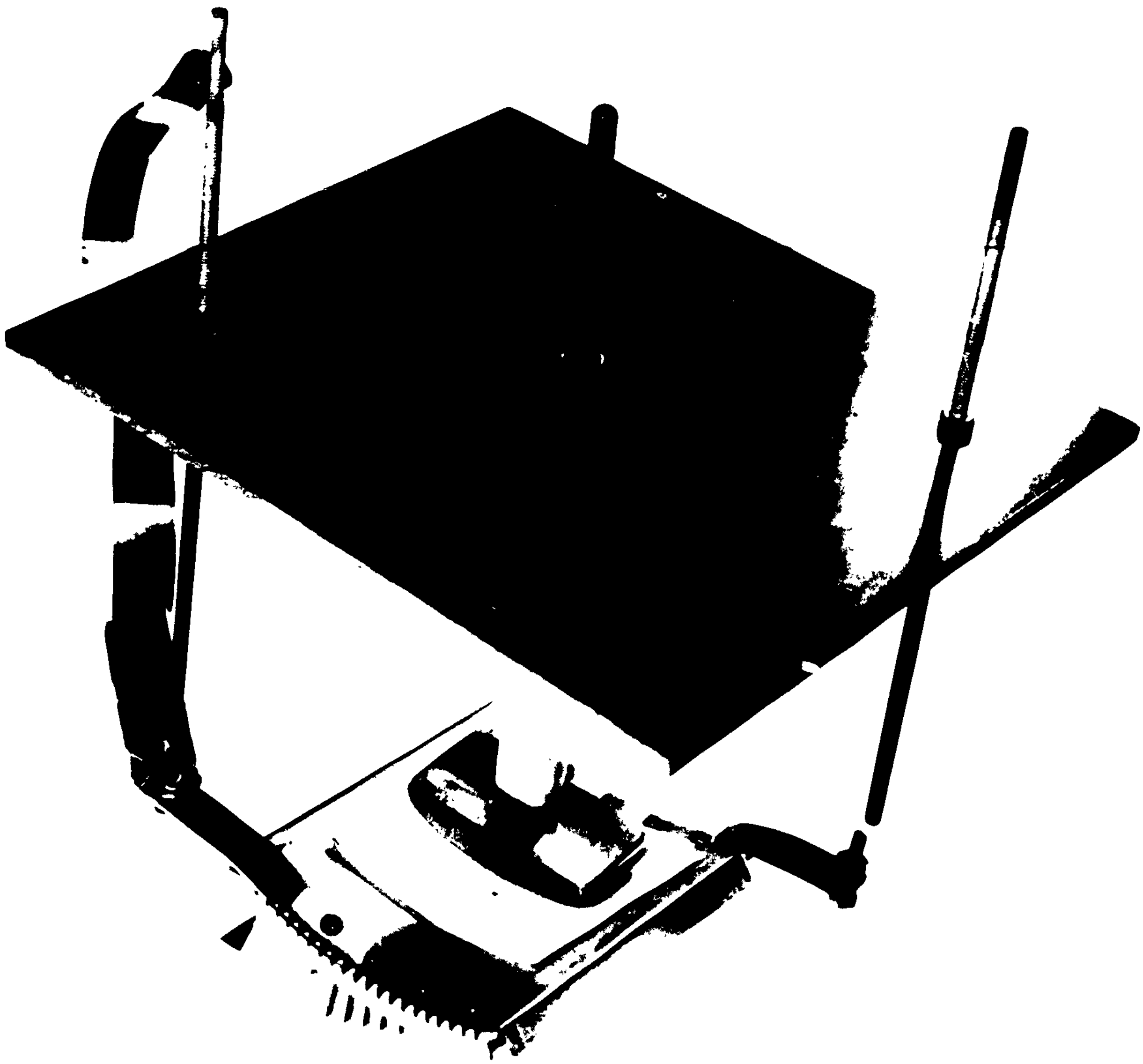


Fig. 14

Fig. 15

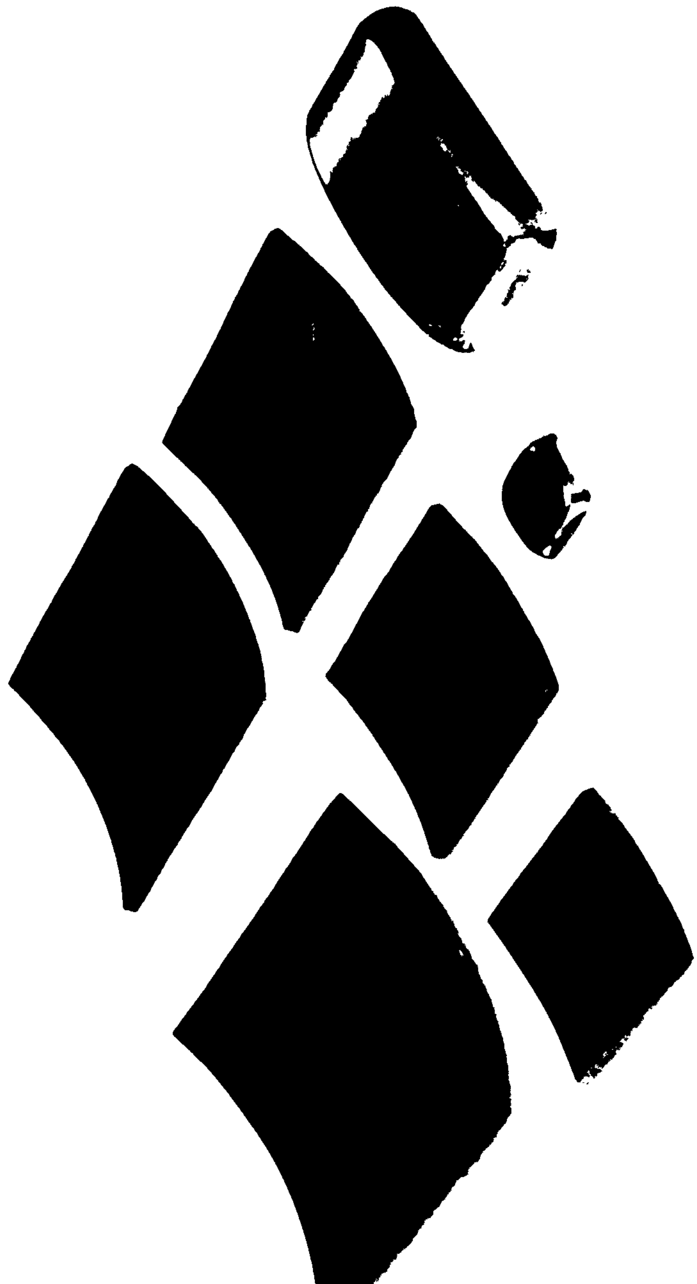


Fig. 16

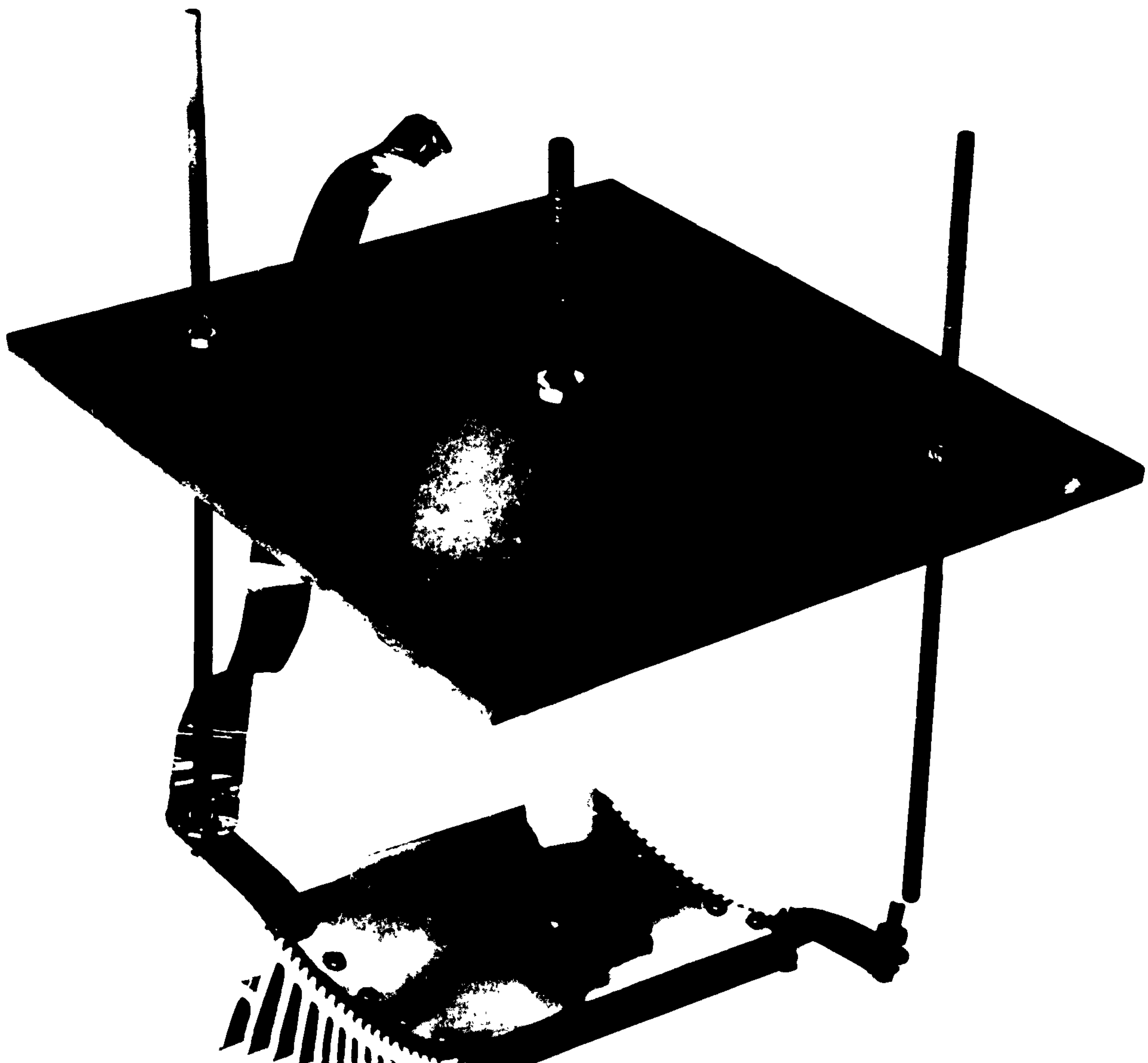


Fig. 17

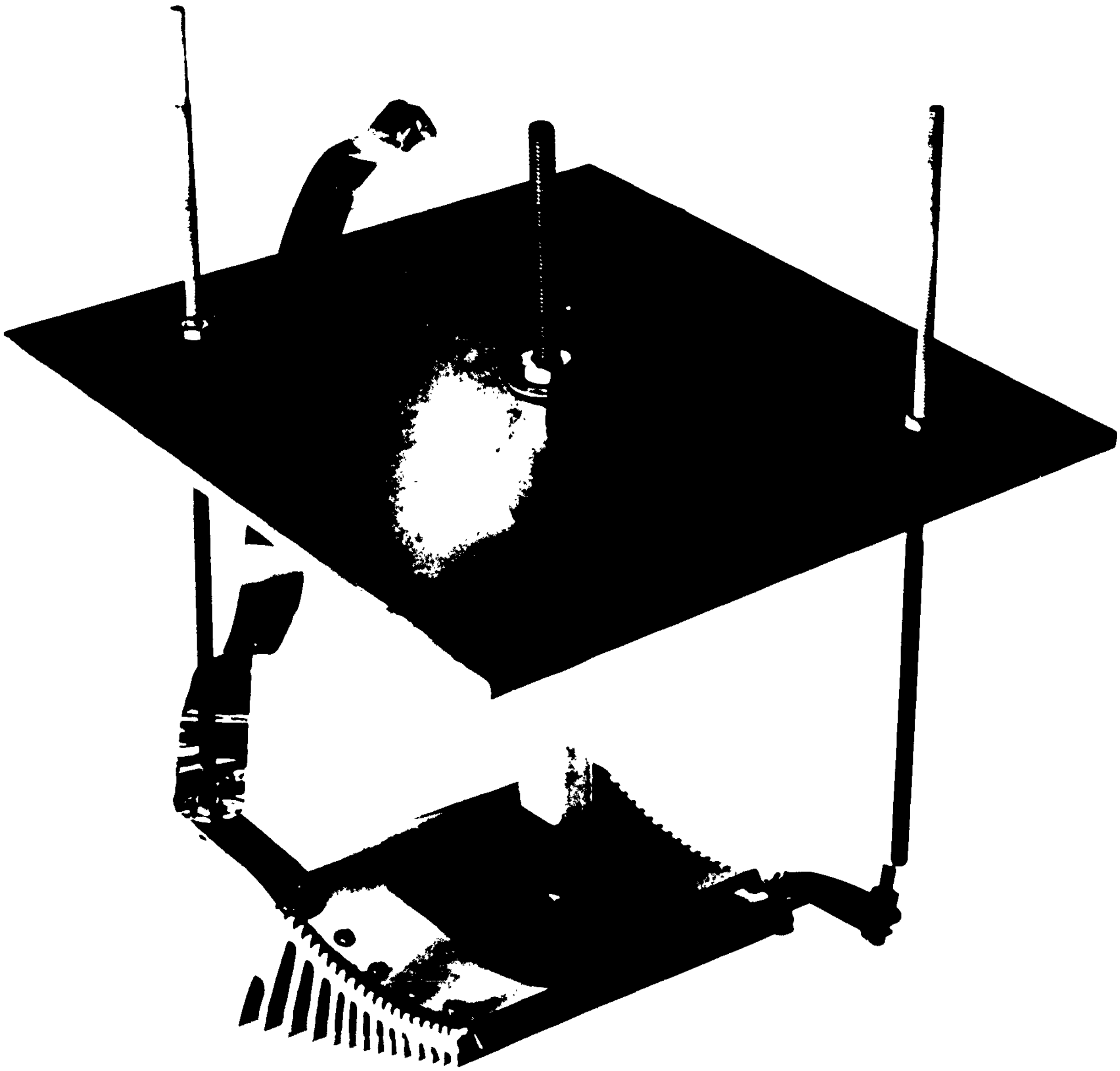


Fig. [illegible]

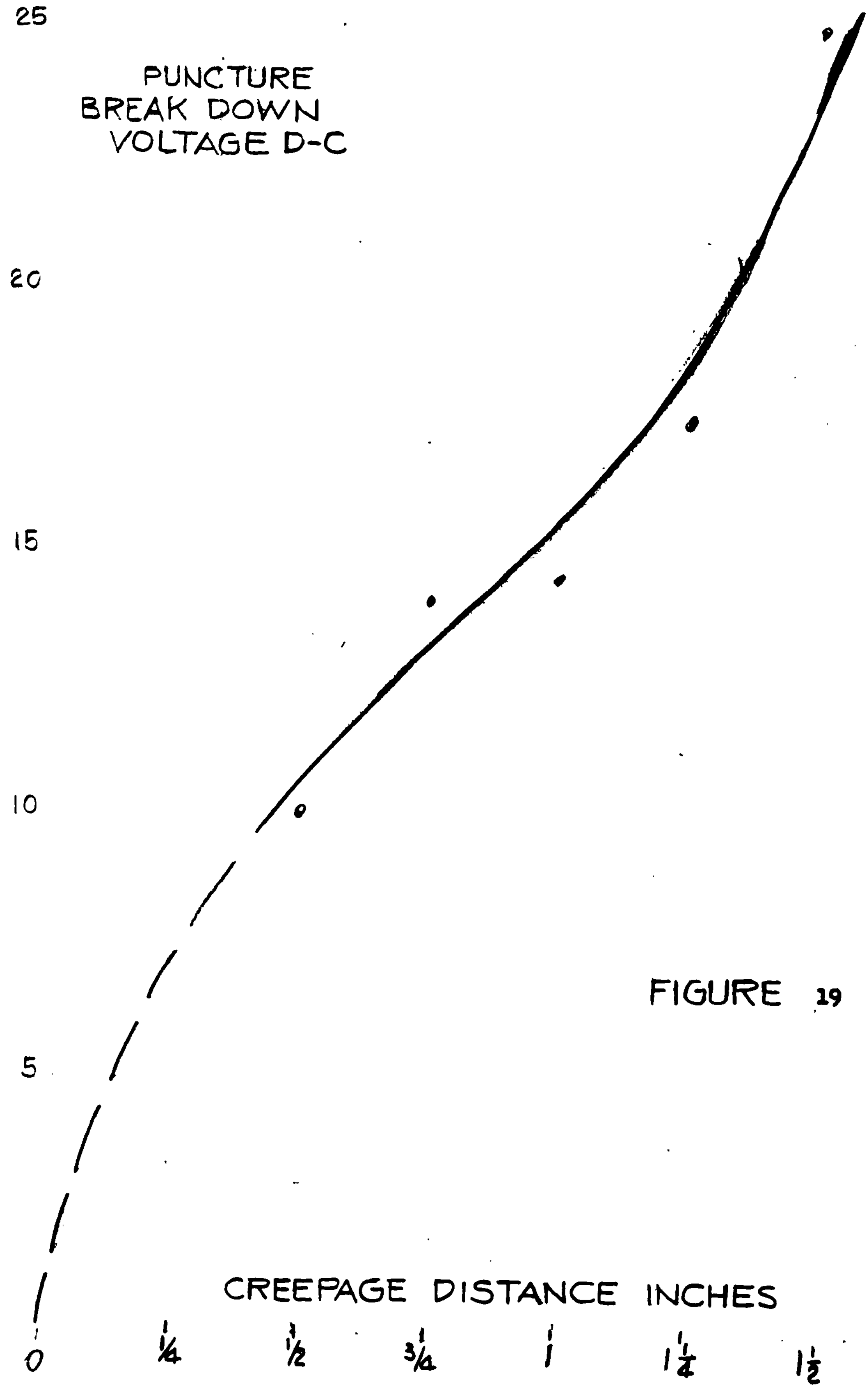

25
PUNCTURE
BREAK DOWN
VOLTAGE D-C
20
15
10
5
CREEPAGE DISTANCE INCHES
0
¼
½
¾
1
1¼
1½

FIGURE 19

currents causing a certain surface charge and space charge distribution creating enough local field stresses to puncture the insulating material.

Tests which were made with the devices of the fifth set of engineering samples seemed to indicate than an insulating distance of 2" is sufficient to hold the voltage across the same insulating material at full temperature when applied parallel to the laminations of the material. The new test results cast doubt upon this conclusion, a better assumption would be that no high voltages at all should be applied to these tubes. A combined potential stress applied both normally and tangentially to the fibers of the insulating material (as tried in the above tests) has proved to be an unreliable practice for extremely high voltage.

Figure 13 shows a test set up with high insulating distance, eliminating almost entirely the creepage effects. At 120°C a puncture voltage breakdown of 30 KV dc was experienced, much too low for using this material for holding the full voltage of the device.

It was assumed, from the published information, that Teflon (DuPont trademark) would be a much better insulating material at the required temperature. Therefore, a test similar to the foregoing was made on a sheet of Teflon, 4x4" with a thickness of .103". Testing at 120°C and 50 KV dc and ac showed no arc-over, arc-through or measurable leakage current.

Conclusions

Teflon (DuPont trademark) is a very satisfactory insulating material for those structural requirements where a high voltage must be held across a short distance, when subjected to a high temperature under Pyranol.

Melamine-glass (grade G5) is not capable of withstanding high voltages (30 to 50 KV dc) when subjected to temperatures above 120°C submerged in Pyranol. Increasing the flash-over or puncture distances is not an economical remedy.

Insulators for holding the full voltage will be made of ceramic or Teflon materials. Melamine-glass tubes, where required for structural shapes, will be subjected to much lower voltage levels over relatively long distances.

Insulation Between Modules

Although a redesign of all the basic proportions of the rectifier had to be made, to account for the different properties of materials discovered during these tests, the basic concept of the rectifier has remained unchanged. This is essentially: The assembly of a plurality of identical modules (each of them containing a rectifier diode, resistor and capacitor) around the periphery of an insulating tube, these modules progressing in a helix. This is shown on Figures 6, page 13 and 7, page 14, of the Quarterly Progress Report #6.

Because of the helicoidal progress of the series connected string of modules, the voltage from module to module is very low. The highest voltage appearing over a relatively short distance is the one between turns of the helix. Even this voltage is not very high, if the helix is dimensioned properly. Modules are fastened to the insulating tube by means of screws bolted into metallic inserts in the tube. Such screws can be seen on Figure 2, Page 8, of the Quarterly Progress Report #6. Knowing the distance between screws and the voltage applied per module, and hence per turn of the helix, it is possible to predict the distance and the voltage appearing on each insulating segment of the tube. Thus another set of tests were undertaken to prove that the chosen melamine-glass tube (grade G5) would be satisfactory for this application.

The test was performed on a set up similar to the one shown in the foregoing pictures, except that the two electrodes were replaced by brass screws bolted into holes built into the melamine-glass tube. The flash-over distance between screws was held in exact distances of:

1/2 , 3/4 , 1 , 1-1/2 , 2 and 2-1/2 inches.

Several rows of these pairs of screws were made and tested, both with dc and ac, when submerged in Pyranol #1488 at a temperature of 125°C. The results are shown on Figure 20, solid black dots represent flash-over voltages measured with dc voltage applied.

When applying ac voltage, flash-over could only be obtained up to 1" spacing, with the voltage increased up to 48 KV RMS. At the spacing of 1½, 2 and 2½" no flash-over was attained at 50 KV RMS.

The tests prove again that the dc stress under high temperature and Pyranol is much more severe than the ac stress.

The tests prove also that the material can withstand a very substantial voltage below the 30 KV limit over a relatively short distance, but that it is not recommended to hold higher voltages than 30 KV dc, regardless of the distance.

After the actual design of the new assembly was made, the insulating tubing was built for 10-32 brass screws with inserts, mounted 1.82 inches apart, to duplicate the actual mounting. A test voltage of 14.4 KV dc was chosen, to duplicate the worst voltage stress occurring between turns of the helix on the insulating tube. Voltage was applied for 10 minutes at 125°C. After this, the voltage was increased to total breakdown. The test showed no measurable leakage currents or change in the test system after applying 14.4 KV dc for 15 minutes. Increasing the voltage to 20 KV dc, a current of 20 microampere was measured after several minutes. Increasing the voltage to 25KV, the dc leakage current proved to be unstable, increasing gradually to complete electric breakdown after 15 seconds.

Since the 14.4 KV dc represents the peak rectified diode voltage applied over this distance and not the continuous dc voltage, which can never be held at that value for any length of time in the real application, the measured breakdown voltage of 25 KV is considered to be safe. Accordingly, the melamine-glass tube is used as planned.

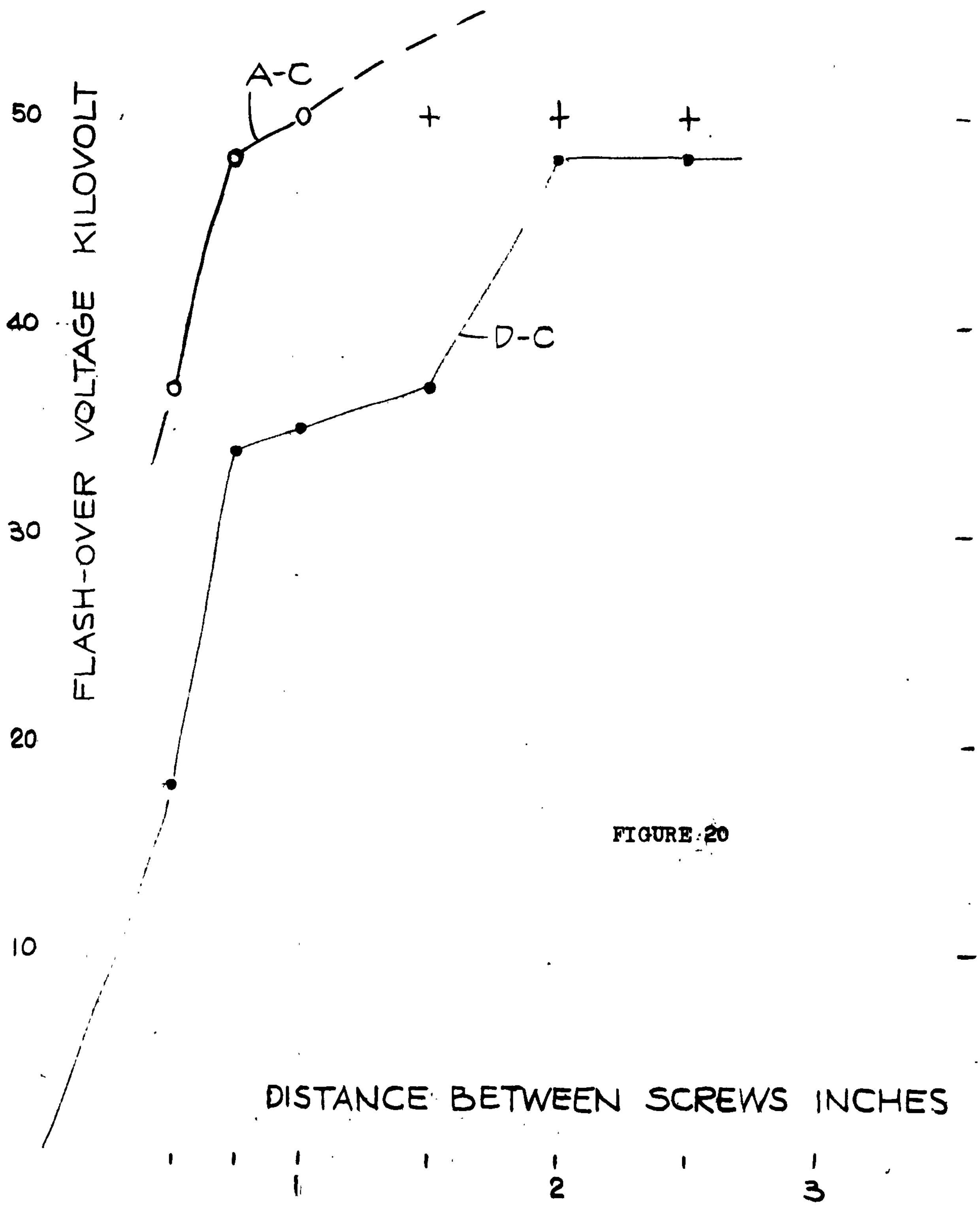

FLASH-OVER VOLTAGE KILOVOLT
50
40
30
20
10
A-C
D-C
DISTANCE BETWEEN SCREWS INCHES
1
2
3

FIGURE 20

ENGINEERING SAMPLES, SIXTH SET

DESIGN TESTING

TESTING OF INSULATING FLUIDS

Acknowledgement

The manufacturer of the insulating fluids (Askarels) with the trade names Aroclor, Pyranol and Inerteen is:

Monsanto Chemical Company
Organic Chemicals Division
St. Louis 66, Missouri

Our investigations were greatly facilitated by the advice and cooperation given by:

Mr. P. G. Benignus
Manager, Technical Service
Aviation and Special Fluids
of Monsanto Chemical Company

Tests described in the following were conducted on free samples obtained from this Company. Samples were returned for chemical analysis provided by the courtesy of the same Company.

Purpose of Test

The previous quarter testing of liquid dielectrics was based on Aroclor 1242.

The new series of tests was initiated on Pyranol 1470 after consulation with Monsanto Chemical Corporation. The reasons for abandoning Aroclor 1242 are outlined on pages 112 and 113 of the Quarterly Progress Report #6.

Test of Pyranol #1470

Pyranol 1470 was selected for these tests because it has the widest span between low temperature limit (pour point) and high temperature limit (distillation start). A summary of its properties is shown in Table I. (Monsanto Chemical Co.):

The composition of Pyranol 1470 is:

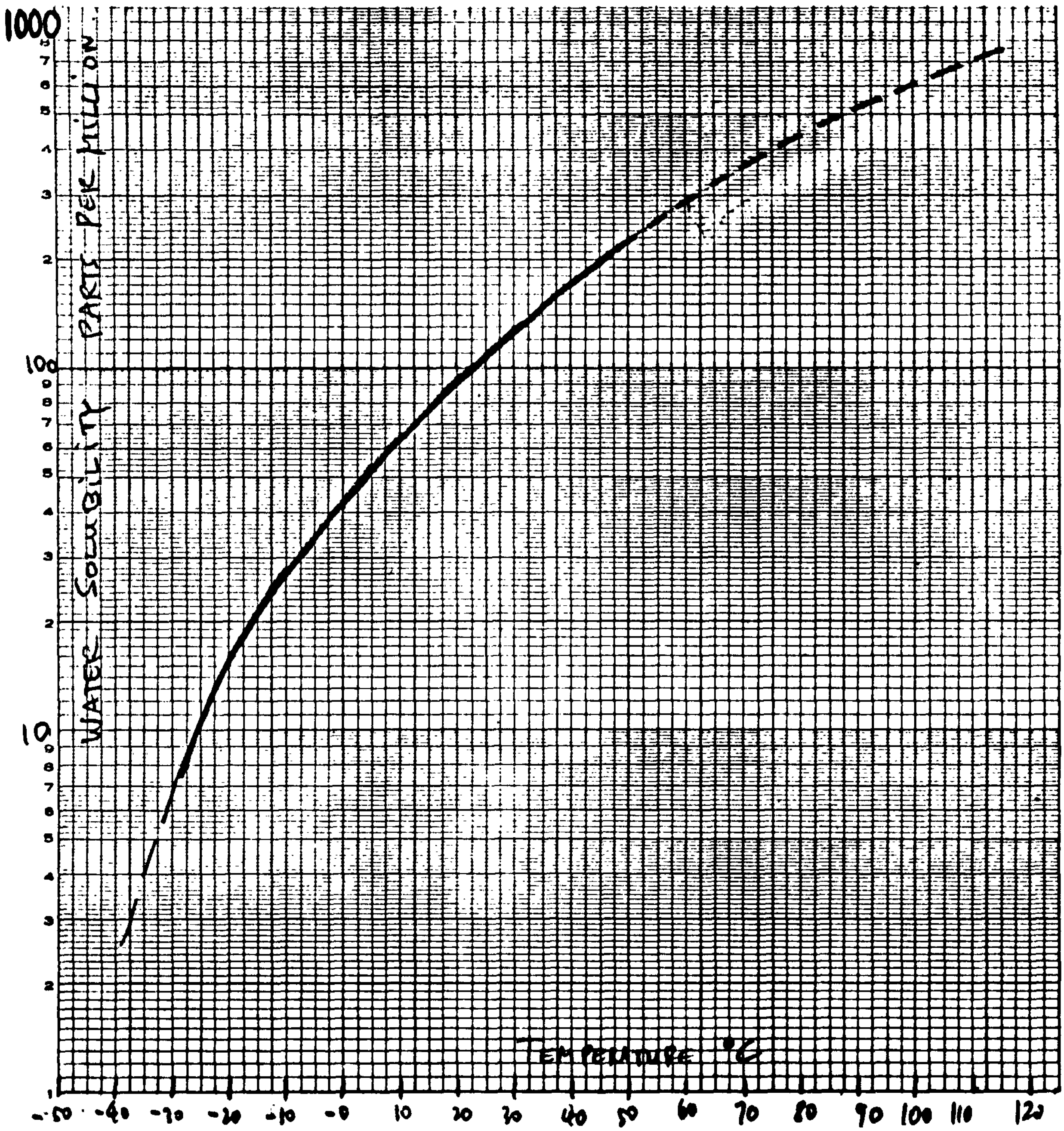
45% Aroclor 1260 (Hexachlorobiphenyl)
55% Tri-,Tetrachlorobenzene mix
0.125% Tin Tetraphenyl Scavenger

Water solubility vs temperature is shown on Figure 21. Dashed lines are extrapolations. The curve illustrates the necessity to eliminate all humidity in the immersed parts, otherwise water will be dissolved by the Pyranol (dehydrating the parts) at high temperature; later it will precipitate in the Pyranol at low temperature, which ruins its dielectric properties.

TABLE I

Transformer Askarel
Shipping Specifications

Properties	Pyranol 1467	Pyranol 1470	Inerteen PPO
Color, APHA	150 max.	150 max.	150 max.
Condition	Clear	Clear	Clear
Water content, ppm (ASTM D1533-60)	30 max.	30 max.	30 max.
Acidity, mg. KOH/g. (ASTM D974-55)	0.01 max.	0.01 max.	0.01 max.
Dielectric Strength, 25°C., 0.1 inch gap (ASTM D877-49)	35 KV, min.	35 KV, min.	35 KV, min.
Dielectric Constant, 100°C., 1 KC (ASTM D924-49)	3.7 to 4.0	3.8 to 4.3	3.7 to 4.0
Volume Resistivity, 100°C., 500 volts DC 0.1 inch gap, 10^9 ohm-cm.	100	100	100
Inorganic chlorides, ppm.	0.10 max.	0.10 max.	0.10 max.
Refractive index, 25°C. (ASTM D901-56)	1.6137 to 1.6147	1.6075 to 1.6085	1.6137 to 1.6147
Viscosity at 37.8°C. (ASTM D88-56) Saybolt Universal Seconds	54 ±2	41 to 45	54 ±2
Pour point °C. (ASTM D-97-57)	−32 or lower	−44 or lower	−32 or lower
Specific gravity 15.5/15.5°C. (ASTM D287)	1.560 to 1.563	1.563 to 1.571	1.560 to 1.568
Burn point (ASTM D92)	None to boiling	None to boiling	None to boiling
Distillation range (ASTM D20-56) corrected for stem and barometric pressure	1st drop 200°C. min. 40% below 270°C. 90% 395 to 415°C.	1st drop 210°C. min. 35% 240 to 256 55% 290 to 330 65% 385 to 400 95% 395 to 415	1st drop 200°C. min. 40% below 270°C. 90% 395 to 415°C.
Fixed chlorine	59.1% min.	60.5 ±5%	59.1% min.
Corrosion test	After heating with aluminum for 6 hrs. at 200 to 220°C., the aluminum must not be corroded either on visual or weight inspection and the askarel should meet the following specifications:		
Color, APHA	200 max.	200 max.	200 max.
Acidity, mg. KOH/g.	0.01 max.	0.01 max.	0.01 max.
Inorganic chlorides ppm.	5.0 max.	5.0 max.	2.0 max.
Condition	Clear	Clear	Clear
Scavenger content	0.125% tin tetraphenyl	0.125% tin tetraphenyl	0.18 to 0.22% phenoxy propene oxide
Arc formed gases	Less than 1.0% of total combustible gases including carbon monoxide, hydrogen and volatile hydrocarbons.		



1000
100
10
1
WATER SOLUBILITY PARTS PER MILLION
TEMPERATURE °C
-50 -40 -30 -20 -10 -0 10 20 30 40 50 60 70 80 90 100 110 120

FIGURE 22

The testing apparatus, power supplies and measuring equipment is the same as described in the Quarterly Progress Report #6, pages 91-107.

The electrode configuration was in accordance with Figure 31 and 34 of the Quarterly Progress Report #6. The tester was first set at a distance of 3/8" between electrodes. At room temperature the electrodes were subjected to both ac voltage, up to 50 KV rms and dc voltage up to 48 KV. In neither case a flash-over was experienced and the leakage current was immeasurably small. Hence, Pyranol 1470, at room temperature, with this electrode configuration, gives good dielectric performance.

Corona measurements with ac at a peak voltage of approximately 40 KV showed a noise of 800 MV. The corona was unilateral with small discharge peaks occurring randomly at substantial intervals.

Increasing the ac voltage to 50 KV RMS (70 KV peak) showed substantial corona occurring almost over the entire cycle at every cycle, forward and backward and with a magnitude of 10 V or more.

Corona measurements with dc showed corona of approximately 1 volt at 26 KV dc. The frequency of the corona was low.

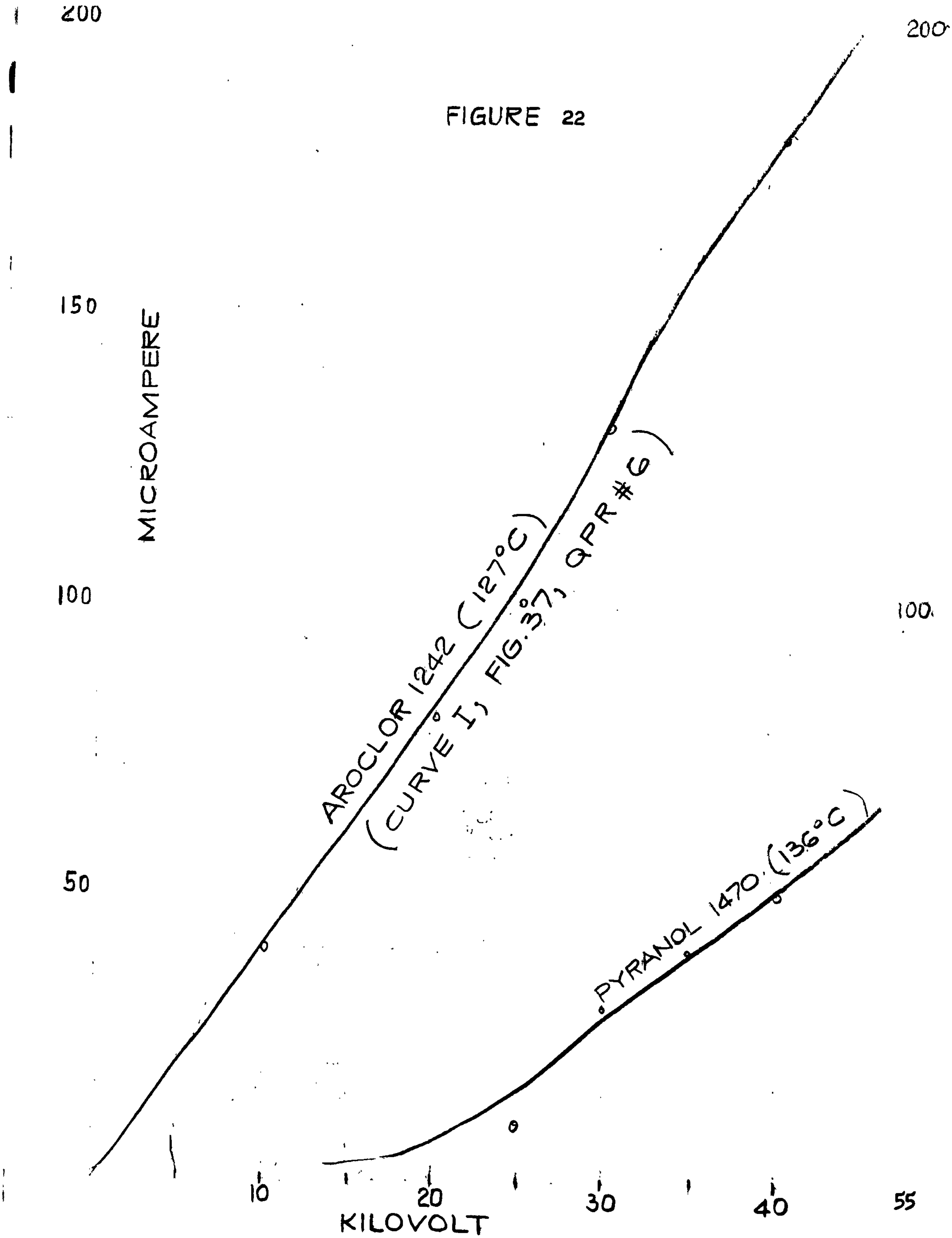
It was hard to determine if the above described corona was in the liquid, or on the test leads in air.

Using the same set up, the tester was heated to a temperature of 136°C and the leakage current was measured. This is shown in Figure 22 as a comparison of the performance of Pyranol 1470 at 136°C, and Aroclor 1242 at 127°C (curve I, Figure 37, page 111, Quarterly Progress Report #6). At this electrode distance, the performance in Pyranol 1470 could not be improved by letting the set stay at high temperature and high voltage (which greatly improved the Aroclor 1242). Thus no cleaning of fluid by electric stress at high temperature was experienced.

A further test was made with a spacing of 7/8" at a temperature of 125°C. Initially, at 40 KV a leakage current of 19 microampere was observed. After 5 minutes at 40 KV the dc leakage current was reduced to 5 microampere, later decreasing to 1 microampere or less. Accordingly, it was concluded that the Pyranol was slightly contaminated and at this large electrode distance it was cleaned up by the flow of dc current at high temperature and high voltage. The test proves definitely that Pyranol 1470 has a very high resistivity at high temperature and voltage and that this resistivity improves with the applied electric stress by internal clean-up of the liquid, however, a large electrode spacing is required for this effect to take place.

A further test was made with the same spacing of 7/8" but a temperature of 150°C. Initially, the leakage current was measured to be 30 microampere, decreasing to 20 microampere after 5 minutes, after 5 minutes intervals decreasing to 10 microampere, later 2 microampere and finally 1 microampere and less.

FIGURE 22



200
150
100
50
200
100
MICROAMPERE
AROCLOR 1242 (127°C)
(CURVE I, FIG. 37, QPR #6)
PYRANOL 1470 (136°C)
10
20
30
40
55
KILOVOLT

The above tests show that the dielectric performance of Pyranol 1470 under direct potential is very good. It seemed to be a substance suitable for the particular application. However, during these tests it was observed that black deposits were forming in the Pyranol. Hence they were repeated with an observer located close to the tester in the high voltage enclosure. This showed the rapid growth of very thin black whiskers between the electrodes, starting at the negative grounded electrode and protruding towards the positive (smaller) electrode.

After discussing this penomena with Monsanto Chemical Company it was assumed that these whiskers were formed by the scavenger additive in the Pyranol (0.125% of Tin tetraphenyl).

The high voltage tests were then interrupted to procure another grade of Pyranol 1488 which does not contain this scavenger.

Test of Pyranol 1488

Because of the problems encountered with the formation of black whiskers in Pyranol 1470, a test quantity of Pyranol 1488 was obtained. This material is a mixture of 60% Aroclor 1260 (hexachlorobiphenyl) and 40% Trichlorobenzene without the addition of any scavenger. Therefore, it was assumed that no whiskers would appear.

The test was repeated with the smooth electrodes shown in the Quarterly Progress Report #6, Figures 31 (page 103) and 34 (page 106).

The first test was made with a spacing of 3/8". The test results are shown on Figure 23. Curve A shows the dc leakage current (microampere) against applied dc voltage (kilovolt) at room temperature.

The same tests were then repeated at 125°C, curve B, and 150°C, curve C. These curves are interesting inasmuch as they show a very different behavior in increasing and in decreasing voltages, as indicated by the arrows. In each case the voltage was driven to 50 kilovolt and maintained there for 5 minutes, after which it was slowly decreased to zero. It can be seen by these curves that a definite amount of cleaning of the Pyranol by the influence of applied dc potential and temperature is achieved.

Comparing these curves with the results of curves A and B, Figure 35, page 109 of the Quarterly Progress Report #6, shows the great improvement in the performance of this Pyranol over the Aroclor 1242. It is also interesting to note that the descending branch of the curve for Pyranol 1488 is very similar to the curve obtained with Pyranol 1470 as shown in Figure 22, page . Therefore, the insulating properties of these two Pyranols are assumed to be very similar.

Tests were run at 50 kilovolt dc and 150°C to obtain whiskers. No whiskers could be observed.

Further tests were run at room temperature, with the same spacing of 3/8" with ac voltage applied. At 50 kilovolt RMS ac voltage, no

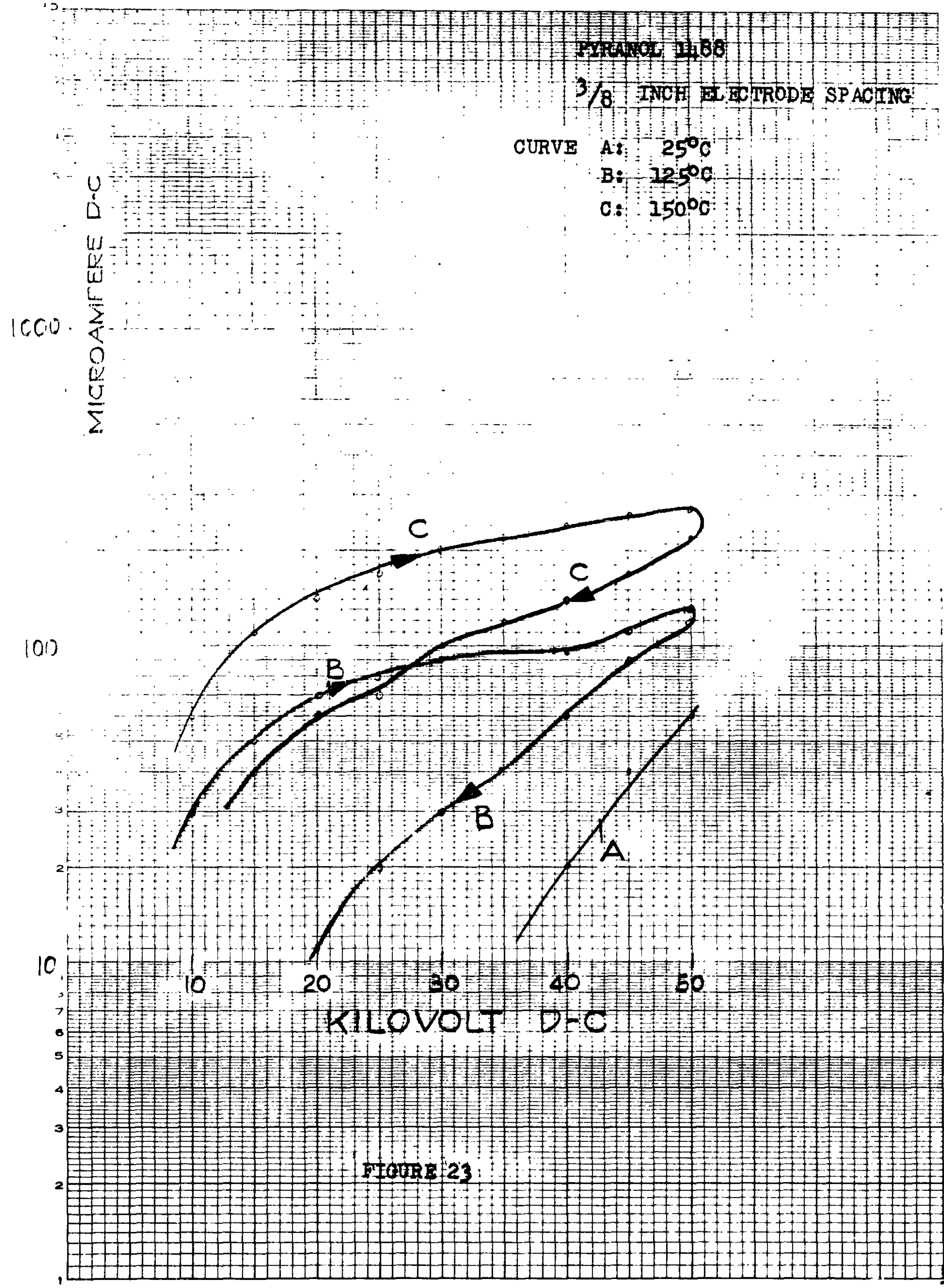

PYRANOL 1468
3/8 INCH ELECTRODE SPACING
CURVE A: 25°C
B: 125°C
C: 150°C
MICROAMPERE D-C
1000
100
10
10
20
30
40
50
KILOVOLT D-C
A
B
C

FIGURE 23

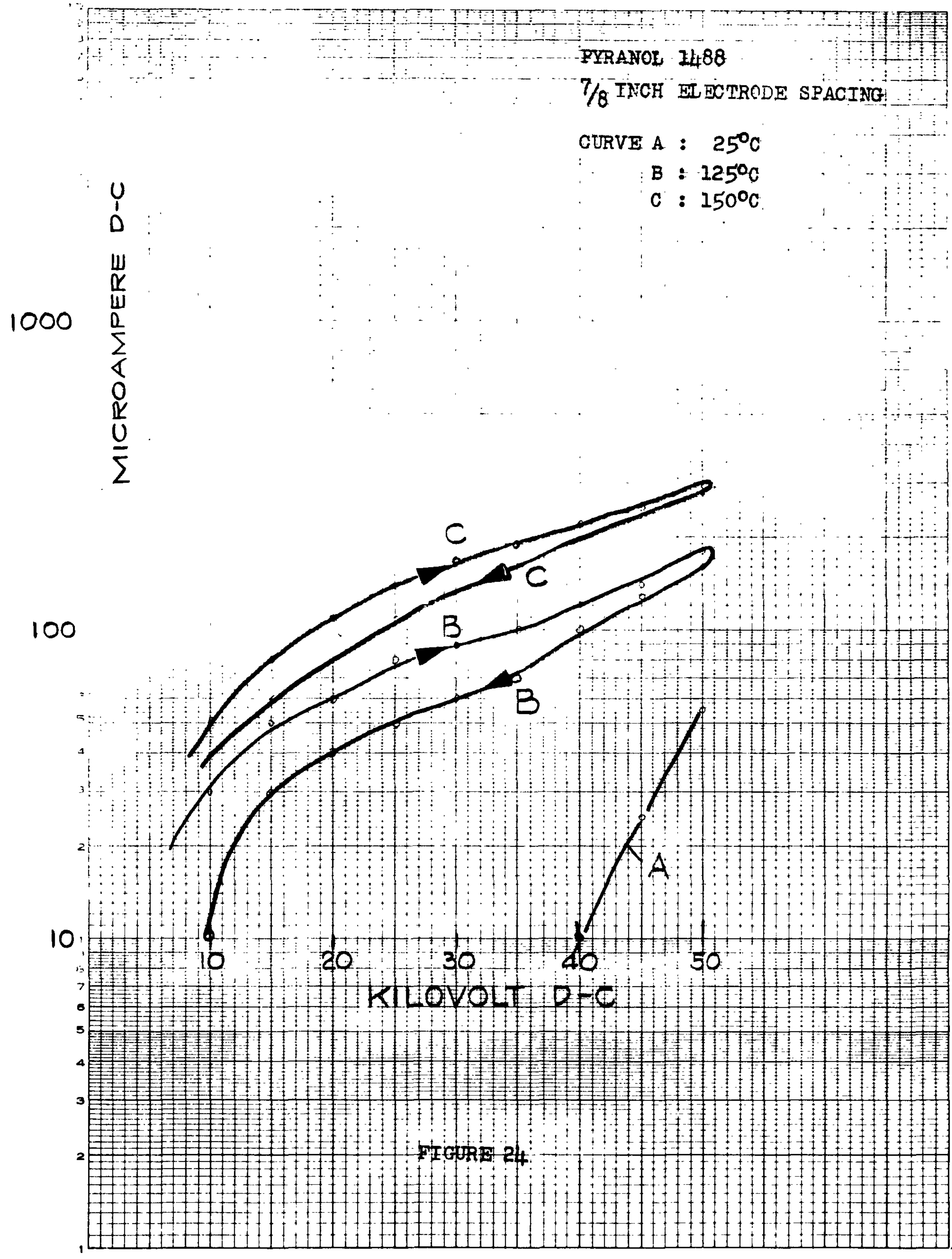

PYRANOL 1488
7/8 INCH ELECTRODE SPACING
CURVE A : 25°C
B : 125°C
C : 150°C
MICROAMPERE D-C
1000
100
10
KILOVOLT D-C
10
20
30
40
50
A
B
C

FIGURE 24

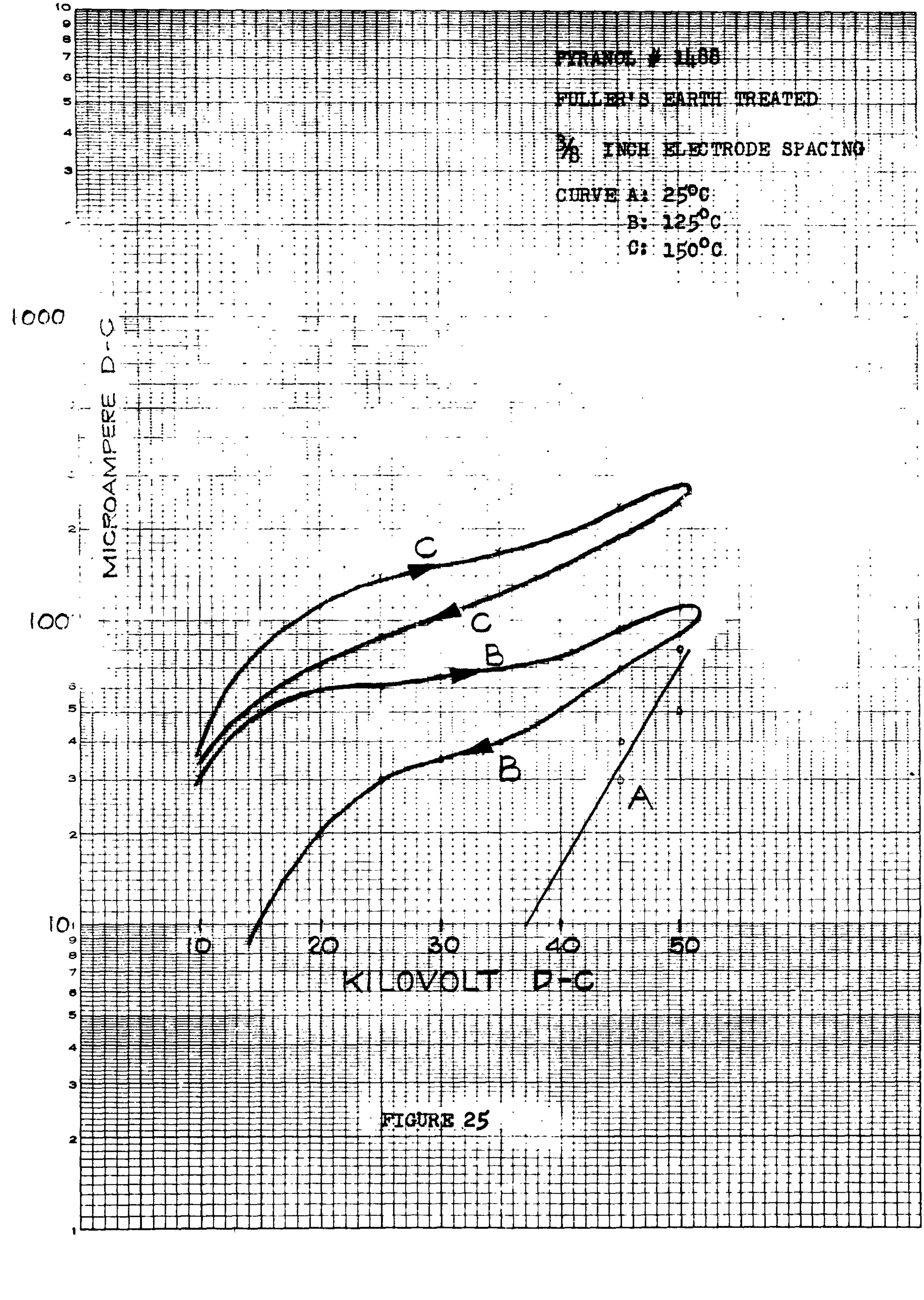

PYRANOL # 1468
FULLER'S EARTH TREATED
3/8 INCH ELECTRODE SPACING
CURVE A: 25°C
B: 125°C
C: 150°C
1000
100
10
MICROAMPERE D-C
KILOVOLT D-C
10
20
30
40
50
A
B
B
C
C

FIGURE 25

reverse current could be measured and no flash-over occurred. Repeating the test at 125°C it showed again no measurable reverse current or flash-over at 50 kilovolt ac RMS. Subjecting this to the corona test showed a corona of 1 volt. This may have been in the parts exposed to the air, not in the liquid.

Another set of tests were performed at an electrode spacing of 7/8". These results are shown on Figure 24. Curve A shows again the results of the test performed at room temperature. It is apparent that increasing the spacing reduces the current only very slightly, but that the current values are very low. Repeating the test increasing and decreasing in the voltage at 125°C gives curve B. Another test at 150°C showed the results of curve C.

From these tests we conclude that the material is able to withstand this voltage without obtaining black whiskers, which were observed neither on ac nor on dc, for both spacings, with voltages up to 50 KV dc and 50 KV RMS ac. The results show also that the material was formerly contaminated with water and thus gave unreliable results.

Accordingly, the entire series of tests was repeated after the Pyranol was treated with Fuller's earth. This treatment is a standard procedure for the treatment of transformer Pyranol or Askarel and serves to eliminate all the moisture from the fluid. The test was performed as soon as possible after the treatment had been performed. The results of these tests are shown on Figures 25 and 26.

Figure 25 shows test results for Pyranol 1488, immediately after Fuller's earth treatment, with the same electrodes as in the former tests, set at a spacing of 3/8". Curve A represents the current versus applied voltage at room temperature. Curve B shows the current versus voltage at a temperature of 125°C. The decreasing curve was taken 5 minutes after the increasing curve. As before, the simultaneous application of dc voltage and temperature causes some improvement in the dielectric properties. In this case, since the fluid was treated with Fuller's earth, the humidity must have been reduced, still the effect prevails. Comparing this curve with Figure 23, page , shows that a definite improvement was achieved but the material is still not very stable.

Curve C shows the same test performed at 150°C. Apparently at this high temperature the purification is more apparent, the curve shows a narrower looping and a definitely lesser current than in the former tests. In accordance with these tests we may conclude that the originally selected distances of 3/8" for 30 kilovolt and 1/2" for 40 kilovolt were sufficient, if we could use the proper fluid with the proper chemical treatment. Still, it was concluded that the danger of contamination is too great so that the material should be stressed at a lesser level to allow for a safer performance over a long time.

For this reason the sequence of tests was repeated with an electrode-spacing of 7/8". This is shown in Figure 26. Curve A shows again the performance at room temperature. Curve B shows a performance at 125°C. Evidently, the looping of the curve has been greatly

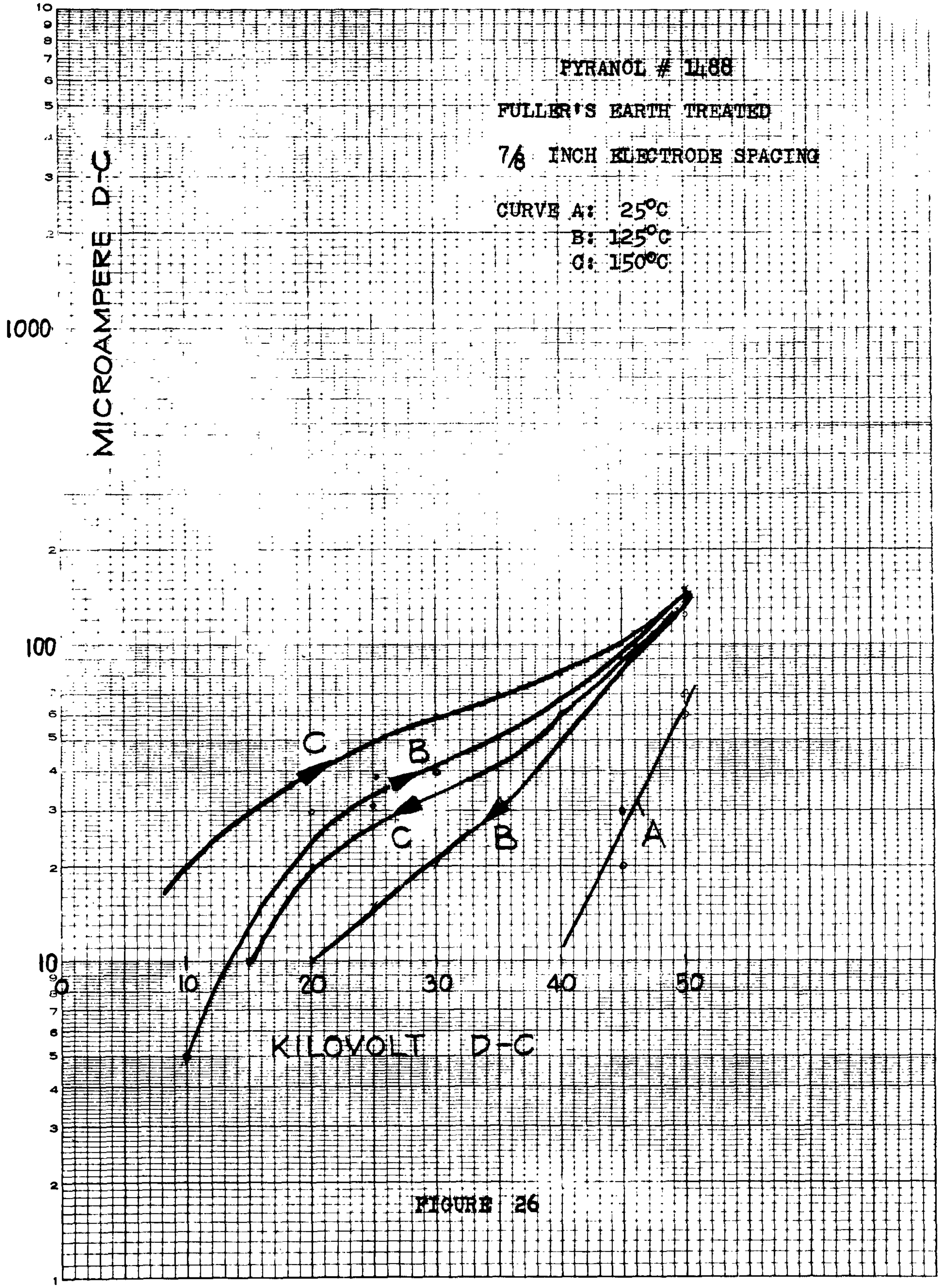

PYRANOL # 1488
FULLER'S EARTH TREATED
7/8 INCH ELECTRODE SPACING
CURVE A: 25°C
B: 125°C
C: 150°C
MICROAMPERE D-C
1000
100
10
KILOVOLT D-C
0
10
20
30
40
50
A
B
C

FIGURE 26

reduced by the purification of the fluid. Furthermore, when comparing with Figure 24, which shows the same test with unpurified liquid, it is apparent that the current was reduced by approximately 50% at the maximum voltage of 40 KV. Thus the purification is a great improvement. This is even more apparent in curve C, which shows also a very substantial reduction. The apparently greater looping in Figure 26 is only due to the logarithmic scale in the ordinate, in reality the difference between increasing and decreasing current is the same or less, whereas the current at 40 KV was reduced to 36% of its former value.

From Figure 26 we conclude therefore that the greater dielectric safety distance between tank and module is particularly useful when the dielectric fluid is held very pure and dry and the greatest improvement will be brought at the highest temperature. Thus this increased safety distance is most usable in the highest performance region. Therefore, the redesign, in conjunction with the improvement of the material, is a decided improvement and offers great advantages.

The tests with dried Pyranol 1488 were also performed with ac up to 50 KV ac RMS, to determine corona and the growth of black whiskers. In both cases the 3/8" spacing and 7/8" spacing no flash-over or damaging arc was observed, the corona measured with the corona tester was very low, below 1 volt noise, and no whiskers were observed. This confirms the formerly reached conclusion that the real serious test is the dc high voltage test, whereas the performance under ac voltage is much better.

Polarity Influence

In all the foregoing tests the smaller electrode was held at positive potential, whereas the base electrode was held at negative potential. To find the difference of polarity, a new set of tests were made with both polarities in both positions.

The polarities tests were made at a spacing of 7/8" between the same electrodes as used before. In a first set of tests, Pyranol 1488 was used unrefined, therefore containing a certain amount of humidity. Figure 27 shows the test results. Curve A is the dc current leakage versus dc voltage at room temperature. Curve R shows the same curve with reverse polarity of electrodes.

The tests were then repeated at a liquid temperature of 125°C. Curve B shows the performance with standard polarity of electrodes, whereas curve S shows the performance with reverse polarity of electrodes. At the point F the test equipment broke down, punching a hole through the glass jar to the hot plate. Thus the test had to be stopped. These tests show that the influence of the polarity is small, however, the performance was very poor because the Pyranol was greatly contaminated with humidity.

The test was repeated with the same setting of electrodes, Pyranol 1488, at room temperature, and 125°C. after Fuller's earth treatment. The results are shown in Figure 28. Curve A shows again the room temperature test at standard polarity, curve R the room temperature test at reverse polarity. Curve B shows the high

PYRANOL 1488

7/8 INCH ELECTRODE SPACING

CURVE A: Standard Polarity: 25°C

R: Reverse Polarity: 25°C

B: Standard Polarity: 125°C

S: Reverse Polarity: 125°C

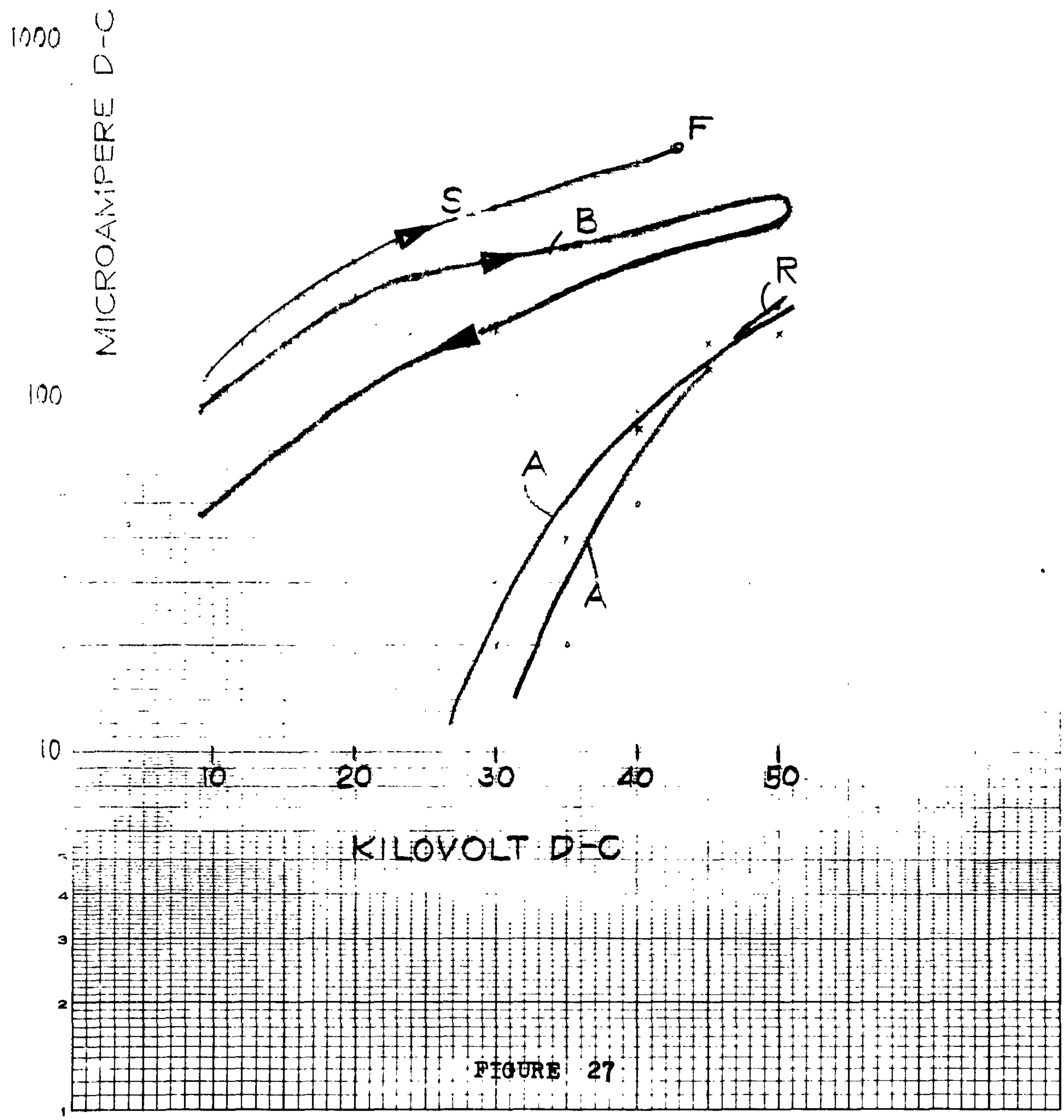


FIGURE 27

PYRANOL 1488
FULLER'S EARTH TREATED
7/8 INCH ELECTRODE SPACING

CURVE A: Standard Polarity, 25°C
R: Reverse Polarity, 25°C
B: Standard Polarity, 125°C
S: Reverse Polarity, 125°C

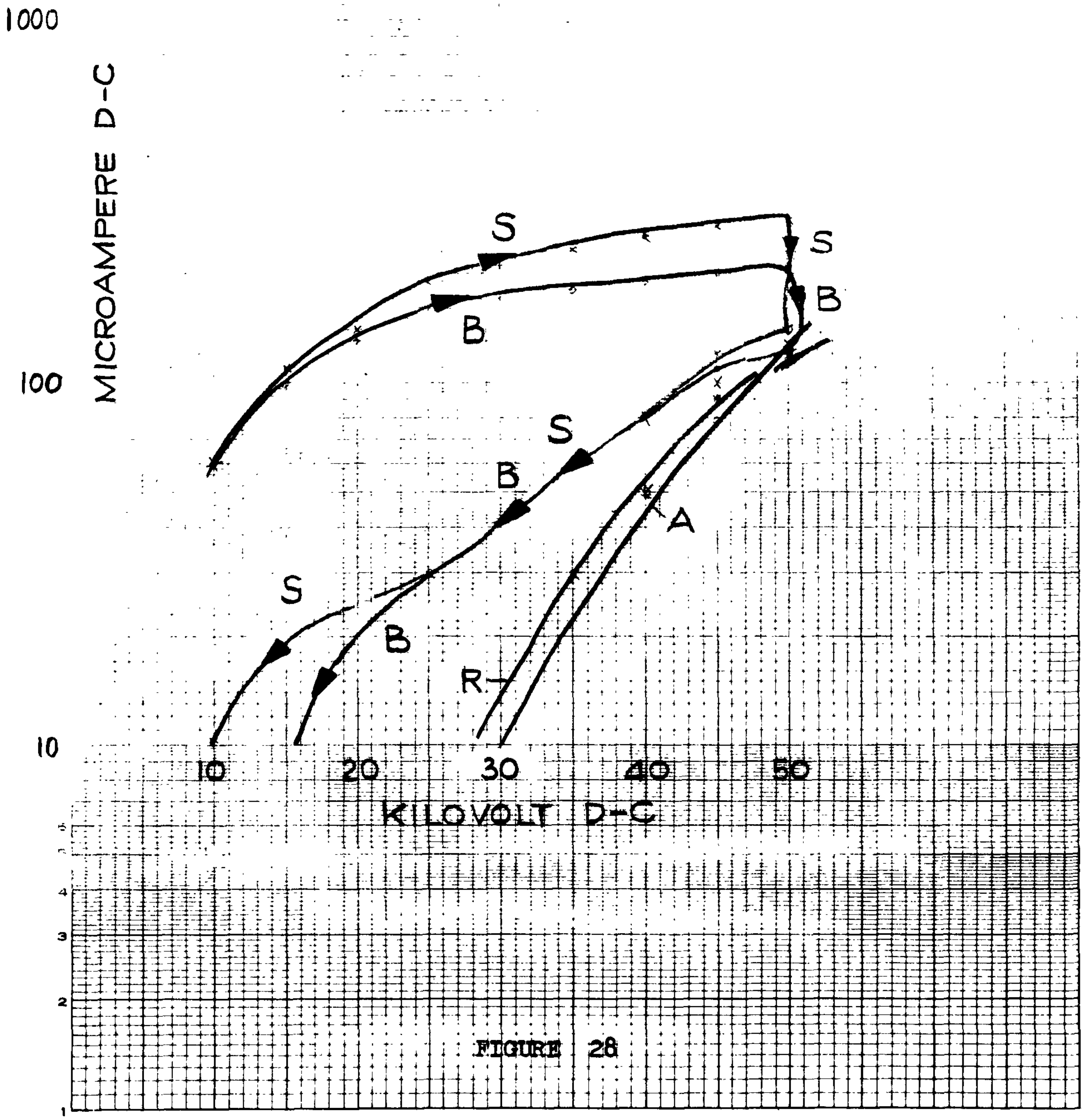


FIGURE 28

temperature 125°C tests of standard polarity (negative grounded), and curve S the high temperature test with reverse polarity. The pure Pyranol shows a definite improvement, also that the polarity sensitivity has been almost completely eliminated. It is most remarkable in these tests that the combined application of high temperature and high voltage still achieves a substantial improvement of the dielectric performance of the Pyranol. Since this improvement is greater with the pure dry Pyranol than with the humid Pyranol we have no explanation for this penomenon. It should be noted that all these tests were made with open vessels (as shown on Figure 22 through 26 on pages 94 through 98 of the Quarterly Progress Report #6). Accordingly the combined application of high voltage and high temperature may cause some evaporation of impurities of unknown nature which may not be possible in the fully enclosed vessel. It may, therefore, be necessary, when the fully enclosed vessel is available, to make specific tests to investigate these properties.

The foregoing tests were then repeated at 150°C. Curve F shows the behavior at normal forward polarity, small electrode positive, large electrode on the bottom negative. Upon reversing the polarity, curve G, Figure 29, was measured. It is very noticeable that on the upward trace the dc leakage current was very high. After five minutes at high temperature the reverse current was substantially reduced and the downward trace of curve G was measured. Thus, apparently, the reverse polarity performance requires a certain amount of "cleaning time", after which the performance in both polarities is approximately equal. At this high temperature and high potential, a small amount of black deposit was noticed inside the fluid. However, this was not a true formation of whiskers but possibly the result of breaking down some of the fluid. Black particles seemed to be dissolved by the fluid after the termination of the tests.

High Temperature Storage Test

In order to determine the influence of high temperature and high voltage over a longer time, the test was repeated with the same electrodes and the same Pyranol (No. 1488). The tester was set with standard polarity, positive on top, negative on the bottom and the voltage raised from 0 to 50 KV dc, resulting in the leakage current shown in the curve A of Figure 30. The voltage was then held at 50 KV for 15 hours, after which curve B was measured in the descending order.

Evidently, the high temperature high voltage operation is an open vessel for 15 hours eliminated some unknown impurities from the Pyranol (probably humidity), which resulted in a reduction of the leakage current, at 50 KV, from 340 microampere to 40 microampere, or from 100 to 12%. This test shows convincingly that utmost purity of the fluid is of prime importance and that the dielectric properties of the liquid, at high temperature and under dc stress, are absolutely not constant and can only be obtained with the greatest care in purity and treatment of all the devices.

Another interesting observation of this long time test on Pyranol

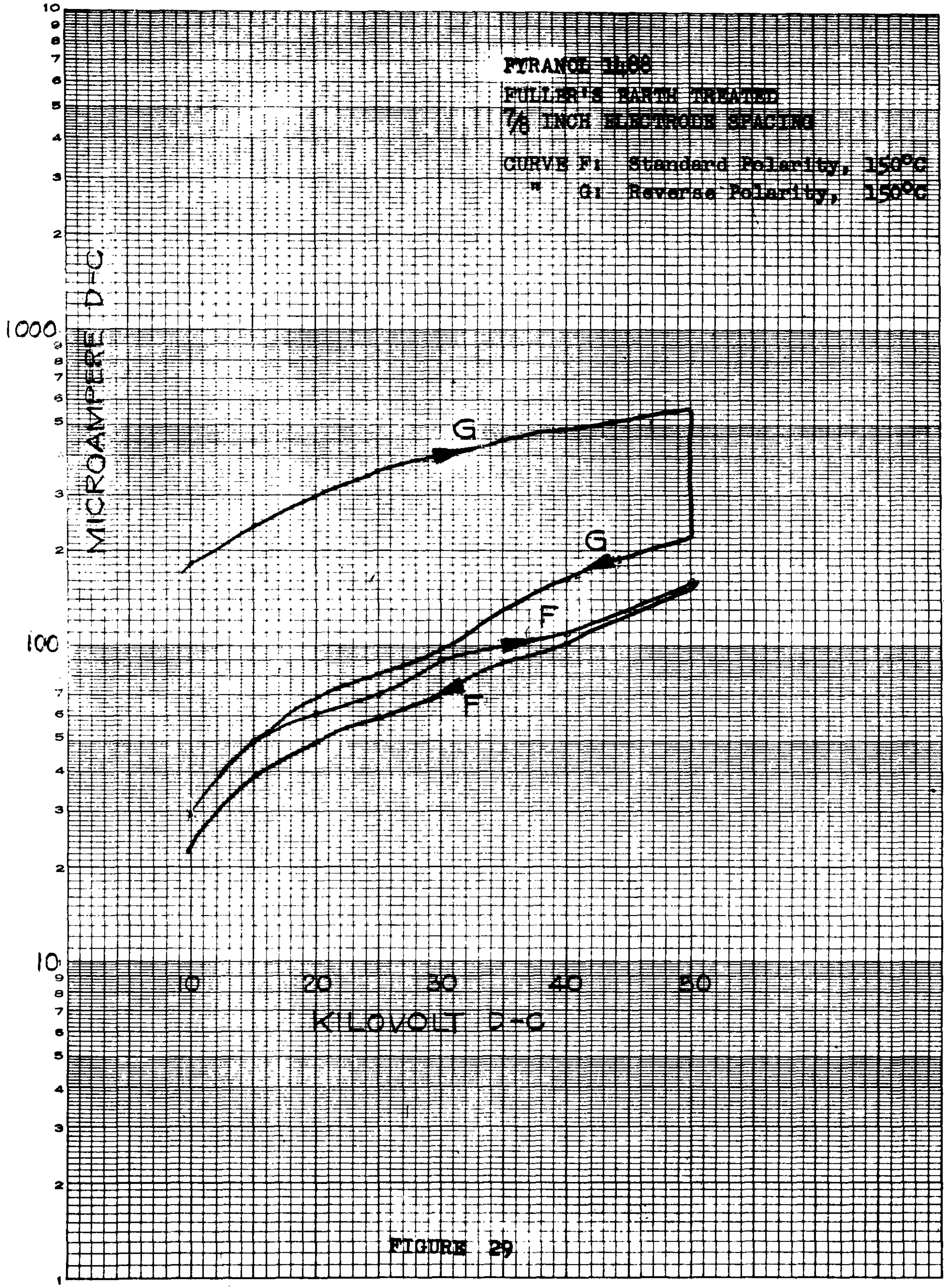

PYRANOL 1488
FULLER'S EARTH TREATED
7/8 INCH ELECTRODE SPACING
CURVE F: Standard Polarity, 150°C
" G: Reverse Polarity, 150°C
MICROAMPERE D-C
KILOVOLT D-C
G
G
F
F
1000
100
10
10
20
30
40
50

FIGURE 29

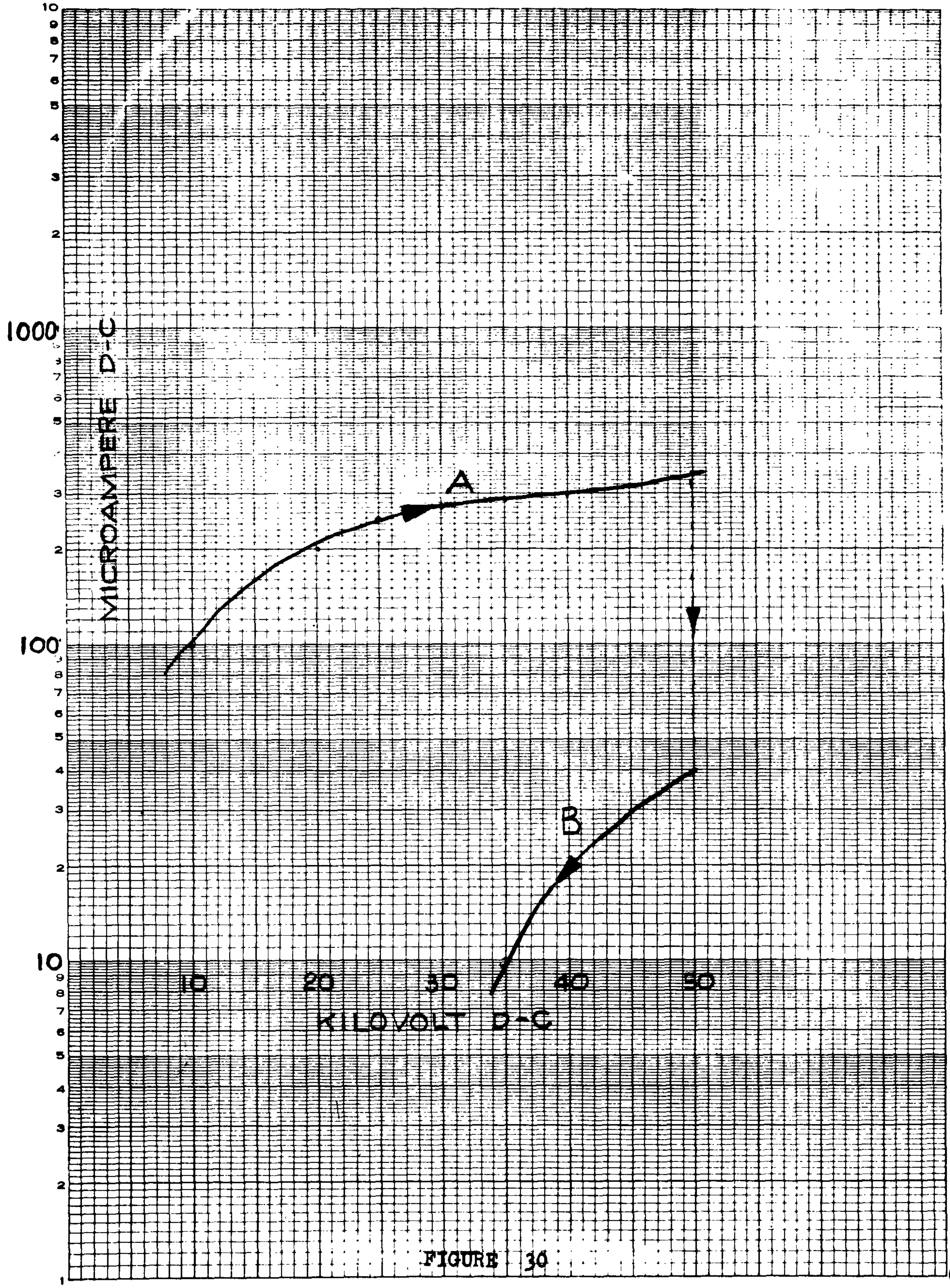


FIGURE 30

1488 was that no formation of whiskers was present.

Artificial Contamination with Water

In the foregoing tests, Pyranol was taken from the original container as shipped from the manufacturer and tested with a minimum of delay. Furthermore, tests were made after decontaminating the Pyranol as much as possible.

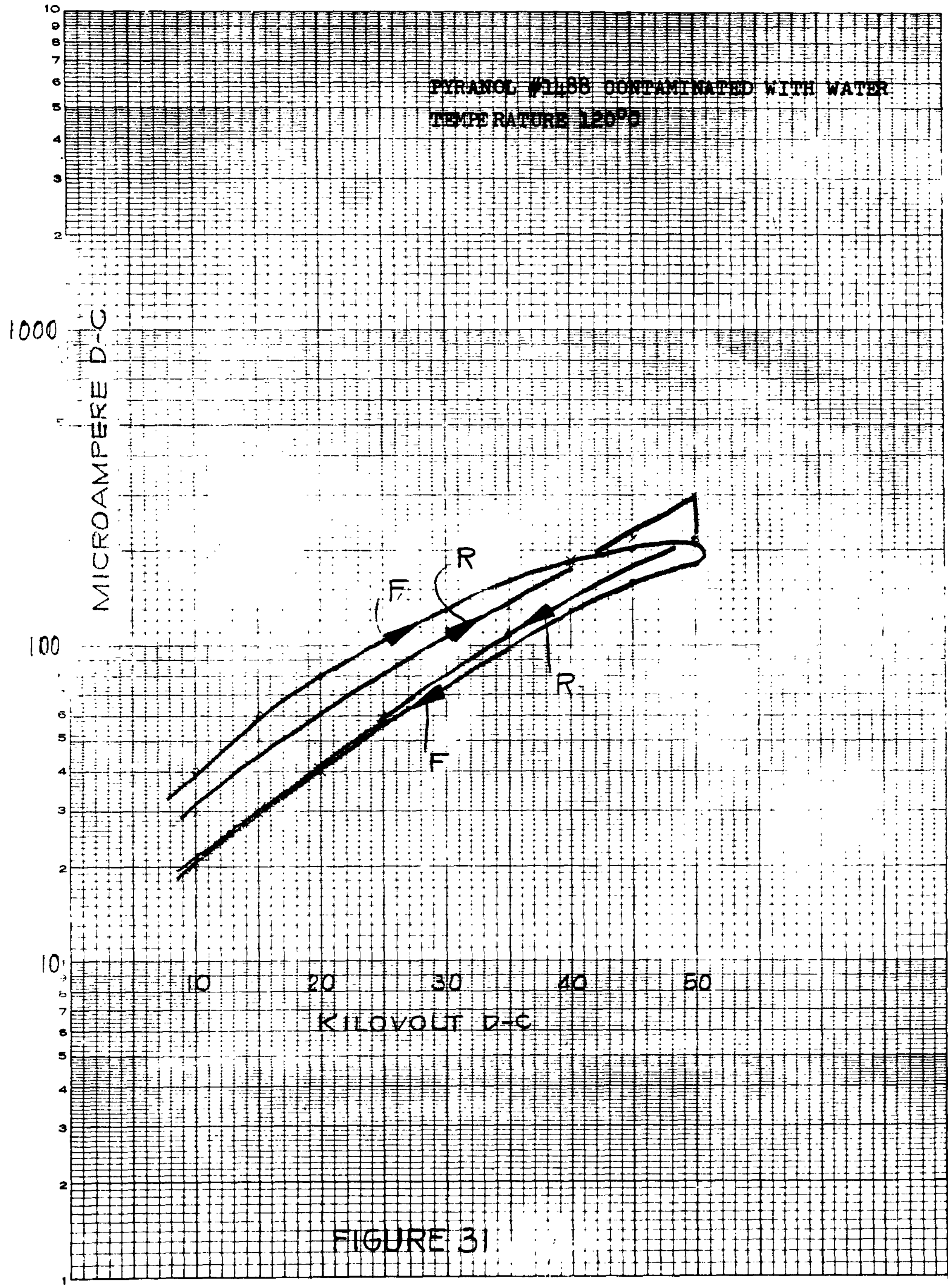
An attempt was made to deliberately contaminate the Pyranol with water by adding 1/2 ounce to the hot Pyranol and stirring it. The tests were then repeated at 120°C, as shown in Figure 31. This set of tests corresponds to the curves B and S of Figure 28, page As the test results show, there is no great difference, indicating that deliberate contamination with water in the hot state is not effective, apparently because Pyranol is not able to absorb the water by chemical bonding. Furthermore it may be concluded that the Fuller's earth treatment to decontaminate the Pyranol was not effective, either because the Fuller's earth was not able to absorb enough water or because the treating method was not effective. This resulted in an investigation to improve the Fuller's earth treatment and the drying of the Pyranol to obtain higher quality material for the ultimate application.

It should be noted, although the Pyranol may or may not be contaminated, and that the water contamination experiment performed in accordance with this test was a failure, the insulating material is sufficient to provide a good rectifier. All the further test and design efforts were made to achieve a greater degree of control over the quality of the assembly.

A further test to artificially contaminate the Pyranol with water was attempted at room temperature. The Pyranol volume of approximately one gallon was contaminated by adding 1/2 ounce of water, stirring the mixture repeatedly, after which the test was performed again. This test is shown in Figure 32. Evidently, when comparing these results with the ones shown in Figures 27 and 28, the contamination by water is very effective. The curve marked F, Figure 32, is for the normal or forward polarity (base negative top electrode positive) whereas the curve R is for the reverse polarity. Evidently, deliberate contamination with water at room temperature is easily feasible. Accordingly, the gross contamination with water is dangerous at room temperature, whereas the smallest and last traces of contamination at elevated temperature are very hard to eliminate but are very harmful for the dielectric performance.

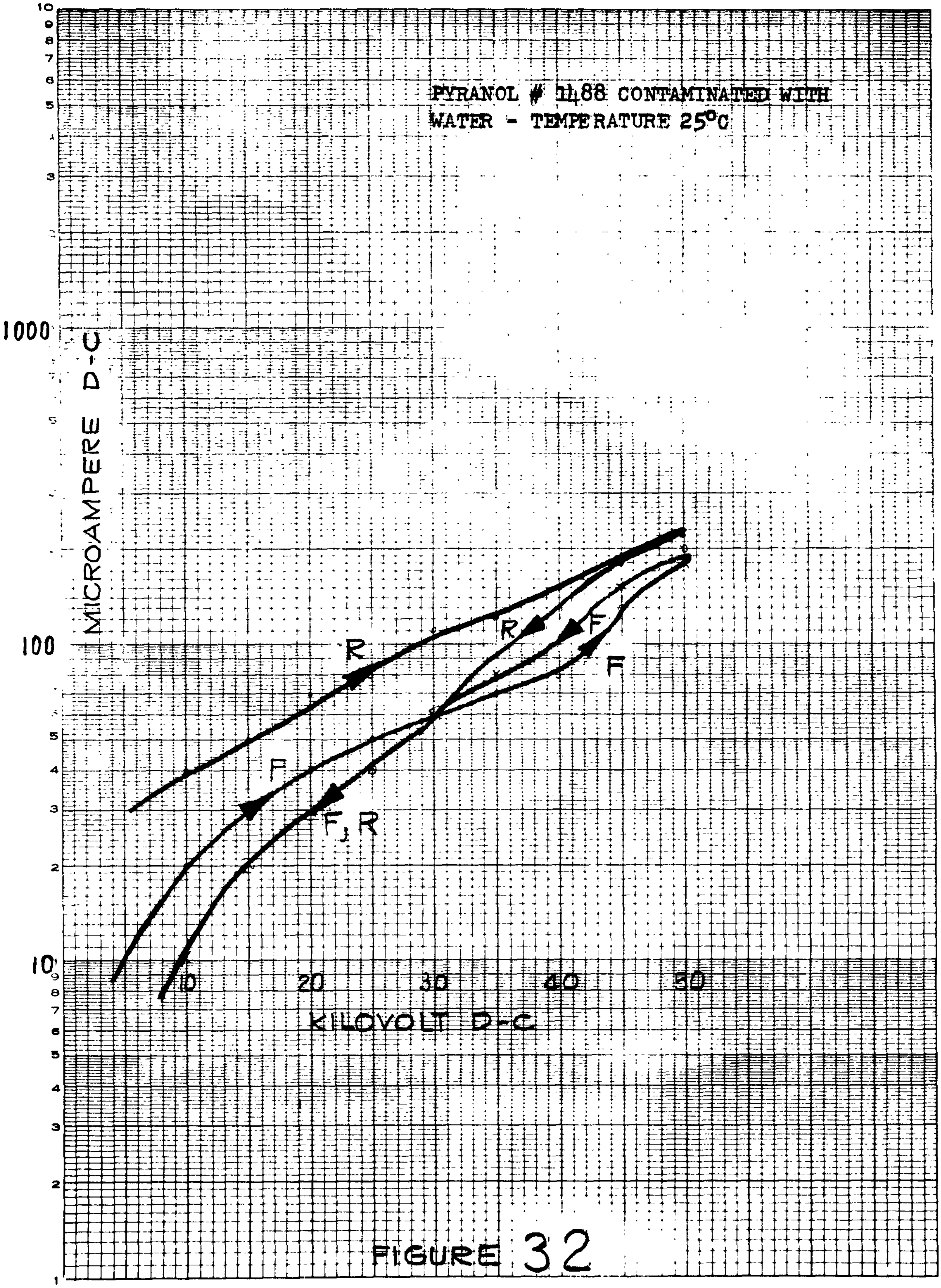
Discussion of Various Askarels

According to the foregoing tests the best fluid proved to be Pyranol No. 1488, which is a pure mixture of chlorinated hydrocarbons, without additional scavenger. This has the disadvantage that if arcing occurs and hydrochloric acid is developed, the metallic parts in the rectifier may be corroded by the action of this free acid. A fluid containing a scavenger would be much better, except that this scavenger caused black whiskers which were detrimental to the operation under high voltage, high temperature operation at a dc potential.



PYRANOL #1488 CONTAMINATED WITH WATER
TEMPERATURE 120°C
MICROAMPERE D-C
1000
100
10
KILOVOLT D-C
10
20
30
40
50
F
R
R
F

FIGURE 31



PYRANOL # 1488 CONTAMINATED WITH
WATER - TEMPERATURE 25°C
MICROAMPERE D-C
KILOVOLT D-C
1000
100
10
1
10
20
30
40
50
R
R
F
F
F
F, R

FIGURE 32

Accordingly, a sample of Inerteen type BPO was obtained. This material contains the same proportion of Aroclor 1260 and trichlorobenzene as Pyranol 1488, except that a small percentage (0.20%) of a phenoxy propene oxide scavenger is added. It was assumed that the growth of whiskers with this type of material would not re-occur. Another set of tests were run in normal polarity and reverse polarity, under dc stress up to 50 KV, similar to the foregoing tests, at room temperature and high temperature. The results of these tests are not reported in detail because our first attempt to make tests at high voltage and high temperature showed immediately a rapid development of black clouds in the material, resulting in a complete blackening of the liquid so that it became unobservable and the tests were discontinued. Thus it was concluded that Inerteen BPO is not suitable for this work because under high temperature and high dc voltage the scavenger polymerizes (or decomposes). After the test the liquid apprently re-dissolved the polymerized scavenger so that its color reverted almost to normal!

Tests in ASTM Cup

Pyranol No. 1488 as received from the manufacturer, was tested in the standard ASTM cup with a gap of .100" between electrodes. The applied voltage was ac, ranging from 5 to 40 KV RMS. The cup broke down after 20 seconds at 40 KV RMS ac. This shows that the material is of good quality, which has also been borne-out by the more practical tests reported above.

ENGINEERING SAMPLES, SIXTH SET

DESIGN TESTING

REVERSE CURRENT, HIGH POTENTIAL AND CORONA TESTS

To evaluate the design and performance of the sixth set of engineering samples, the test program listed below was established and each unit was subject to the test series at room temperature and at 125°C. For the elevated temperature measurements, the tanks were heated on a hot plate.

Test Program

1. AC Reverse Voltage Test and Corona Observation

   1.1 With the unit connected per test circuit shown in Figure 33, increase voltage in steps to 21.2 KV RMS for LIRC 28, and 28.3 KV RMS for LIRC 37, and record reverse current and corona picture at each step. Make measurements at 25°C and 125°C. Tank to be well insulated from ground in all measurements.

   1.2 Repeat 1.1 but with negative terminal (anode) of unit connected to tank.

2. AC High Potential Test

   2.1 With unit connected per test circuit shown in Figure 34, increase voltage steps to 21.2 KV RMS for LIRC 28, and 28.3 KV RMS for LIRC 37, and record corona picture at each step. Make measurements at 25°C and 125°C.

3. DC Reverse Voltage Test and Corona Observation

   3.1 With the unit connected per test circuit shown in Figure 35, increase voltage in steps to 30 KV dc for LIRC 28, and 40 KV dc for LIRC 37, and record reverse current and corona pictures. Make measurements at 25°C and 125°C.

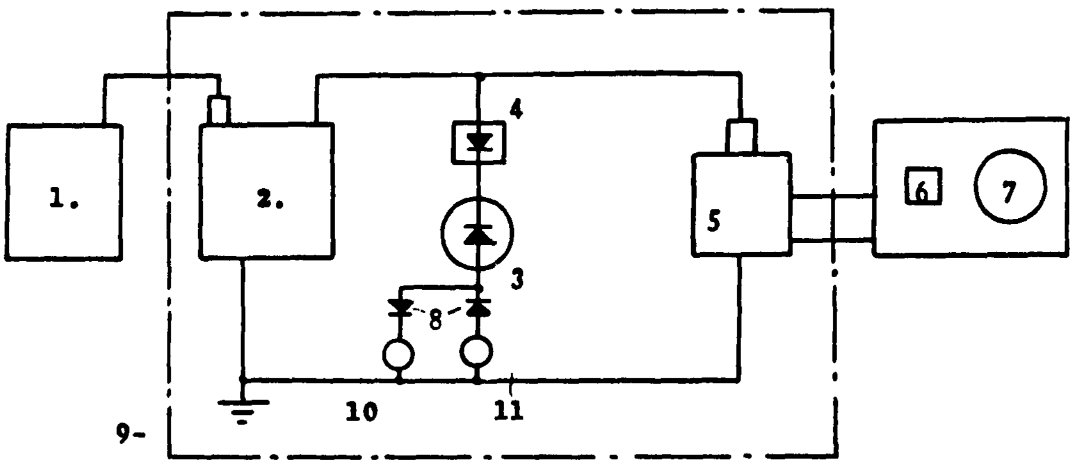
   3.2 Repeat 3.1 but with negative terminal (anode) of unit connected to tank.

4. DC High Potential Test

   4.1 With the unit connected per test circuit shown in Figure 34, increase voltage in steps to 30 KV dc for LIRC 28, and 40 KV dc for LIRC 37, and record leakage current and corona picture at each step. Make measurements at 25°C and 125°C.

FIG. 33

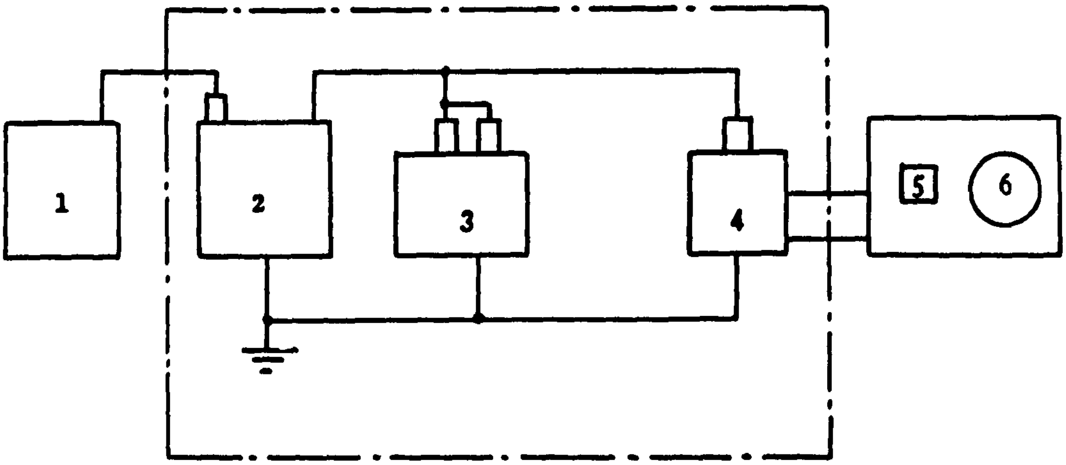
A-C Reverse Voltage and Corona Observation Test Set-up



1. Transformer control
2. High voltage transformer
3. Test specimen
4. High voltage blocking column
5. Power separation filter
6. Voltmeter
7. Oscilloscope
8. Blocking diode
9. Screen
10. Current meter for measuring reverse current through test specimen
11. Current meter for measuring reverse current through blocking column.

FIG. 34

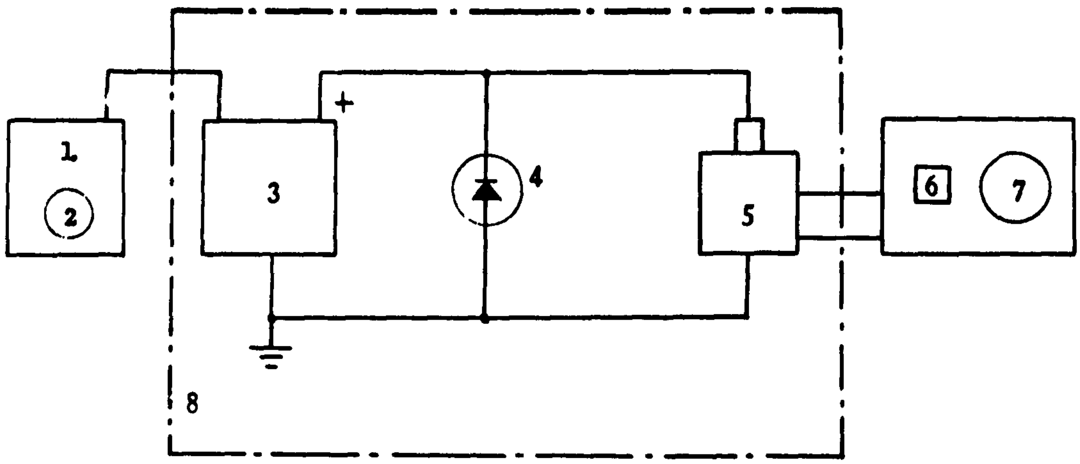
High-Potential and Corona Obersvation Test Set-up



1. Transformer control
2. High voltage supply
3. Test specimen
4. Power separation filter
5. Voltmeter
6. Oscilloscope
7. Screen

FIG. 35

D-C Reverse Voltage and Corona Observation Test Set-Up



1. Transformer Control
2. Current Meter
3. High Voltage Supply
4. Test Specimen
5. Power Separation Filter
6. Voltmeter
7. Oscilloscope
8. Screen

ENGINEERING SAMPLES, SIXTH SET

Design Test Results

Unit #1 — Test Date: March 13, 1963

This unit was a 30 KV stack with Pyranol #1488.

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments

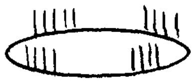
AC Reverse Voltage Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV RMS	0.11 ma avg		No corona
25	10	0.42		No corona
25	15	0.70		No corona
25	21.2	1.0		No corona

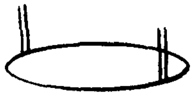
AC Reverse Voltage Test with Anode Connected to Tank

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV RMS	0.28 ma avg		No corona
25	10	0.50		No corona
25	15	0.75		No corona
25	21.2	1.10		No corona. The variation of current with reverse voltage is shown by curve A in Fig. 36.

AC High Potential Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV RMS	1.04 ma avg		No corona
25	10	2.15		600 mv corona, max.
25	15	3.2		600 mv corona, max.
25	21.2	4.6		700 mv corona, max. Unit held at 21.2 KV RMS for 3 minutes. The variation of leakage current with voltage is shown by curve B in Fig. 36.

DC Reverse Voltage Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV dc	.36 ma dc		No corona
25	10	.73		No corona
25	15	1.10		No corona
25	20	1.45		No corona
25	25	1.85		No corona
25	30	2.20		8 V corona, max.

Unit #1, Continued

DC Reverse Voltage Test with Anode Connected to Tank

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV dc	0.37 ma dc		No corona
25	10	0.74		No corona
25	15	1.10		No corona
25	20	1.45		No corona
25	25	1.80		No corona
25	30	2.25		8 V corona max. The variation of reverse current with voltage is shown by curve A in Fig. 37.

DC High Potential Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV dc	0.010 ma dc		No corona
25	10	0.030		No corona
25	15	0.040		No corona
25	20	0.060		No corona
25	25	0.08		No corona
25	30	0.09		8 V corona, max. Reading made at that time. The variation of current with voltage is shown by curve B in Fig. 37.

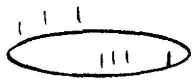
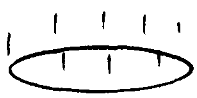
AC Reverse Voltage Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
130	5 KV RMS	0.95 ma avg		No corona
130	10	1.8		No corona
130	15	2.65		No corona
130	21.2	3.7		Intermittent corona 200 mv, max.

AC Reverse Voltage Test with Anode Connected to Tank

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
130	5 KV RMS	0.98 ma avg		No corona
130	10	1.9		No corona
130	15	2.8		No corona
130	21.2	3.8		Very little intermittent corona. The variation of current with voltage is shown by curve C in Fig. 36.

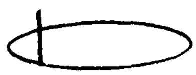
Unit #1, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
AC High Potential Test				
130	5 KV RMS	1.2 ma avg		No corona
130	10	2.4		Very little intermittent corona
130	15	3.6		Very little intermittent corona
130	21.2	5.0		Corona, 800 mv, max. 3 minutes,no change. The variation of current with voltage is shown by curve D in Fig. 36.
DC Reverse Voltage Test				
130	5 KV dc	1.0 ma dc		No corona
130	10	1.85		No corona
130	15	2.6		No corona
130	20	3.7		No corona
130	25	4.7		Low intermittent corona
130	30	5.5		Corona, sparse, 8 V max.
DC Reverse Voltage Test with Anode Connected to Tank				
125	5 KV dc	0.82 ma dc		No corona
125	10	1.6		No corona
125	15	2.35		No corona
125	20	3.3		No corona
125	25	4.2		Intermittent 300 mv, max.
125	30	5.1		Sparse corona 8 v, max. The variation of current with voltage is shown by curve C in Fig. 37.

Unit #1, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
DC High Potential Test				
125	5 KV dc	0.1 ma dc		No corona
125	10	0.22		No corona
125	15	0.3		No corona
125	20	0.38		No corona
125	25	0.45		Sparse corona, 300 mv, max.
125	30	0.48		Sparse corona, 8 V max. Leakage current after 3 minutes:0.39 mAdc The variation of current with voltage is shown by curve D in Fig. 37.

After cooling down to room temperature the unit was retested.

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
AC Reverse Voltage Test with Anode Connected to Tank				
25	5 KV RMS	0.8 ma avg		
25	10	1.55		
25	15	2.8 to 2.9		
25	20			Internal arcing occurred.

Upon opening the unit, it was found that the Pyranol had a milky appearance and that the arcing had occurred across the inner insulating part of the cathode terminal. The arc path was approxi--mately 1.5 inches.

Standard ASTM cup test showed that arcing occurred at 5 KV RMS at 0.1 inch gap. Comparing this voltage with the arcing voltage of approximately 40 KV for new Pyranol, shows that a contamination of the dielectric fluid had taken place.

It is believed that the arcing along the surface of the bushing was caused by the contaminated Pyranol.

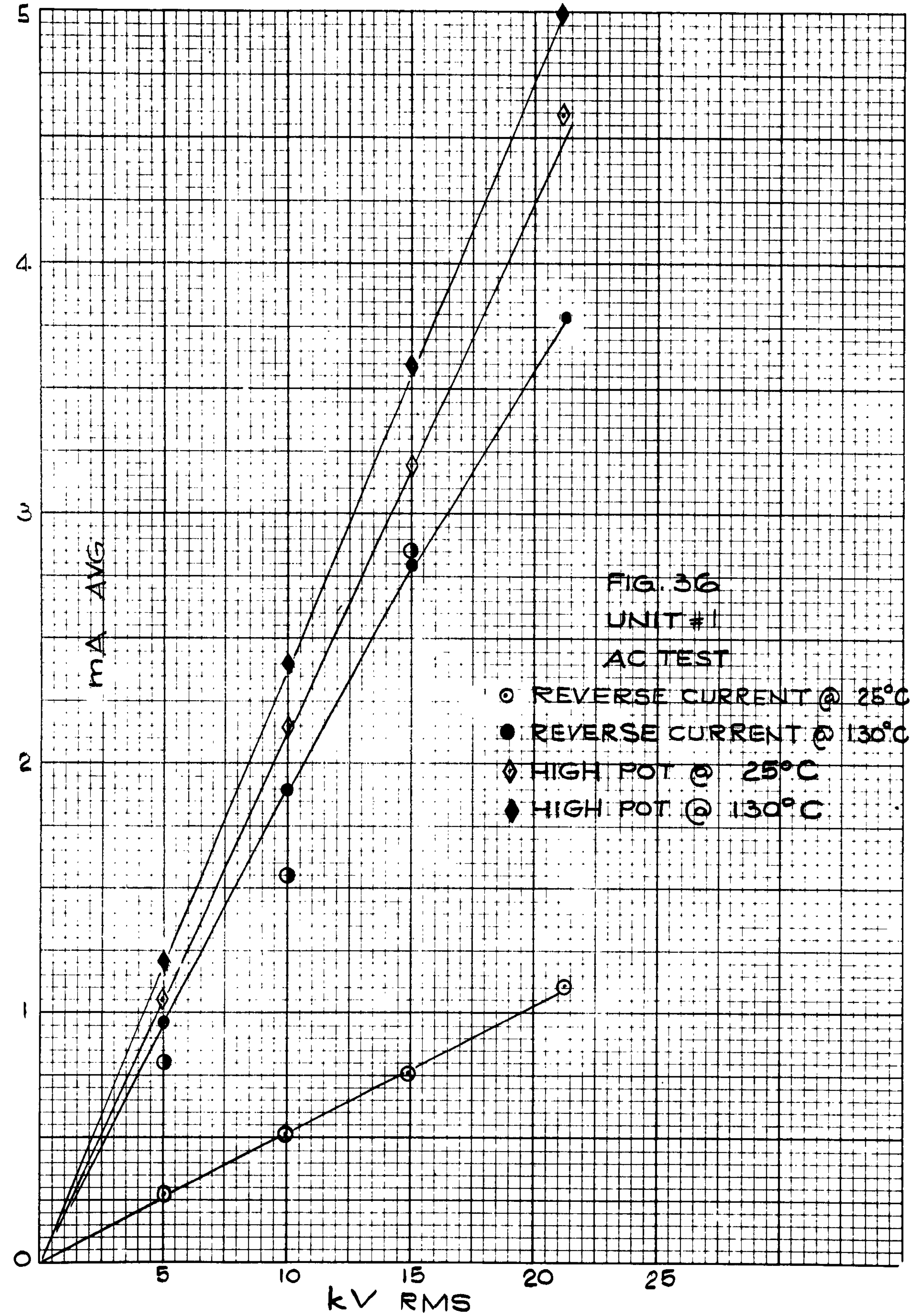


FIG. 36
UNIT #1
AC TEST
⊙ REVERSE CURRENT @ 25°C
● REVERSE CURRENT @ 130°C
◊ HIGH POT @ 25°C
♦ HIGH POT @ 130°C
mA AVG
kV RMS
0
1
2
3
4
5
5
10
15
20
25

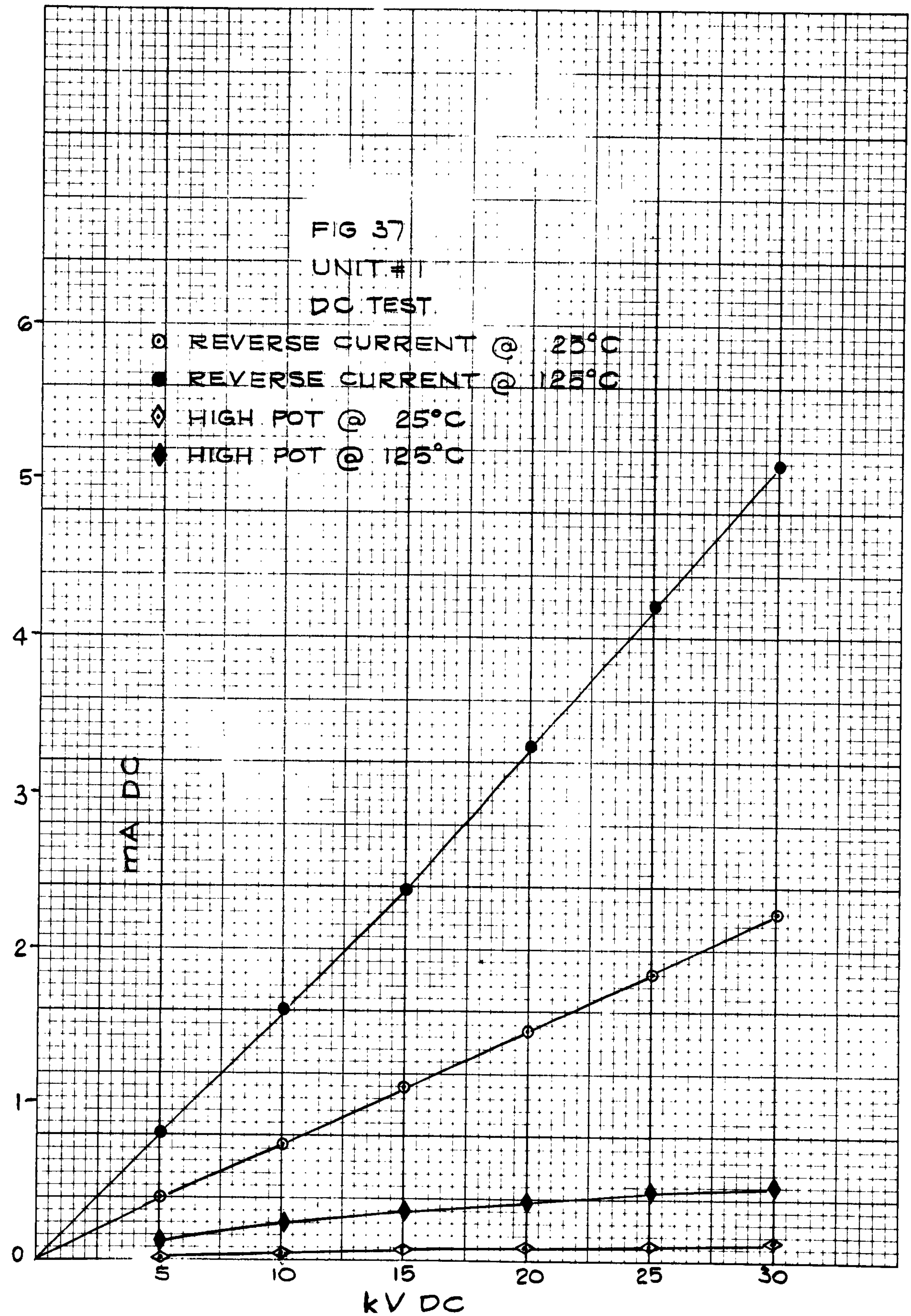
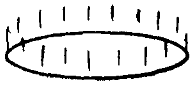
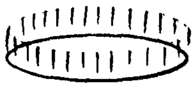


FIG 37
UNIT #1
DC TEST
REVERSE CURRENT @ 25°C
REVERSE CURRENT @ 125°C
HIGH POT @ 25°C
HIGH POT @ 125°C
mA DC
0
1
2
3
4
5
6
5
10
15
20
25
30
kV DC

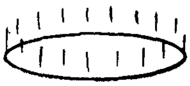
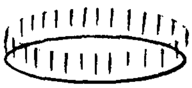
<u>Column 67-7502-1</u> Test Date: March 12, 1963

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
AC Reverse Voltage Test				
25	5 KV RMS	0.4 ma avg		No corona
25	10	0.8		No corona
25	15	1.2		No corona
25	20	1.6		100 mv max corona
25	25	2.0		800 mv max corona
25	28.3	2.2		800 mv max corona
AC Reverse Voltage Test with Cathode Connected to Tank				
25	5 KV RMS	0.42 ma avg		No corona
25	10	0.83		No corona
25	15	1.4		No corona
25	20	1.75		No corona
25	25	2.20		800 mv max corona
25	28.3	2.55		2 v max corona
AC Reverse Voltage Test with Anode Connected to Tank				
25	5 KV RMS	0.44 ma avg		No corona
25	10	0.85		No corona
25	15	1.40		1 v max corona
25	20	1.80		2 v max corona
25	25	2.20		3 v max corona
25	28.3	2.50		8 v max corona. The variation of current with voltage is shown by curve A of Fig. 38.
AC High Potential Test				
25	5 KV RMS	0.56 ma avg		No corona
25	10	2.40		3 v corona, max.
25	15	3.40		3 v corona, max.
25	20	4.60		3 v corona, max.
25	25	5.50		4 v corona, max.
25	28.3	6.30		4 v corona, max. The variation of current with voltage is shown by curve B of Fig. 38.

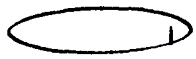
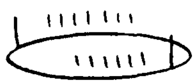
Column 67-7502-1, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
DC Reverse Voltage Test				
25	5 KV dc	0.27 ma dc		No corona
25	10	0.56		No corona
25	15	0.83		No corona
25	20	1.15		No corona
25	25	1.43		No corona
25	30	1.68		No corona
25	35	1.96		No corona
25	40	2.22		No corona
DC Reverse Voltage Test with Cathode Connected to Tank				
25	5 KV dc	0.27 ma dc		No corona
25	10	.57		No corona
25	15	.85		No corona
25	20	1.15		No corona
25	25	1.45		No corona
25	30	1.75		No corona
25	35	2.0		External audible corona
25	40	2.27		External audible corona. The variation of current with voltage is shown by curve A in Fig. 39.
DC High Potential Test				
25	5 KV dc	0.005 ma dc		No corona
25	10	0.01		No corona
25	15	0.06		No corona
25	20	0.08		No corona
25	25	0.10		Intermittent low corona
25	30	0.12		Intermittent low corona
25	35	0.125		External audible corona
25	40	0.15 decreasing to 0.13 after 3 min		External audible corona. The variation of current with voltage is shown by curve B in Fig. 39.

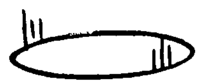
Column 67-7502-1, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
<u>DC Reverse Voltage Test</u>				
25	5 KV dc	0.27 ma dc		No corona
25	10	0.56		No corona
25	15	0.83		No corona
25	20	1.15		No corona
25	25	1.43		No corona
25	30	1.68		No corona
25	35	1.96		No corona
25	40	2.22		No corona
<u>DC Reverse Voltage Test with Cathode Connected to Tank</u>				
25	5 KV dc	0.27 ma dc		No corona
25	10	.57		No corona
25	15	.85		No corona
25	20	1.15		No corona
25	25	1.45		No corona
25	30	1.75		No corona
25	35	2.0		External audible corona
25	40	2.27		External audible corona. The variation of current with voltage is shown by curve A in Fig. 39.
<u>DC High Potential Test</u>				
25	5 KV dc	0.005 ma dc		No corona
25	10	0.01		No corona
25	15	0.06		No corona
25	20	0.08		No corona
25	25	0.10		Intermittent low corona
25	30	0.12		Intermittent low corona
25	35	0.125		External audible corona
25	40	0.15 decreasing to 0.13 after 3 min		External audible corona. The variation of current with voltage is shown by curve B in Fig. 39.

Column 67-7502-1, Continued

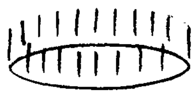
Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
AC Reverse Voltage Test				
125	5 KV RMS	0.46 ma avg		No corona
125	10	0.92		No corona
125	15	1.40		No corona
125	21.2	1.80		No corona
125	28.3	2.5		600 mv max corona
AC Reverse Voltage Test with Anode Connected to Tank				
125	5 KV RMS	0.54 ma avg		No corona
125	10	1.05		No corona
125	15	1.6		No corona
125	21.2	2.20		No corona
125	28.3	2.80		800 mv max corona. The variation of current with voltage is shown by curve C in Fig. 38.
AC High Potential Test				
125	5 KV RMS	0.56 ma avg		No corona
125	10	2.30		100 mv max corona
125	15	3.40		200 mv max corona
125	21.2	5.50		400 mv max corona
125	28.3	6.30		500 mv max corona. Small corona spikes probably caused by external corona. The variation of current with voltage is shown by curve D in Fig. 38.

Column 67-7502-1, Continued

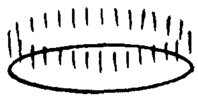
Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
<u>DC Reverse Voltage Test</u>				
125	5 KV dc	0.36 ma dc		No corona
125	10	0.72		No corona
125	15	1.05		No corona
125	20	1.40		100 mv corona, pick-up from line
125	25	1.75		No corona
125	30	2.05		300 mv max corona
125	35	2.35		7 v max corona
125	40	2.65		10 v max corona

Column 67-7502-1, Continued

DC Reverse Voltage Test with Anode Connected to Tank

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
125	5 KV dc	0.35 ma dc		No corona
125	10	0.71		No corona
125	15	1.05		100 mv corona, pick-up from line
125	20	1.43		100 mv corona, pick-up from line
125	25	1.79		100 mv corona, pick-up from line
125	30	2.10		8 v corona
125	35	2.38		Above 10 v corona
125	40	2.69		Above 10 v corona. The variation of current with voltage is shown by curve C in Fig. 39

DC High Potential Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
105	5 KV dc	0.15 ma dc		No corona
105	10	0.33		No corona
105	15	0.45		No corona
105	20	0.57		No corona
105	25	0.68		No corona
105	30	0.74		8 v corona
105	35	0.75		8 v corona
102°C tank outside	40	0.56 after 3 min.		8 v corona. The variation of current with voltage is shown by curve D in Fig. 39.

After the unit had cooled to room temperature, a sample of the

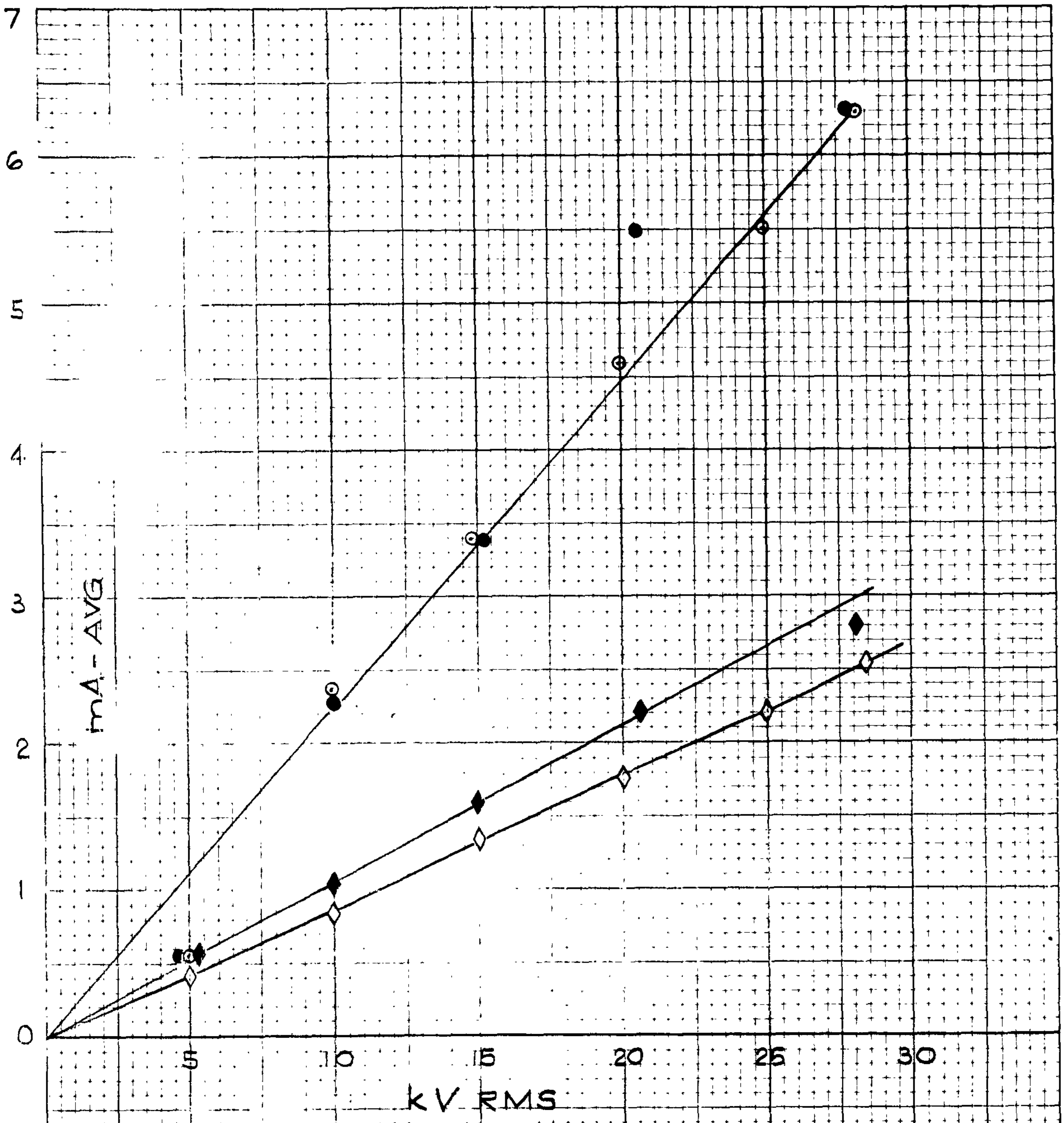


FIG. 38

67-7502-1

AC TEST

⊙ REVERSE CURRENT @ 25°C

● REVERSE CURRENT @ 125°C

◊ HIGH POT @ 25°C

♦ HIGH POT @ 125°C

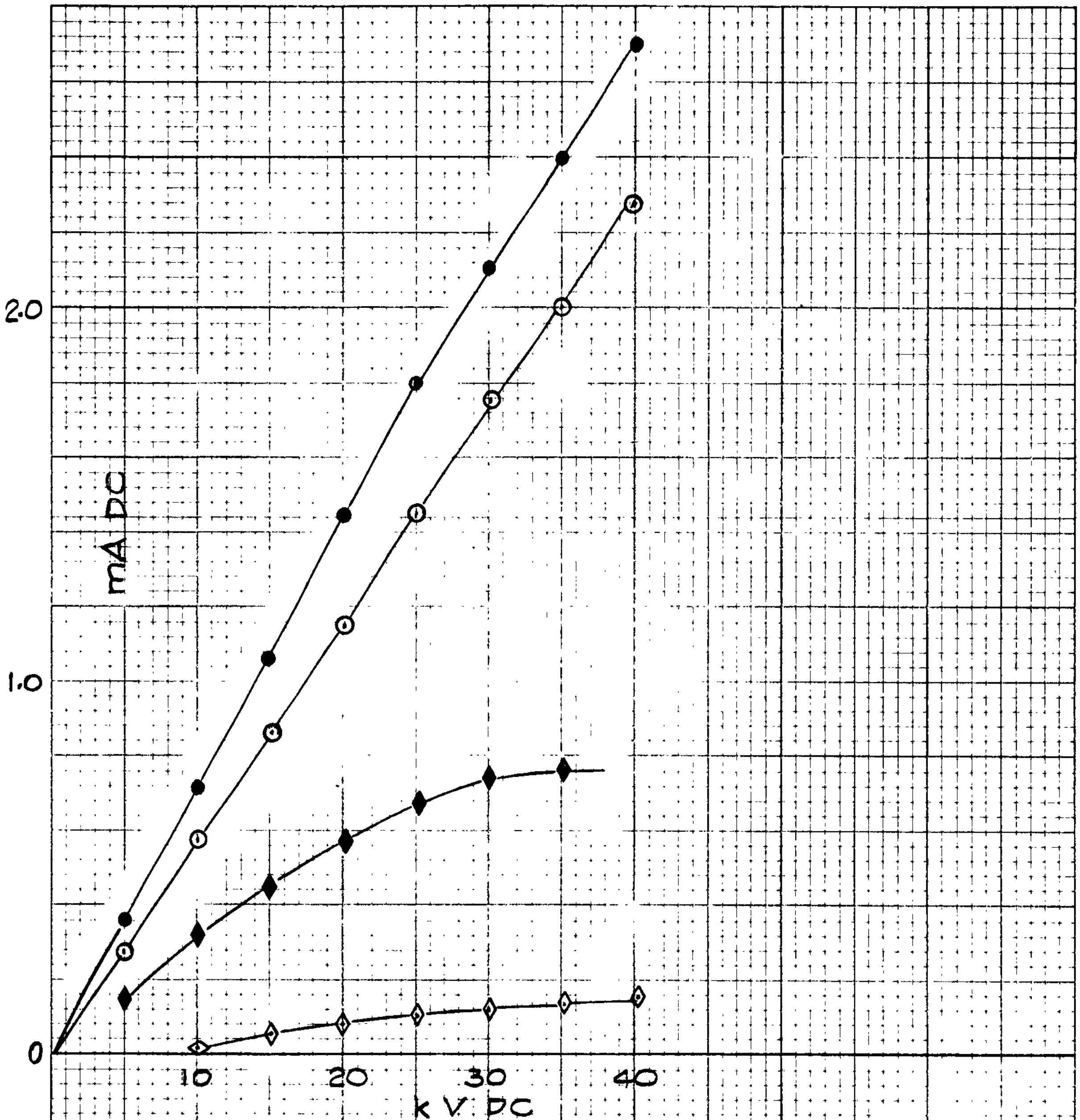


FIG 39

67-7502-1

DC TEST

⊙ REVERSE VOLTAGE @ 25° C

● REVERSE VOLTAGE @ 125° C

◊ HIGH POT @ 25° C

♦ HIGH POT @ 125° C

Pyranol was taken and found to be of milky appearance. Standard ASTM cup test showed that arcing occurred at 5 KV RMS, at room temperature and 0.1 inch gap.

The tank was, therefore, drained of the contaminated Pyranol #1488 and filled with new Pyranol #1488 which had been Fuller's earth treated to remove moisture.

The design testing was then repeated with the following results:

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
AC Reverse Voltage Test				
25	5 KV RMS	0 ma avg		No corona
25	10	0.04		No corona
25	15	0.18		No corona
25	21.2	0.41		No corona
25	28.3	0.70		No corona
AC Reverse Voltage Test with Anode Connected to Tank				
25	5 KV RMS	0 ma avg		No corona
25	10	0.07		No corona
25	15	0.30		No corona
25	21.2	0.65		No corona
25	28.3	1.02		The variation of current with voltage is shown in Fig. 40.
AC High Potential Test				
25	5 KV RMS	0 ma avg		No corona
25	10	0.20		No corona
25	15	0.75		No corona
25	21.2	1.04		No corona
25	28.3 3 min.	2.0		The variation of current with voltage is shown in Fig.40.

Column 67-7502-1, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
DC Reverse Voltage Test				
25	5 KV dc	0.28 ma dc		No corona
25	10	0.57		No corona
25	15	0.84		No corona
25	20	1.15		No corona
25	25	1.40		No corona
25	30	1.70		No corona
25	35	1.95		No corona
25	40	2.20		No corona
DC Reverse Voltage Test with Anode Connected to Tank				
25	5 KV dc	0.29 ma dc		No corona
25	10	0.57		No corona
25	15	0.84		No corona
25	20	1.15		No corona
25	25	1.45		No corona
25	30	1.75		No corona
25	35	2.0		No corona
25	40	2.3		The variation of current with voltage is shown in Fig. 41.
DC High Potential Test				
25	5 KV dc	0.02 ma dc		No corona
25	10	0.04		No corona
25	15	0.06		No corona
25	20	0.08		No corona
25	25	0.101		No corona
25	30	0.140		No corona
25	35	0.180		No corona
25	40	0.220		The variation of current with voltage is shown in Fig. 41.

Column 67-7502-1, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
AC Reverse Voltage Test				
125	5 KV RMS	0.48 ma avg		No corona
125	10	0.90		No corona
125	15	1.4		No corona
125	2.12	1.8		No corona
125	28.3	2.5		No corona
AC Reverse Voltage Test with Anode Connected to Tank				
125	5 KV RMS	0.48 ma avg		No corona
125	10	1.10		No corona
125	15	1.6		No corona
125	21.2	2.4		No corona
125	28.3	3.0		600 mv max corona. The variation of current with voltage is shown in Fig. 40.
AC High Potential Test				
125	5 KV RMS	0.90 ma avg		No corona
125	10	1.8		No corona
125	15	2.9		No corona
125	21.2	4.2		No corona
125	28.3	5.5		The variation of current with voltage is shown in Fig. 40.
DC Reverse Voltage Test				
125	5 KV dc	0.33 ma dc		No corona
125	10	0.64		No corona
125	15	0.90		No corona
125	20	1.25		No corona
125	25	1.55		No corona
125	30	1.85		No corona
125	35	2.30		No corona
125	40	2.40		No corona
DC Reverse Voltage Test with Anode Connected to Tank				
125	5 KV dc	0.33 ma dc		No corona
125	10	0.66		No corona
125	15	0.96		No corona
125	20	1.30		No corona
125	25	1.65		No corona
125	30	1.95		No corona
125	35	2.25		No corona
125	40	2.50		The variation of current with voltage is shown in Fig. 41.

Column 67-7502-1, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
DC High Potential Test				
125	5 KV dc	0.04 ma dc		No corona
125	10	0.09		No corona
125	15	0.15		No corona
125	20	0.21		No corona
125	25	0.27		No corona
125	30	0.31		No corona
125	35	0.37		400 mv max corona, probably external
125	40	0.40		400 mv max corona, probably external. The variation of current with voltage is shown in Fig. 41.

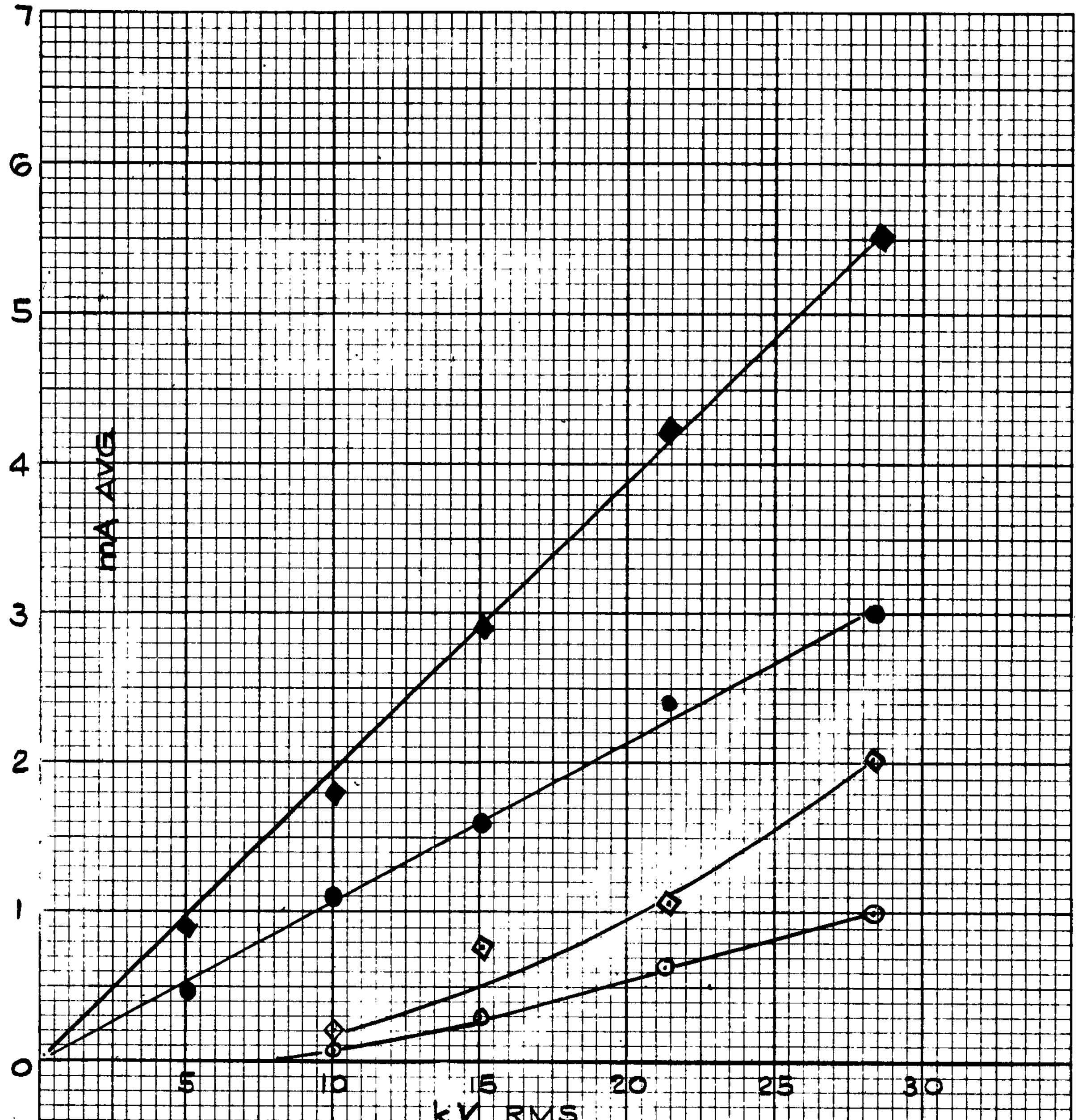


FIG 40
67-7502-1 WITH DRY PYRANOL
AC TEST

⊙ REVERSE CURRENT @ 25°C
● REVERSE CURRENT @ 125°C
◇ HIGH POT @ 25°C
◆ HIGH POT @ 125°C

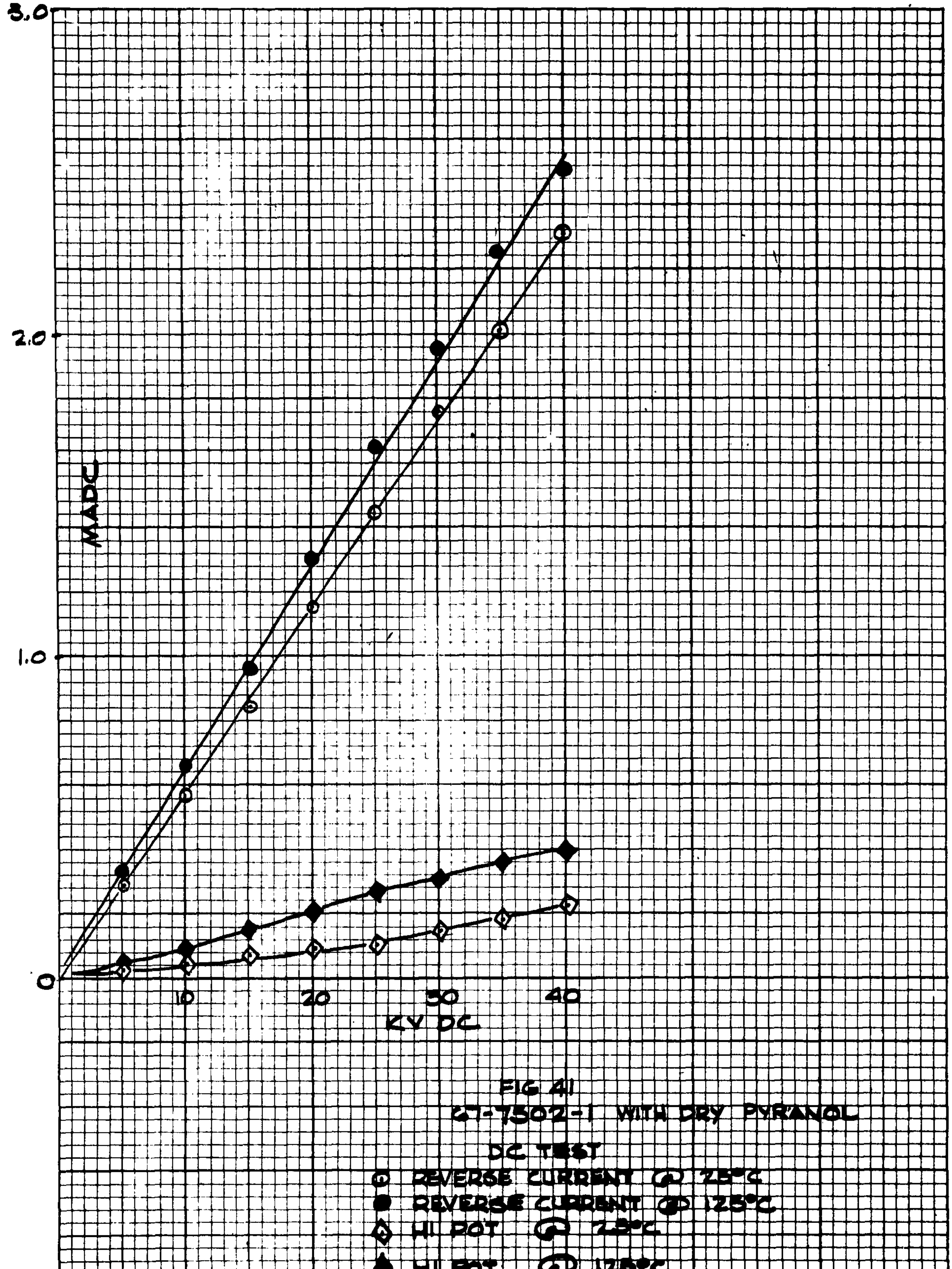
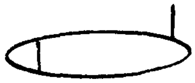
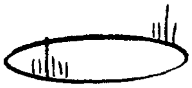


FIG 41
67-7502-1 WITH DRY PYRANOL
DC TEST

Column 67-7502-3 — Test Date: March 27, 1963

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
AC Reverse Voltage Test				
25	5 KV RMS	0 ma avg		
25	10	0.04		
25	15	0.19		
25	21.2	0.42		
25	28.3	0.72		

AC Reverse Voltage Test with Anode Connected to Tank

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV RMS	0 ma avg		No corona
25	10	0.06		No corona
25	15	0.28		No corona
25	21.2	0.60		No corona
25	28.3	0.96		The variation of current with voltage is shown in Fig. 42.

AC High Potential Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV RMS	0 ma avg		No corona
25	10	0		No corona
25	15	0.20		No corona
25	21.2	1.0		No corona
25	28.3 3 min.	2.0		The variation of current with voltage is shown in Fig. 42.

DC Reverse Voltage Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV dc	0.26 ma dc		No corona
25	10	0.56		No corona
25	15	0,84		No corona
25	20	1.15		No corona
25	25	1.45		No corona
25	30	1.75		No corona
25	35	2.0		No corona
25	40	2.3		No corona

DC Reverse Voltage Test with Anode Connected to Tank

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV dc	0.28 ma dc		No corona
25	10	0.58		No corona
25	15	0.84		No corona
25	20	1.15		No corona
25	25	1.45		No corona
25	30	1.75		No corona
25	35	2.0		No corona
25	40	2.30		The variation of current with voltage is shown in Fig. 43.

Column 67-7502-3, Continued

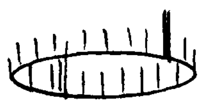
DC High Potential Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV dc	0.02 ma dc		No corona
25	10	0.05		No corona
25	15	0.08		No corona
25	20	0.11		No corona
25	25	0.16		No corona
25	30	0.22		No corona
25	35	0.30		No corona
25	40	0.40		The variation of current with voltage is shown in Fig. 43.

AC Reverse Voltage Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
125	5 KV RMS	0.52 ma avg		No corona
125	10	1.0		No corona
125	15	1.6		No corona
125	21.2	2.1		No corona
125	28.3	2.8		No corona

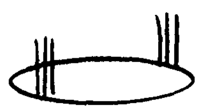
AC Reverse Voltage Test with Anode Connected to Tank

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
125	5 KV RMS	0.29 ma avg		No corona
125	10	1.10		No corona
125	15	1.7		No corona
125	21.2	2.5		No corona
125	28.3	3.3		600 mv max corona. The variation of current with voltage is shown in Fig. 42.

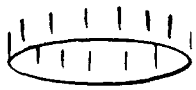
AC High Potential Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
125	5 KV RMS	0.90 ma avg		No corona
125	10	1.8		No corona
125	15	2.9		No corona
125	21.2	4.1		No corona
125	28.3	5.4		800 mv max corona. The variation of current with voltage is shown in Fig. 42.

DC Reverse Voltage Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
125	5 KV dc	0.42 ma dc		No corona
125	10	0.87		No corona
125	15	1.25		No corona
125	20	1.65		No corona
125	25	2.05		No corona
125	30	2.40		No corona
125	35	2.80		Over 1 volt corona
125	40	3.20		Over 1 volt corona

Column 67-7502-3, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
DC Reverse Voltage Test with Anode Connected to Tank				
125	5 KV dc	.40 ma dc		No corona
125	10	.80		No corona
125	15	1.20		No corona
125	20	1.60		No corona
125	25	2.0		400 mv max corona, probably external
125	30	2.35		400 mv max corona, probably external
125	35	2.70		400 mv max corona, probably external
125	40	3.2		The variation of current with voltage is shown on Fig. 43.
DC High Potential Test				
125	5 KV dc	0.04 ma dc		No corona
125	10	0.10		No corona
125	15	0.14		No corona
125	20	0.180		No corona
125	25	0.23		No corona
125	30	0.26		Less than 1 volt corona
125	35	0.28		Over 1 volt corona
125	40	0.31		Over 1 volt corona. The variation of current with voltage is shown in Fig. 43.

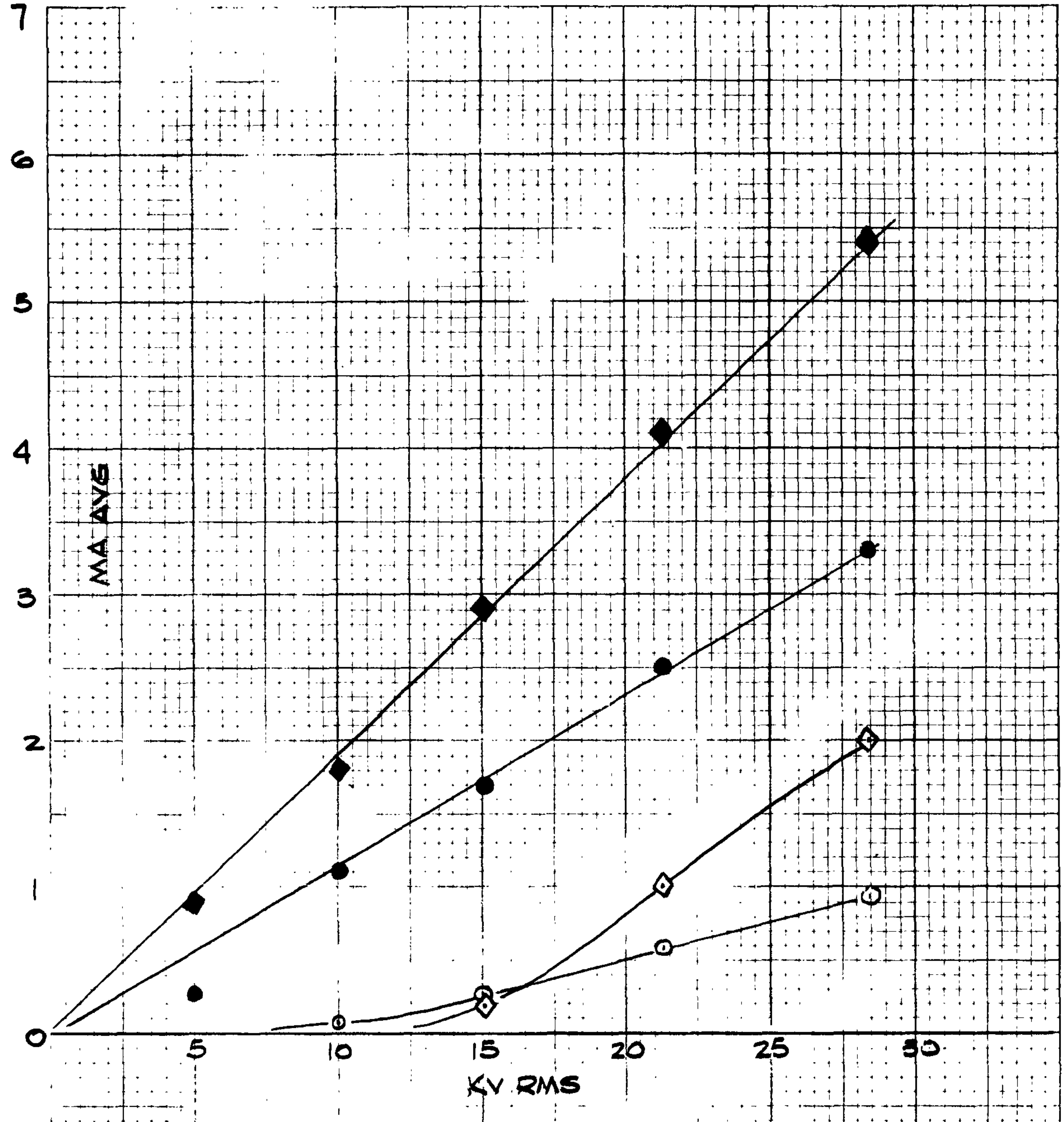


FIG 42
67-7502-3
AC TEST

⊙ REVERSE CURRENT @ 25°C
● REVERSE CURRENT @ 125°C
◊ HI POT @ 25°C
◆ HI POT @ 125°C

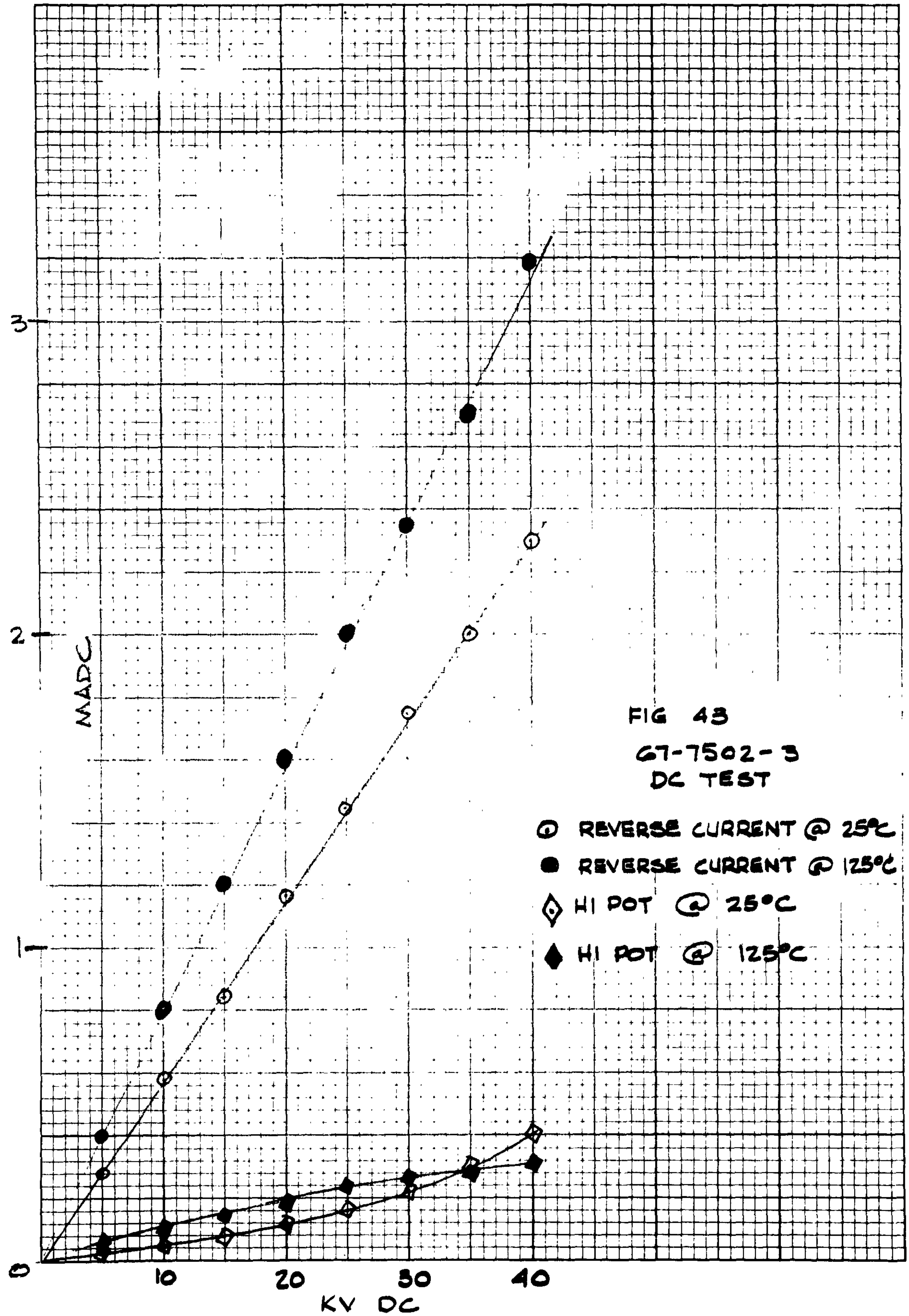


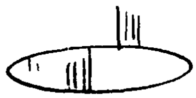
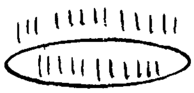
FIG 43
67-7502-3
DC TEST
REVERSE CURRENT @ 25°C
REVERSE CURRENT @ 125°C
HI POT @ 25°C
HI POT @ 125°C
MADC
KV DC
0
10
20
30
40
1
2
3

Column 67-7501-1 **Test Date: March 28, 1963**

AC Reverse Voltage Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV RMS	0.56 ma avg		No corona
25	10	1.1		No corona
25	15	1.6		No corona
25	21.2	2.3		2 volt corona max.

AC Reverse Voltage Test with Anode Connected to Tank

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV RMS	0.62 ma avg		No corona
25	10	1.2		
25	15	1.6		
25	21.2	2.2		800 mv. The variation of current with voltage is shown in Fig. 44.

AC High Potential Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV RMS	0.9 ma avg		Intermittent corona pick-up
25	10	1.9		No corona
25	15	3.1		No corona
25	21.2	4.3 3 min.		No corona. The variation of current with voltage is shown in Fig. 44.

DC Reverse Voltage Test

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV dc	0.36 ma dc		No corona
25	10	0.74		No corona
25	15	1.1		No corona
25	20	1.5		No corona
25	25	1.85		No corona
25	30	2.25		No corona

DC Reverse Voltage Test with Anode Connected to Tank

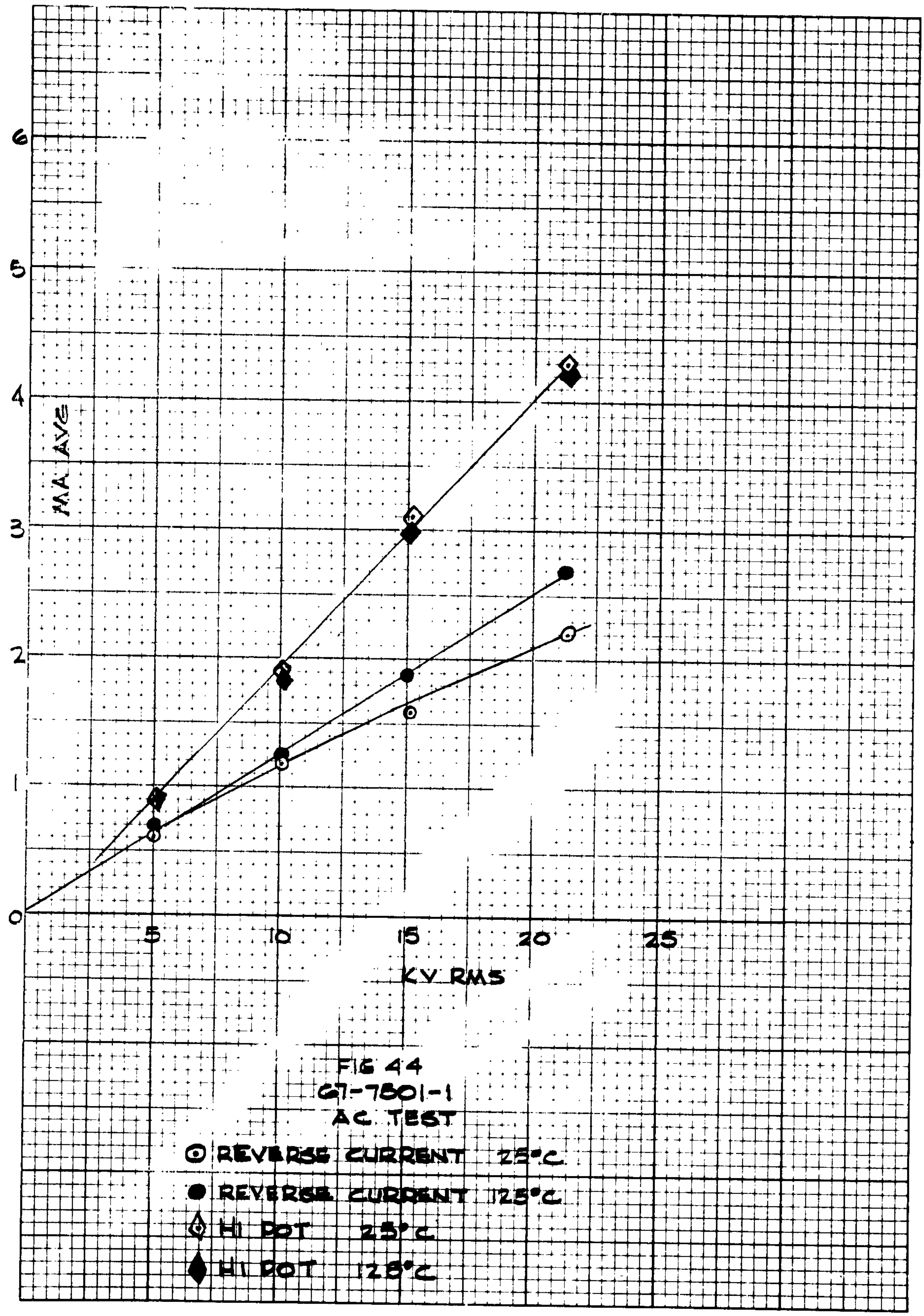
Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
25	5 KV dc	0.37 ma dc		No corona
25	10	0.77		No corona
25	15	1.15		No corona
25	20	1.5		No corona
25	25	1.9		No corona
25	30	2.3		No corona. **The variation of current with voltage is shown in Fig. 45.**

Column 67-7501-1, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
DC High Potential Test				
25	5 KV dc	0.04 ma dc		No corona
25	10	0.07		No corona
25	15	0.1		No corona
25	20	0.15		No corona
25	25	0.19		No corona
25	30	0.22		No corona The variation of current with voltage is shown in Fig. 45.
AC Reverse Voltage Test				
135	5 KV RMS	0.60 ma avg		No corona
135	10	1.20		No corona
135	15	1.80		No corona
135	21.2	2.60		No corona
AC Reverse Voltage Test with Anode Connected to Tank				
135	5 KV RMS	0.70 ma avg		No corona
135	10	1.25		No corona
135	15	1.90		No corona
135	21.2	2.70		No corona The variation of current with voltage is shown in Fig. 44.
AC High Potential Test				
135	5 KV RMS	0.90 ma avg		No corona
135	10	1.85		No corona
135	15	3.0		No corona
135	21.2	4.2		No corona The variation of current with voltage is shown in Fig. 44.
DC Reverse Voltage Test				
135	5 KV dc	0.64 ma dc		No corona
135	10	1.40		No corona
135	15	2.00		No corona
135	20	2.80		No corona
135	25	3.8		No corona
135	30	4.6		No corona

Column 67-7501-1, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
DC Reverse Voltage Test with Anode Connected to Tank				
135	5 KV dc	0.86 ma dc		No corona
135	10	1.8		No corona
135	15	2.60		No corona
135	20	3.60		No corona
135	25	4.70		No corona
135	30	5.70		No corona The variation of current with voltage is shown in Fig. 45.
DC High Potential Test				
135	5 KV dc	0.23 ma dc		No corona
135	10	0.47		No corona
135	15	0.64		No corona
135	20	0.76		No corona
135	25	0.94		No corona
135	30	1.10		No corona The variation of current with voltage is shown in Fig. 45.


MA AVE
6
5
4
3
2
1
0
5
10
15
20
25
KV RMS
FIG 44
G7-7801-1
AC TEST
REVERSE CURRENT 25°C
REVERSE CURRENT 125°C
HI POT 25°C
HI POT 125°C

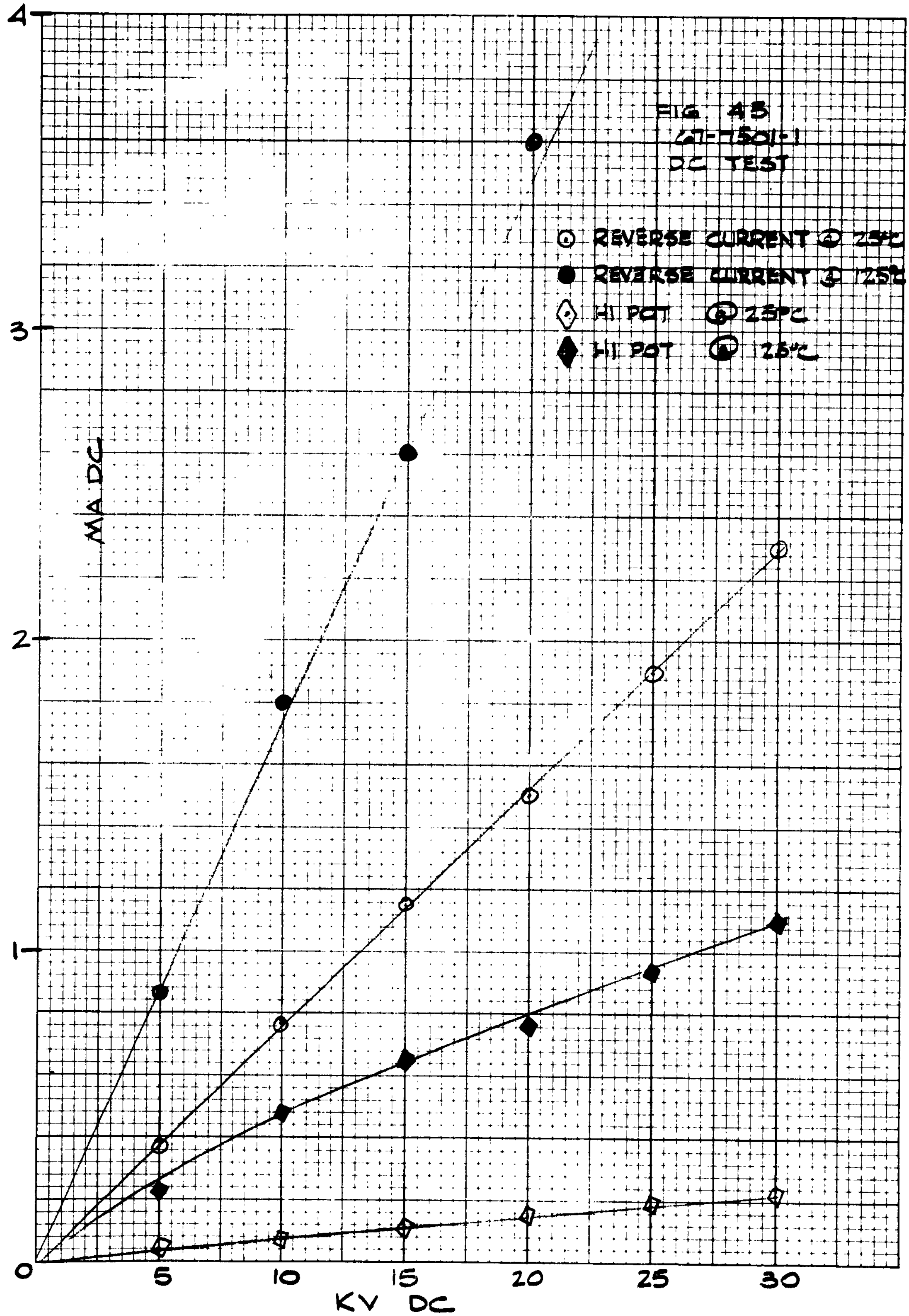
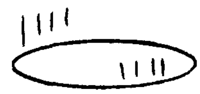


FIG 43
GT-7501-1
DC TEST
REVERSE CURRENT @ 25°C
REVERSE CURRENT @ 125°C
HI POT @ 25°C
HI POT @ 125°C
MA DC
KV DC
0
1
2
3
4
5
10
15
20
25
30

Column 67-7501-2 Test Date: March 27, 1963

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
AC Reverse Voltage Test				
25	5 KV RMS	0.52 ma avg		No corona
25	10	0.95		No corona
25	15	1.5		No corona
25	20	2.0		No corona
25	21.2	2.2		2 volt max corona
AC Reverse Voltage Test with Anode Connected to Tank				
25	5 KV RMS	0.50 ma avg		No corona
25	10	1.0		No corona
25	15	1.6		No corona
25	21.2	2.3		No corona
				The variation of current with voltage is shown in Fig. 46.
AC High Potential Test				
25	5 KV RMS	0.9 ma avg		No corona
25	10	1.9		No corona
25	15	3.1		No corona
25	21.2	4.5		No corona
		3 min.		The variation of current with voltage is shown in Fig. 46.
DC Reverse Voltage Test				
25	5 KV dc	0.37 ma dc		No corona
25	10	0.75		No corona
25	15	1.1		No corona
25	20	1.5		No corona
25	25	1.9		No corona
25	30	2.3		No corona
DC Reverse Voltage Test with Anode Connected to Tank				
25	5 KV dc	0.37 ma dc		No corona
25	10	0.76		No corona
25	15	1.1		No corona
25	20	1.5		No corona
25	25	1.9		No corona
25	30	2.3		No corona
				The variation of current with voltage is shown in Fig. 47.

Column 67-7501-2, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
DC High Potential Test				
25	5 KV dc	0 ma dc		No corona
25	10	0		No corona
25	15	0		No corona
25	20	5 ua		No corona
25	25	0		No corona
25	30	10 ua		No corona
				The variation of current with voltage is shown in Fig. 47.
AC Reverse Voltage Test				
125	5 KV RMS	0.80 ma avg		No corona
125	10	1.50		No corona
125	15	2.20		No corona
125	21.2	3.0		No corona
AC Reverse Voltage Test with Anode Connected to Tank				
125	5 KV RMS	0.80 ma avg		No corona
125	10	1.50		No corona
125	15	2.20		No corona
125	21.2	3.10		No corona
				The variation of current with voltage is shown in Fig. 46.
AC High Potential Test				
125	5 KV RMS	0.90 ma avg		No corona
125	10	1.90		No corona
125	15	3.0		No corona
125	21.2	4.20		No corona
				The variation of current with voltage is shown in Fig. 46.
DC Reverse Voltage Test				
125	5 KV dc	0.64 ma dc		No corona
125	10	1.30		No corona
125	15	1.85		No corona
125	20	2.35		No corona
125	25	3.20		No corona
125	30	3.90		No corona

Column 67-7501-2, Continued

Temp. °C	Applied Voltage	Reverse Current	Corona Picture	Comments
DC Reverse Voltage Test with Anode Connected to Tank				
125	5 KV dc	0.57 ma dc		No corona
125	10	1.20		No corona
125	15	1.70		No corona
125	20	2.30		No corona
125	25	3.10		No corona
125	30	3.70		No corona The variation of current with voltage is shown in Fig. 47.
DC High Potential Test				
125	5 KV dc	0.07 ma dc		No corona
125	10	0.15		No corona
125	15	0.20		No corona
125	20	0.28		No corona
125	25	0.34		No corona
125	30	0.40		No corona The variation of current with voltage is shown in Fig. 47.

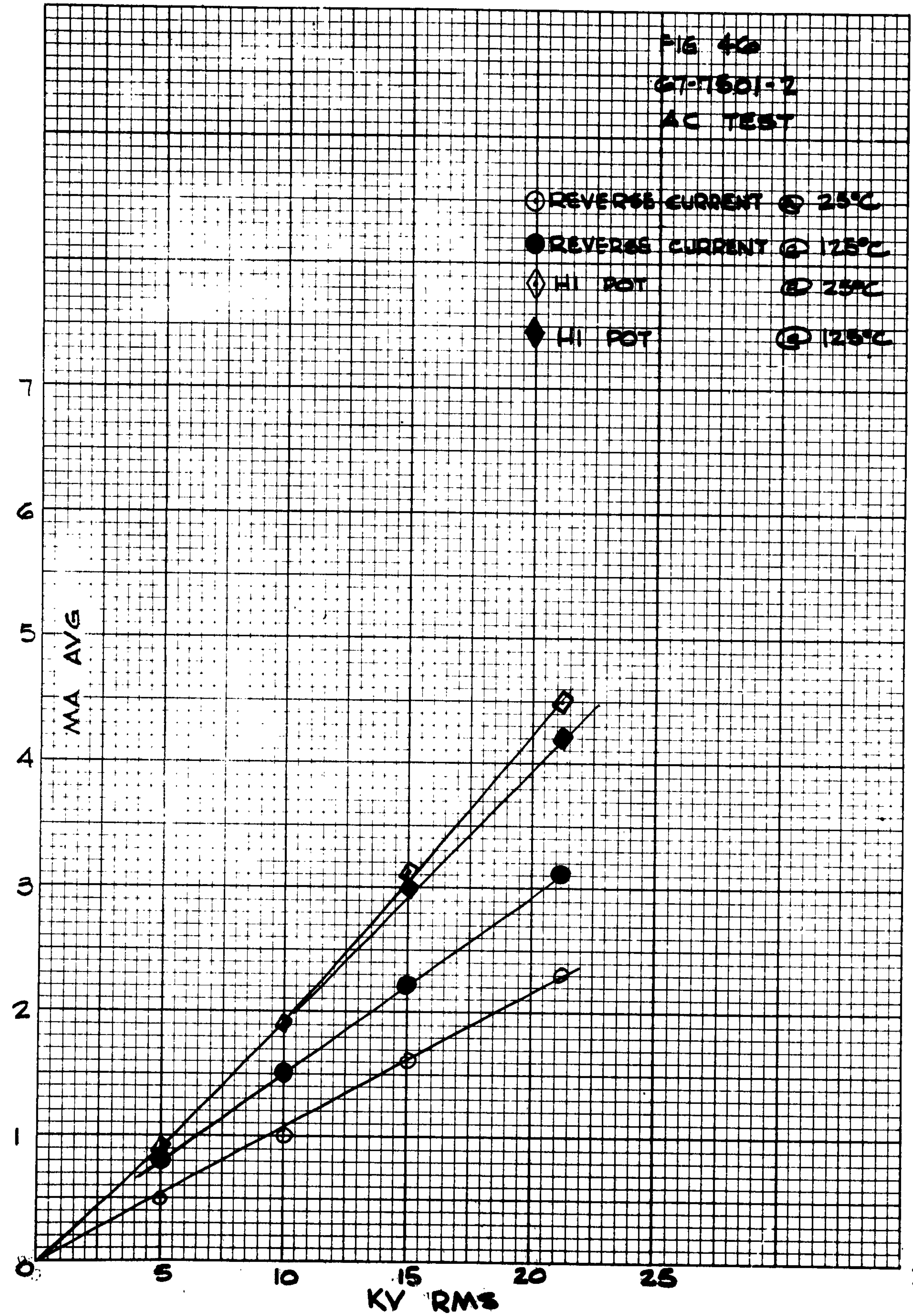


FIG 46
67-7601-2
AC TEST
REVERSE CURRENT @ 25°C
REVERSE CURRENT @ 125°C
HI POT @ 25°C
HI POT @ 125°C
MA AVG
KV RMS
0
1
2
3
4
5
6
7
5
10
15
20
25

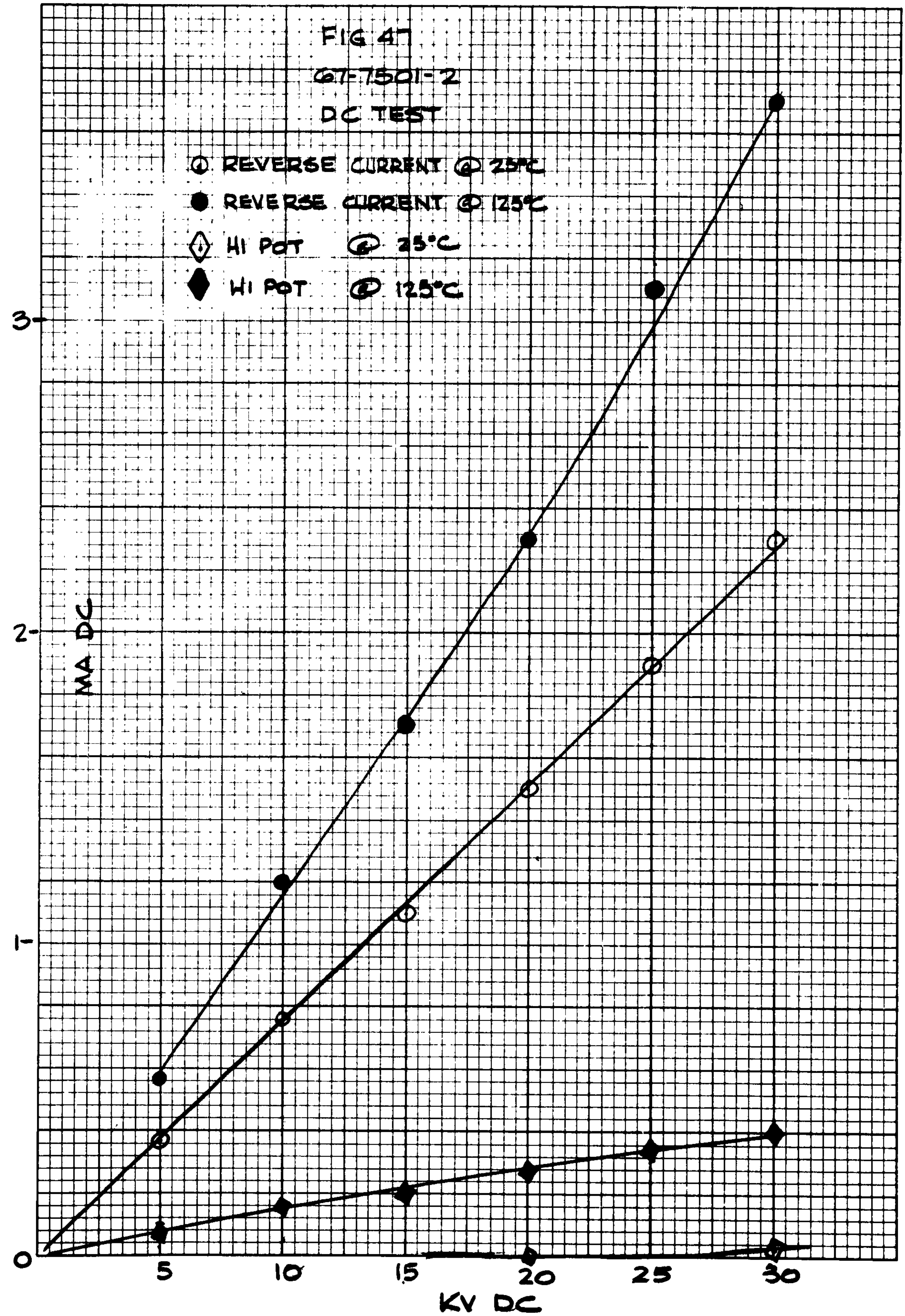


FIG 47
67-7501-2
DC TEST
REVERSE CURRENT @ 25°C
REVERSE CURRENT @ 125°C
HI POT @ 25°C
HI POT @ 125°C
MA DC
0
1
2
3
5
10
15
20
25
30
KV DC

Discussion

The results of the measurements are summarized in Table II. The table shows all reverse current or leakage current measurements at full voltage at 25°C and approximately 125°C. A number of the data do not fall into a clear pattern.

The DC reverse voltage test gives the expected reverse current of approximately 2.3 ma dc. At elevated temperature, however, the reverse current increases to values between 2.5 and 5.7 ma dc. A part of this increase in current can be explained by increased leakage current between the live parts and the grounded tank, as a glance at the results from the high-potential test shows. The major part of the increase in reverse current must be caused by a different phenomena. It is possible that the surface leakage on the insulating tube between modules increases because of some contamination of the Pyranol.

The DC high-potential test gives a rather erratic picture at room temperature, the leakage current ranging from 0.01 to 0.4 ma dc. At elevated temperature the values approach each other and are in the range of 0.31 to 0.74 ma dc with the exception of one value which is 1.1 ma dc. The particular unit giving the higher value was, however, at a slightly higher temperature, ie, 135°C, than the remaining units. This seems a likely explanation when the rapid increase in leakage current with temperatures above 125°C is considered.

The AC high-potential test at elevated temperature gives a rather uniform result,i.a, a current ranging from 4.1 to 5.5 ma. Such current corresponds roughly to the calculated capacitance between life parts and tank.

The room temperature values are closely related to the elevated temperature values except for two measurement, which give values 1/4 to 1/3 of the elevated temperature readings and the other room temperature data. An error in instrument reading is suspected.

Finally, the AC reverse voltage test gives relatively consistent values at elevated temperature with the reverse current in the range of 2.7 to 3.8 ma avg.

The room temperature readings, however, do not seem to fall into a logical pattern when compared with each other or with the elevated temperature data.

It is expected that further testing on subsequent units performed under closer control of variables will give a clearer picture of the behavior of the high voltage rectifier stacks under voltage stress.

TABLE II

Test	Temp.	Voltage	Unit #1	67-7501 -1	67-7501 -2	67-7502 -1	67-7502 -1 with dry Pyranol	67-7502 -3
	°C	KV	ma	ma	ma	ma	ma	ma
AC Reverse Voltage	25	21.2 28.3	1.1 -	2.2 -	2.3 -	2.2 2.5	0.65 1.02	0.60 0.96
	125	21.2 28.3	3.8 -	2.7 -	3.1 -	2.2 2.8	2.4 3.0	2.5 3.3
AC Hi-Pot	25	21.2 28.3	4.6 -	4.3 -	4.5 -	4.6 6.3	1.04 2.0	1.0 2.0
	125	21.2 28.3	5.0 -	4.2 -	4.2 -	5.5 6.3	4.2 5.5	4.1 5.4
DC Reverse Voltage	25	30 40	2.25 -	2.30 -	2.30 -	1.75 2.27	1.75 2.30	1.75 2.3
	125	30 40	5.1 -	5.7 -	3.7 -	2.10 2.69	1.95 2.50	2.35 3.2
DC Hi-Pot	25	30 40	0.09 -	0.22 -	0.01 -	0.12 0.15	0.14 0.22	0.22 0.40
	125	30 40	0.48 -	1.10 -	0.40 -	0.74 0.56	0.31 0.40	0.26 0.31

ENGINEERING SAMPLES, SIXTH SET

RECTIFIER DIODE

The rectifier diode used for the sixth set of engineering samples is identified by International Rectifier Corporation part number 66-6736. Its physical outline is shown in Fig. 48.

This diodes has a basic rating of 16 A at 150°C stud temperature. The forward conduction power loss as a function of the average forward current for the diode is given in Fig. 49.

In forward voltage drop and surge capability, the diode is similar to the diode used for the fifth set of engineering samples as described in the Sixth Quarterly Report, pp. 72-75.

The reverse voltage rating of the diode 66-6736 is 1200 V dc. At this voltage and a temperature of 125°C, the reverse current must be less than 400 microamperes and be stable. The diodes are selected at 1400 V peak at room temperature.

Blocking Life Test

Fifteen samples were operated at 1200 V peak and 150°C case temperature in a dynamic test for 700 hours. At the end of the test one unit had shorted and one unit showed increased reverse current when subjected to 1200 V dc at 25°C and 150°C.

A second dynamic blocking life test was performed on 20 samples. This test was run for 1000 hours at 125°C at 1200 V peak. At the completion one unit had shorted. The results of the test are shown in Table III.

FIG. 48

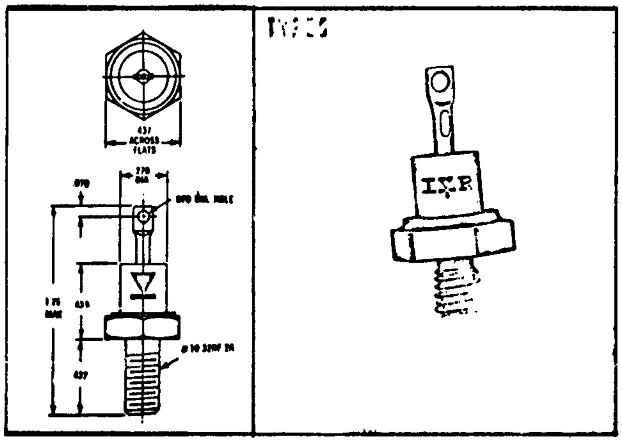


FIG. 49

Forward Conduction Power Losses Vs.
Average Forward Current ($T_j = 125°C$)

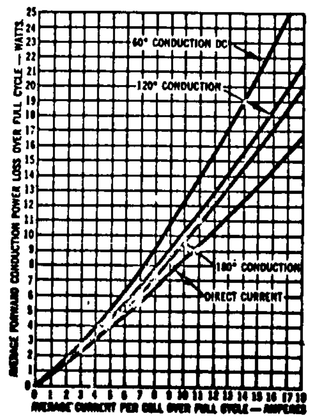


TABLE III. Blocking Life Test at 125°C

Rectifier Diode Number	Initial Measurement Reverse Current @ 1200 volt dc @ 25°C uA dc	Initial Measurement Reverse Current @ 1200 volt dc @125°C uA dc	500 hr. Measurement Reverse Current @ 1200 volt dc @ 25°C uA dc	500 hr. Measurement Reverse Current @ 1200 volt dc @ 125°C uA dc	1000 hr. Measurement Reverse Current @ 1200 volt dc @ 25°C uA dc	1000 hr. Measurement Reverse Current @ 1200 volt dc @ 125°C uA dc
1	1.4	200	1.2	230	2.2	190
2	1.1	190	1.3	190	1.6	140
3	0.5	90	2.2	110	0.8	120
4	1.2	120	1.4	110	1.8	120
5	0.8	100	3.5	100	2.8	100
6	0.7	120	2.0	130	2.3	140
7	0.8	140	1.3	140	1.4	140
8	1.0	140	0.8	140	1.2	130
9	0.6	120	0.9	110	0.8	105
10	0.8	70	1.0	80	0.6	70
11	0.4	110	1.1	100	0.9	100
12	1.4	170	1.2	170	2.8	170
13	2.4	240	1.0	240	2.2	200
14	1.3	170	0.7	150	0.9	150
15	1.8	220	0.9	210	2.0	210
16	1.5	200	1.5	200	1.7	190
17	3.0	180	1.4	170	1.8	170
18	1.4	160	short	short	short	short
19	1.7	140	1.0	140	1.0	120
20	2.1	200	2.2	210	2.0	180

Storage Life Test

Nineteen samples were subjected to a 1000 hour storage life test at 150°C. The end point measurement at 1200 V dc and 125°C showed one failure. One unit had, accidentally, been dropped to the cement floor and showed damage to the hermetic seal in a helium leak detector test. This unit was, therefore, not subjected to the storage life test. The test results are shown in Table IV.

TABLE IV. Storage Life Test at 150°C

Rectifier Diode Number	Initial Measurement Reverse Current @ 1200 volt dc @ 25°C uA dc	Initial Measurement Reverse Current @ 1200 volt dc @ 125°C uA dc	500 hr. Mesurement Reverse Current @ 1200 volt dc @ 25°C uA dc	500 hr. Mesurement Reverse Current @ 1200 volt dc @ 125°C uA dc	1000 hr. Measurement Reverse Current @ 1200 volt dc @ 25°C uA dc	1000 hr. Measurement Reverse Current @ 1200 volt dc @ 125°C uA dc
21	100	200	85	210	25	170
22	0.7	110	0.8	110	0.6	100
23	1.0	105	1.1	110	0.6	100
24	75	100	6.0	100	5.8	90
25	130	130	1.5	140	0.8	110
26	2.0	200	120	300	120	220
27	1.5	160	100	170	10	160
28	2.2	170	2.7	180	2.0	160
29	1.0	120	2.0	130	1.1	110
30	1.0	120	1.1	130	0.7	110
31	0.8	140	1.0	140	0.7	120
32	70	170	38	160	27	130
33	2.6	230	3.8	240	2.0	200
34	1.2	200	1.0	200	0.8	180
35	0.6	150	0.7	150	0.5	140
36	1.7	130	1.7	140	0.9	110
37	0.8	120	1 mA @ 1150 V	1 mA @ 900 V	1 mA @ 950 V	1 mA @ 950 V
38	1.0	120	1.3	130	0.8	110
39	120	1 mA @ 500 V	-	-	-	-
40	0.8	130	0.8	130	0.6	120

Note: Unit 39 was accidentally dropped and damaged.

CONCLUSION

A redesign of the rectifier stack was made within the allotted time and samples were produced on schedule.

The electrical design testing shows that this design will meet the electrical specifications.

Further design tests will be performed to evaluate the mechanical aspects of the design, particularly the ability to withstand shock and vibration. No problems are anticipated.

It is planned to make the preproduction samples of nearly identical design to the sixth set of samples.

PROGRAM FOR THE NEXT QUARTER (March 24, 1963 to June 24, 1963)

1. Design testing of units similar to the sixth engineering samples.
2. Procure material for the preproduction samples.
3. Manufacture the preproduction samples for testing by May 15, 1963.
4. Start Group B testing on May 15, 1963, for completion by June 30, 1963.

Estimate of Required Man Hours for Next Quarter

Mechanical Design	25 hours
Drafting	50 hours
Testing	150 hours
Reports, Analysis and Coordination	200 hours
Administration	50 hours
Manufacturing	260 hours
Total	735 hours

IDENTIFICATION OF PERSONNEL

The technical personnel named below contributed to various phases of the overall contract during the period covered by this report.

PROFESSIONAL PERSONNEL ASSIGNED:

Diebold - - - - - - - - - - - - -	100 hours	(Administration, Design, Report)
Luft- - - - - - - - - - - - - - -	216 hours	(Coordination, Report, Test)
Milligan- - - - - - - - - - - - -	120 hours	(Manufacturing, Test)
Wislocky- - - - - - - - - - - - -	100 hours	(Mechanical Design)
Ortner- - - - - - - - - - - - - -	37 hours	(Mechanical Design)
Pauli - - - - - - - - - - - - - -	16 hours	(Mechanical Design)
	489 hours	
Drafting- - - - - - - - - - - - -	410 hours	
Technician Support(Testing) -	113 hours	
Labor (Manufacturing) - - - -	262 hours	
TOTAL	1274 hours	

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