CONTACT BEHAVIOR AND GAS PHENOMENA IN A VACUUM SWITCH

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Summary of results.

Initially a conditioned vacuum switch opens a circuit with a small, momentary arc. This arcing releases gas from the electrodes so that with continued operation a definite rise in gas pressure within the switch was observed. The rate at which gas is evolved was seen to depend both on the value of the interrupted current and on the circuit voltage, increasing either for increasing current or for increasing voltage. Further, definite evidence of getter-action or electrical clean-up of gas in the switch was obtained. Thus the resultant gas pressure was found to be due to that part of the evolved gas not removed by getter-action; and a limiting equilibrium case was found in which the gas evolution and getter-action balance each other to give a constant operating pressure for indefinitely continued switch operation. Moreover, the pressure range thruout which satisfactory operation is possible was determined to be from that of the best obtainable vacuum to one of the order of 10^{-3} mm. In addition, the tests included rupture of currents that gave excessively high current densities, and demonstrated that current break is possible even with severe heating of the contacts. Similarly, a limiting value of current density of the order of 10,000 amperes per square inch appeared to be permissible without effecting serious damage to the contacts. And, in general, copper, the metal most desirable from a commercial standpoint, was found to give better operating results than either of the other two metals investigated.

The investigations on which this thesis is based are a part of the program being followed at the California Institute of Technology as a result of the highly encouraging experiments made on the problem of breaking current at high voltage in vacua. Those experiments established beyond any question the soundness of the fundamental idea: that alternating current of high amperage at high voltage can be broken successfully in vacuum with no deleterious arcing. The results of those tests(1) are thus of signal importance, and by way of introduction will be summarized briefly.

Vacuum switch number one was built entirely of glass and had two leads brot into the vacuum chamber thru copper disk seals. The circuit was made and broken between the two electrodes thru a bridge attached to an iron plunger operated externally by a solenoid. The distance between the seals, the minimum distance for creepage, was but six inches. Yet despite these small dimensions the switch broke successfully currents up to 150 amperes at 15,000 volts with no unfavorable symptoms.

Switch number two was practically identical in construction with that of number one, but had more generous proportions, and was provided with a charcoal trap for taking up gas during operations with the vacuum pump cut off. A final test of this model was made after it had been standing for three months sealed off from the pumps. The switch handled in a quite satisfactory manner currents to 600 amperes at a voltage of 15,000, the maximum kv-a. capacity available for test.

(1) Sorensen and Mendenhall, Journal A.I.E.E., December 1926.

These two switches, however, were of a design quite unsuited for commercial application. Hence switch number three was built with engineering requirements in mind. The motion of switch operation was brot into the glass vacuum chamber from the outside thru a flexible copper bellows, and provided a single break between bayonet type contacts that could thus be mechanically locked outside the switch in either the open or the closed position. This third model was found likewise in test to be satisfactory, breaking a current of 920 amperes at 42,000 volts with but a negligible flash. As with switch number two the actual operating limit remained unknown because of a lack of additional capacity in the testing circuit.

In short then, the obvious conclusion to be drawn from these experiments is that the idea of breaking current in vacuum is sound. Sufficient work has been done to show conclusively that the results as outlined can be reproduced again and again. The switch performance is not a matter of chance.

The basis for the operation of the vacuum switch is stated in the conclusion: "that if the vacuum is sufficiently high and all adsorbed gases have been removed from the metal electrodes, very large currents can be broken without formation of enough vapor to maintain an arc." (1). Or in other words two conditions are prerequisite, a proper vacuum, and outgassed contacts. Immediately a first question arises: with outgassed contacts what order of vacuum is necessary for successful switching, or within what limits of gas pressure will the switch operate without failure? The tests referred to give no information as to whether or not a poorer vacuum than that employed would have resulted in switch failure or satisfactory break. They were performed at the best vacuum obtainable, of the order of 10^{-5} mm. of mercury, either with the switches on the pumps or with liquid air on a charcoal trap to take up any gas evolved in switching. The intuitive impression was, however, that the break could be made in a much poorer vacuum. Thus, one of the objects of the research with which this thesis is concerned was to determine in a general quantitative way within what range of gas pressure in a vacuum switch successful operation might be expected. This point, however, was secondary and required no unique investigation, as the effect of gas pressure on switching was continuously observable during the detailed work on the contacts themselves.

The primary object of this research thus resolved itself into a general study of vacuum switch contacts of widely different materials when subjected to abnormal duty. The mechanical and electrical behavior of the contacts during and after the period of "conditioning" was carefully observed, with special attention directed toward any signs of damage to the contacts thru wear or pitting. Then in particular, the problem of gas evolution from the contacts is of interest and importance, and was investigated thruout a wide range of currents and voltages in an effort to determine if the amount of gas set free at each switch operation is in any way dependent upon circuit voltage or contact current density. Such information is of course valuable as a basis for predicting probable switch performance either under normal duty or overload conditions, since the amount of gas present in the vacuum chamber during current rupture appears to be the factor determining either switch failure or successful opening of the circuit.

Thus, in order to study conveniently the gas conditions resulting from switching, as well as to observe the behavior of the contacts themselves, a small vacuum switch was constructed as shown in figure 1.

The bulb was of Pyrex glass sealed thru copper-to-glass tube seals to two flexible copper bellows between which it floated, free from the mechanical stress and vibration occasioned by switching. From the bulb the pumping tube passed, thru a liquid air trap and a mercury cut-off, to a two stage diffusion pump backed with the ordinary fore pump. The mercury cut-off served as a convenient means for effectually isolating the switch from the pumps. The total volume of the switch bulb and connection to the cut-off was 90 cubic inches.

The switch itself was made electrically as simple as possible. Butt contacts, C, of end section varying from 0.01 sq. in. to 0.20 sq. in. were screwed into rods R of half inch diameter copper. The rods were supported by guides G which fastened to porcelain insulators; one rod was stationary and was soldered to the guide G_1 at S_1, the other was free to move forth and back thru guide G_2 a distance of an inch, altho the normal movement or contact separation was approximately one fourth of an inch. The flexible bellows were soldered between guide G_2 and an end piece D which in turn was soldered to the movable rod. Such construction was adopted because of the ease with which contacts could be replaced; by unsoldering the joints S_1 and S_2 the rods could be removed without any manipulation of glassware. An operating lever mechanism closed the contacts thru a coil spring so that the shock of bringing the contacts together was partially cushioned, and when closed they were thus held in contact under a fixed compression force of ten pounds. For manual operation of the switch an insulating rod was used, while for remote control a solenoid latch device opened the breaker. And altho the switch was built for convenience in testing, the whole arrangement is nevertheless of a design that could readily be adapted to meet practical engineering requirements, and was therefore entirely suitable for these investigations.

For measurement of gas pressure within the switch an ionization gage sealed into the pump tube adjacent to the switch bulb was used. Such a gage was particularly applicable to this work as readings could be taken rapidly and with reasonably consistent accuracy. Naturally, such measurements were of gage ion current, and in order to interpret these currents in terms of absolute pressures a calibration was made against a McCleod gage that was also connected into the pumping tube. This comparison gave the calibration for the ionization gage as,

$$p = 3.2 \cdot I_g \cdot 10^{-4} \text{ mm.}$$

for an electron current of one milliampere, and in which I_g is the ion current in microamperes.

Of course these pressure readings made thus with the ionization gage are somewhat open to question since at any given pressure the measured ion current depends not only on the quantity but also on the nature of the gas present. Yet if the reasonable assumption be made, that thruout the investigations the gas or mixture of gases resulting from switching has always the same essential composition, the pressure readings will then be consistent with themselves, and comparisons of switch performance under different conditions will have meaning.

The leads from the ionization gage were brot to two telephone jacks fastened to the cap of a standard porcelain insulator. The plugs for these jacks carried the connections to the meters and filament current source, and were removed during switching so that in event of failure of the switch the ionized gas in the vacuum system could not ground the high voltage power source thru the gage meters and connections.

In general, in this arrangement of the switch more exposed metal surface was included within the vacuum than was desirable for these tests. Furthermore, in combining the several parts of the switch, several soldered joints were used, which are undesirable from the point of high vacuum technique. Then too, since positive mechanical motion of the contacts by external levers was necessary to insure positive action under high current densities the copper bellows were employed to obtain this flexibility, introducing, again, more exposed metal surface as well as walls that may have been thin enough in spots to be slightly permeable for gas. And, of course, such an arrangement does not lend itself to any baking-out process, with the result that some correction was necessary in the readings of pressure in the switch to account for gas coming from exposed surfaces not directly involved in current rupture. Such correction, fortunately, was found to be small in relation to the gas pressure being measured so that this extraneous gas introduces no ambiguity in the results. Furthermore, as numerous trials indicated, no appreciable pressure reduction took place during runs due to the presence of the liquid air trap.

For power loads to be switched by this breaker various circuits were employed to obtain a wide range in current, voltage, and power-factor, limited, of course, by laboratory facilities. The maximum kilovolt-ampere capacity available for this work was about 2500, single phase at 15,000 volts. To be sure, such power is insignifigant as far as a commercial switching problem is concerned. So, to simulate conditions of abnormal duty, these tests were done with small switch contacts, giving thereby current densities at rupture comparable with those existing in a normal breaker under severe duty. In a 3,000 volt circuit correspondingly higher currents could be had with resulting densities in the switch as high as 24,000 amperes to the square inch of contact area. Most of the testing, however, was done with a switch duty cycle consisting of short-circuiting and immediately opening the short on the high side of a 15000/220 volt, 10 kv-a. transformer. Under the short-circuit condition the current thru the switch was approximately five amperes, adjustable within a range of from three to nine amperes thru a controlling resistance in the primary circuit; and the voltage across the open contacts was of course 15,000. Other voltages were tried, up to 35,000, as high a value as could be used without external flashover of the switch.

The numerical data taken were measurements of gas pressure existing within the switch subsequent to various amounts of operation. This pressure of gas evolved thru switching was found to increase in a quite consistent way, and gave reproducible curves of pressure plotted against the number of switch operations. Such curves were obtained in the following way. The switch was evacuated to the minimum pressure obtainable and isolated from the pumps with the mercury cut-off. The test circuit, containing a properly adjusted load, was then made and broken repeatedly thru the switch, with pauses at intervals of ten or twenty operations for measurement of gas pressure. Generally such runs consisted of one hundred circuit closings and openings, altho some tests were extended to switch failure, and, in one case, to one thousand operations. Careful note was made during each run of time for each reading in order that comparisons might be made with curves of pressure rise in an equivalent period of time due simply to leakage. From these latter curves of leakage were obtained pressure values, which, by simple subtraction, corrected the operating data for the effect of extraneous gas.

Many runs of this sort were made with copper contacts, tungsten, and aluminum, all of which gave corrected pressure curves of similar form. During the first few operations of the switch the pressure was found to increase rapidly, and with subsequent operation, continued to increase, but at a lower rate. Then, in general, after some 80 or 100 operations, the pressure increased very slowly for a considerable number of additional switching cycles, and then underwent a rapid increase that usually resulted in switch failure. A curve of that form is given in figure 2, and is typical of many such runs. The switch contacts were of copper of 0.01 square inch cross-section, giving, accordingly, for a current of 3.7 amperes a density of 370 amperes per square inch. As was mentioned previously, each operation, or, as is commonly said, each switch cycle consisted of closing and immediately opening the circuit, the time interval between make and break being sufficient to allow the current to attain a steady value. After each ten operations the gas pressure was measured with the ionization gage, and values resulted which follow a fair curve as shown. Between the readings after 90 and after 100 operations the pressure rose suddenly, but no switch failure resulted, even at the final high pressure of 2×10^{-2} mm. Then immediately following the run the switch was evacuated and again cut off from the pumps for a period of time corresponding to that required for the run, fifteen minutes, while pressure readings for a leakage curve were obtained. This leakage curve is indicated by the light line in figure 2 that rises slightly from the initial pressure valve, and shows well the unimportance of this extraneous gas when compared with that liberated by switching.

Such a pressure curve then is indicative of the way in which gas is set free by the arc attending current rupture; and, indeed, it is not a chance effect, but rather, is definitely reproducible. Many runs made under identical conditions of current and voltage gave substantially the same results. However, after some hundreds of operations the amount of gas resulting from a given amount of switching becomes less as the contacts "clean up". Curve (b) of figure 3 indicates that effect, and gives a pressure after 100 operations of one half of that existing at the end of the run of figure 2. The curve of figure 5 was taken 800 operations later than that of figure 2, and the difference between the two indicates clearly the importance of making comparative runs under identical conditions. For example, in order to check the rate of gas evolution at one current density with that at another density, the two runs should be made consecutively, thus having one condition of the contacts thruout the two curves. Consequently, all curves that for the purpose of comparison are drawn on the same diagram have been plotted from data taken during consecutive runs.

Figure 3 represents two such runs, the one for opening the circuit only, and the other for closing and opening the circuit. As would be expected, the curve for the complete switching cycle shows the greater amount of gas. The other run, however, representing current rupture only, liberated nearly as much gas, and shows that the opening operation of the cycle is largely responsible for the pressure increase. Practically this point is important, for it indicates that a vacuum switch should not evidence distress - as does an oil switch - when it is closed, completing the circuit to a heavy load; nor should the gas liberated thru closing the contacts be sufficient in quantity to render the switch inoperative for an immediate opening.

Naturally, these curves represent, in a sense, average values of pressure increase, since readings were taken at intervals of ten operations. The gas resulting from any one operation is not necessarily one tenth of the observed increment; it may be one tenth, or it may be one half of the total for the ten operations. This erratic behavior may be seen in the following tabulated data which are pressure readings taken after single operations, up to fifteen in number, for each of four runs with identical conditions of contacts, voltage, and current. The contacts were of copper of 0.01 square inch section; the voltage was 15,000 and the current, 3.7 amperes.

Operation Number	Resulting pressures in microamperes			
	I	II	III	IV
0	0.2	0.2	0.2	0.2
1	1.5	0.25	0.5	0.5
2	2.0	1.25	0.5	0.75
3	2.5	2.25	1.75	1.5
4	3.0	2.75	2.25	2.0
5	3.9	3.0	2.5	2.75
6	4.25	3.25	2.5	2.75
7	4.5	3.5	3.0	3.0
8	5.0	3.5	3.0	3.5
9	5.5	4.0	3.25	3.75
10	6.0	4.0	3.25	4.0
12	6.5	4.25	4.0	4.5
15	6.5	4.5	4.5	5.5

The results of the tests suggest that the pressure rise for any one current break probably depends on the instantaneous value of the current at the time of contact separation. Then too, variations in arc conditions probably are introduced by the different speeds of contact travel which must have resulted, thruout the several runs, from manual switch operation, causing, in turn, differences in gas evolution. These reasons for individual variations in pressure are mentioned here simply by way of explanation of the chance crossing of curves (a) and (b) of figure 3.

Figure 4 shows the behavior of gas pressure when the current in the switching circuit was changed. The voltage across the open switch was 15,000 for both runs; the current for curve (a) was 3.7 amperes, and that for (b), 8.4 amperes, giving densities of 370 and 840 amperes per square inch. These densities, by way of comparison, are in magnitude of the order a switch would be subjected to in normal service. These curves, which are typical of several such comparative runs, indicate clearly that the pressure resulting from any number of operations is decidedly less for the run with the higher density of current.

A somewhat different effect, given in figure 5, resulted from tests with abnormally high densities. For these runs, unfortunately, by reason of power limitations, a lower voltage, 2300, was used; and direct comparison with the previous curves can not be made. However, the interesting fact appears, that even with the extremely high density of 24,000 amperes to the square inch the pressure existing in the switch after 100 operations was only one fifth of that subsequent to like operation at 15,000 volts and 3.7 amperes. Furthermore, curves (a) and (b) for densities of 3500 and 12,500 amperes per square inch show that the switch pressure remained practically constant thruout the runs. Here again the test results give promise of successful vacuum switch performance in commercial service, inasmuch as the extremely high current density, corresponding sensibly to severe switch duty in practice, and high enough actually to melt the contact tips, did not give resultant gas pressures sufficiently high to cause switch failure.

These curves, moreover, when compared as to magnitude of pressure with those taken at lower current densities but higher voltage suggest another factor that greatly influences the quantity of gas resulting from switching. Hence, changes in circuit voltage were tried while the current was maintained constant. The effect of such voltage variation appears strikingly in figure 6. Naturally, as mentioned before, these curves represent data taken during consecutive runs, in order that they be comparable with one an other. These pressure curves are quite distinct, and show definitely higher pressures for each higher value of voltage. Thus it is seen that voltage as well as current in a vacuum switch influences the gas pressure resulting from operation, a conclusion that was anticipated, in a sense, from earlier, non-quantitative work. For, in the testing of the three vacuum switches referred to at the start of this paper it was observed that once the contacts had been "seasoned", or "conditioned" for a given voltage subsequent increases in current resulted in nothing but successful breaks. Or, in other words, the voltage appeared as a factor in the conditioning or outgassing of the switches, but once the contacts were in proper shape higher current densities at rupture set free no large amounts of gas.

These test data have resulted from operation with copper contacts of 0.01 square inch area. The effect on the contacts themselves of the service with extremely high current density was surprisingly little. During the run made at the density of 24,000 amperes per square inch the contacts appeared to suffer considerable damage, since bits of molten copper were observed to fly about in the switch bulb. Of course such behavior was to be expected, as with no switching whatsoever the high current density alone would very quickly fuse the contacts. This I^2R heating together with the energy of the arc which maintained for a maximum time of 0.01 second after each switch operation brot the contact tips to the melting point. Yet current rupture was entirely satisfactory under this extremely unfavorable condition, and very little gas resulted from the run of one hundred operations. A later examination of the contacts showed them to have suffered surprisingly little damage, as may be seen in figure 7. Some beading appears at the ends, but the excessive pitting and burning which similar service in air or oil would have produced is entirely lacking. At a lower current value of 100 amperes scarcely any signs of damage to the contacts appeared. And for reasonable currents there are no deleterious effects whatever.

These tests with the very small contact points were repeated for copper tips of 0.03 square inch area. The results were essentially the same. Pressure curves identical in character with those previously discussed were obtained, but which exhibited one marked distinction in that they represent at all times lower gas pressures. The behavior for high current densities was similar to that experienced before, except that the limiting density at which contact damage began to appear was

10,000 amperes per square inch. This value is substantially lower than the 24,000 figure for the smaller area, which is to be expected on the basis of the well known "hot spot" theory for separating contacts. That is, the current is presumed to localize at points on the parting surfaces, and thus produce hot spots in spite of the large amount of additional area of the contacts. A comparison of the two sizes of copper tips pictured in figure 7 gives an idea of the relative damage experienced by the two contact surfaces for the same value of current.

Immediately before the form of the larger contacts was destroyed with high currents, and following many runs at low current values and high voltages, beautiful evidence of "getter action" began to appear. This "getter" clean-up naturally should be present in the vacuum switch since conditions are right for it. A deposit of contact metal, condensed copper vapor, gradually forms on the walls of the switch chamber, and acts to clean up the gas which is ionized at each switch operation. Then too, the copper vapor in the arc of half-cycle duration very probably takes up gas by some process not definable. By such an action the pressure curves of figures 4 and 5 would result. Conceivably the high current density run liberated gas in amounts greater than could be taken up by the vaporized copper and the wall deposit; hence, the net pressure continued to increase with the number of operations.

Evidence more conclusive is that offered by the following tabulated data. They represent one of two similar runs made with a current density of 170 amperes per square inch at a voltage of 15,000. The number of the operation, the elapsed time from the start of the run, and each resulting pressure as read with the ionization gage in microamperes are given.

Operation number	Pressure	Elapsed time in minutes
0	0.4	0
10	3.5	1
20	6.0	2
40	7.0	3
60	8.0	4
80	9.0	5
100	9.0	6
140	10.0	8.5
200	11.0	13.5
300	10.0	20
400	9.0	26
500	9.5	32
580	9.0	40

At this point the switch was allowed to stand without operation for a period of twenty eight minutes while the gas pressure was caused to rise by leakage. The run then continued.

580	15.0	68
600	10.5 **	70
620	8.5	71
640	9.0	72

A similar pressure rise was brot about.

640	16.0	85
660	10.0 **	86
680	10.0	87
700	10.0	88

Again the pressure was increased thru leakage.

700	16.0	96
720	10.0 **	97
740	9.5	98
800	9.0	102

And a fourth time the pressure was raised, but to a higher value.

800	31.0	175
820	15.0 **	177
840	11.0	178
860	9.0	180
900	8.6	185
1000	8.5	192

It will be observed that thruout the extended run the gas pressure tended to maintain a sort of equilibrium value around nine microamperes, equivalent to 2.9×10^{-3} mm. of mercury. Initially the pressure rose to nine or ten, and remained essentially constant. Pressures above this equilibrium value were reduced by subsequent switching, as noted in the table by the asterisks. Or, in short, the electrical clean-up, or getter action took care of not only all gas evolved thru switching operations, but also that entering as leakage. After 1000 operations the behavior was identical with that thruout the run, and apparently the number of switching cycles could have been extended indefinitely. Indeed, after the switch had stood for several hours at a poor fore-vacuum and had then been pumped down again, this clean-up action was as vigorous and definite thruout a similar run as it was in the preceding test. This electrical clean-up very likely took place both in the vaporized copper in the arc, and at the wall deposit, but probably to the greater extent in the latter way.

This behavior was of course that of copper. The other two metals, aluminum and tungsten, which were used as contacts gave satisfactory switch performance, and exhibited the same general characteristics as copper under like conditions. Inasmuch as these two metals, due to their electrical and mechanical properties, are of less practical importance than copper they were investigated in less detailed fashion. Aluminum followed quite closely the characteristic pressure curves for copper, but a suspected getter action markedly greater than that of copper was not found. Tungsten, on the other hand, while giving pressure curves for low current values similar to those previously obtained, gave radically different results at high current densities. Figure 8 for densities of 4,500, 11,000, and 21,000 amperes per square inch shows rates of pressure rise that increase with increasing densities. Or, the gas pressure resulting from a given number of operations is higher for larger current at the contacts. Evidently the clean-up effect of the tungsten arc is not appreciable.

In general, then, these pressure curves for aluminum and copper give the characteristic behavior of a vacuum switch when in operation. And, these curves give as well the range in pressure thru which good current rupture can take place. A further item of incidental interest is the physical appearance of the contacts themselves as they clean up, or, are conditioned in service.

The change in outward appearance of the contacts is typical of all vacuum switches that have been studied. The contacts and other metallic surfaces exposed to the vacuum arc have initially the normal appearance of, say, copper. The first few switch operations have invariably been failures, due to the large amount of surfact gas present, and the resulting arcs have been allowed to maintain for brief intervals, limited by safe heating, to augment the surface clean-up. After several such arcs the surface of the copper has become blackened with a thin layer that is apparently oxide. "Conditioning", then, accurately defined, consists of the removal of this surface coating thru subsequent switching.

The first area of clean copper occurs at the tips of the contacts and then spreads in an irregular manner to include more and more of the metal surface as switching proceeds. The blackened area has in it scattered patches of clean metal, curious tree-like designs, quite similar to the well-known Lichtenberg figures. Presumably these spots result from virtual explosions which open tiny gas pockets immediately below the oxide layer. Such figures in the blackened film cam be seen on the contact tips which were referred to before, and on the head of the vacuum chamber and contact rods, illustrated in figure 9, which were removed from the original three phase switch assembly. In the latter instance it will be observed that conditioning had only begun.

Obviously then, a mimimum of metallic surfact to be conditioned is desired in a switch. The three phase design given in figures 10 and 11 was built with a vacuum chamber almost wholly of metal, the object beign to reduce the hazard of physical damage; and a clean-up resulted that was unprecedentedly slow. In fact, after many arcs resulting from failure in this switch the clean area consisted of only a small portion of the contact blade and clips, and a number of scattered figures.

From these and the preceding phenomena some notions may be taken concerning the mechanism of outgassing in a vacuum switch. Continuously present is the process of slow diffusion by which the gas within the metal gradually finds its way to the surface and is eventually pumped out. Moreover, if high electric stress exists at the metal surface this removal of gas is more rapid, and gas pockets appear to open in a metal stratum, say a few atoms deep, with explosive violence that causes an eruption of metallic particles as well as the gas. This effect is of course well known and has been definitely observed for small wires in strong fields. It exists in the vacuum switch due to electric stress, both between open contacts and between contacts and ground.

Thru switching an additional scavenging results; the arc of momentary duration, or the arc of failure acts to speed greatly the removal of surface gas, conceivably thru a process of ionization. The effect of this last process is enormously greater than that of the other two.

With such conditioned or so-called outgassed electrodes in a vacuum switch the actual gas-free layer probably extends to a depth of only a few microns. Subsequent switching duty tends to liberate gas thru the two slow processes, diffusion and electrical stress, and thru the more vigorous action of mechanical wear and arc vaporization of the contact metal. Each bit of metal that is removed by either of these two agents exposes fresh material beneath that contains gas. This gas comes out in quantities that are sufficiently small as to cause no failure of the switch; nevertheless, as is evident from the data that have been discussed, gas is continually liberated by switch operation. The mechanical abrasion should be negligible for butt contacts. And, to test this point, actual measurements showed that the gas set free by this action was inappreciable. Thus, the bulk of the gas given out by operation results from the vaporization of the contact material.

Fortunately, the vaporization of the metal tending to set gas free acts definitely, in the case of copper, as a getter, thus keeping down the resulting gas pressure. Tungsten contacts, tho, when subjected to abnormal currents gave off greater and greater amounts of gas. This difference in behavior of the two metals is possible due to a situation of this sort. The tungsten, when conditioned, may be outgassed to a depth considerably less than that of the gas-free copper layer, and the surface vaporization would thus expose a greater number of the infinitesmal gas pockets. Then too, the getter action of the ionized tungsten vapor is probably less effective than that of the copper, and the net result of increasing the current density, and the vaporization, would be to liberate greater amounts of gas without the compensating clean-up afforded by copper.

The gas pressure characteristics for copper contacts justify the notion that getter action takes place in the metallic arc as well as between the gas and the wall deposit. This metal arc is likewise a necessary part of the mechanism by which the vacuum switch is able to open altermating current circuits without excessive transient voltage surges. As many oscillograms of switch operation show, the current continues to flow as an arc discharge during the brief time interval between the instant of contact separation and the instant at which the normal current wave would have passed thru its zero value. This arc maintains for a time up to 0.01 second, while the current is carried in some manner, by a gaseous arc, an electron discharge, or a metallic arc. A gas discharge of sufficient volume to maintain a current of several hundred amperes would be an extremely unlikely possibility, since after the brief moment of zero current the gas would still be present in the switch chamber to ionize and cause the arc to restrike. Such is the phenomenon of failure that occurs with new, unconditioned contacts, and is accompanied by high values of gas pressure. Conversely, with clean contacts, current rupture gives only a slight increase in the amount of gas. Presumably, therefore, the larger part of the carriers for the arc must come from some source other than the gas. Ionized metal vapor can readily be present in an amount sufficient to maintain the discharge; and these ions on becoming neutral as the current passes thru zero, unlike those of the gas, condense on the walls and other parts of the switch and no longer are present to cause a restriking of the arc. Such is conceived to be the general mechanism of current rupture, since the third possible means, a pure electron discharge without positive ions seems improbable.

This conclusion may be somewhat strengthened by a representative calculation. A mechanism in which electrons are the only carriers present immediately suggests that the arc characteristics should be consistent with the well-known space-charge equation. However, the actual cathode has thus far not been accurately defined; and, accordingly, the area of the cathode, to which the saturation current is proportional, is not definitely known. Yet, if as the most favorable value for this area the whole surface of the contact be taken, and a reasonable contact separation be assumed, the voltage between the electrodes necessary to maintain a current of, say, 250 amperes is required by the equation to be of the order of several thousand times that of the measured arc voltage of twenty volts. Or, in other words, even tho this direct application of the equation is somewhat questionable, the result is interesting in that it indicates the marked disagreement between tha arc characteristics as observed and those as expected on the basis of pure electronic conduction. And the inference is that positive ions must be present in the arc to reduce any effect of space charge.

Hence, for no space-charge in the arc, the number of ions equals the number of electrons. The current involves both the charges and the velocities of the carriers, but since the electron velocity, v, in the expression for the current,

$$i = Nev + Nev',$$

is predominately greater than the ion velocity, v', the latter may be neglected, giving,

$$i = Nev.$$

If a fairly low velocity of 10^6 centimeters per second is assumed for the electrons over the distance of 0.5 centimeters, and, as before, a current of 100 amperes is taken, N is readily computed to be 6.4×10^{14}, the number of electrons or ions. N is also equal to the number of atoms present in the arc, of gas and of metal, that are in the ionized state. Assuming that copper alone is present, the very reasonable figure of 6.5×10^{-8} grams of copper results. The energy necessary to vaporize this amount of metal from the electrodes is considerably less than one one-thousandth part of the observed energy of some twenty watt-seconds actually dissipated in the discharge. Of course, this energy is primarily a function of the probability of the current value at the time of contact separation. That is, with current a sinusoidal function of time, the magnitude of the current at the instant the contacts separate may be anything between zero and the maximum value; and, accordingly, the resultant arc may be sustained for a length of time from zero to 0.01 second with a 50 cycle source. Hence, while the arc voltage has been found to be essentially constant at 20 volts the arc energy and the consequent vaporization of metal is a variable quantity. But, for a condition of low arc energy, that is, for a low value of decreasing current, the amount of metal vapor necessary in the arc is also small. Consequently the belief based on these calculations that the momentary arc in the vacuum switch is a result of ionization of contact metal appears to be reasonable.

Finally, in summarizing the numerical data which have been obtained and the deductions made from observed performance, certain salient results are evident. Initially a conditioned vacuum switch opens a circuit with a small, momentary arc. This arcing releases gas from the electrodes so that with continued operation a definite rise in gas pressure was observed. The rate at which gas is evolved was seen to depend both on the value of the interrupted current and on the circuit voltage, increasing either for increasing current or for increasing voltage. Further, definite evidence of getter action or electrical clean-up of gas in the switch was obtained. Thus the resultantgas pressure was found to be due to that part of the evolved gas not removed by getter action; and a limiting equilibrium case was found in which the gas evolution and getter action balance each other to give a constant operating pressure for indefinitely continued switch operation. Moreover, the pressure range thruout which satisfactory operation is possible was determined to be from that of the best obtainable vacuum to one of the order of 10^{-3} mm. In addition, the tests included rupture of currents that gave excessively high current densities, and demonstrated that current break is possible even with severe heating of the contacts. Similarly, a limiting value of current density of the order of 10,000 amperes per square inch appeared to be permissible without effecting serious damage to the contacts. And in general, copper, the metal most desirable from a commercial standpoint, was found to give better operating results than either of the other two metals investigated.

There remain, however, certain brief remarks of critical and speculative nature to be made relative to this work. Naturally, these investigations have been largely exploratory in scope; they were intended to determine rather definitely the behavior in service of the two vital elements of a vacuum switch, the contacts, and the vacuum itself. The results obtained are entirely reasonable and are quite consistent with previous vacuum switching experience. Moreover, they not only corroborate the earlier results and confirm certain suspicions as to essential vacuum and possible clean-up action suggested by the preceding set of experiments, but also afford new information of a quantitative sort on switch performance. Definitely, these data are insufficient as a basis for switch design, but nevertheless they are indicative of probable switch operation under various conditions of vacuum and duty. And, in short, they imply even more favorable possibilities in vacuum switching than earlier experiments intimated.

Finally, the results obtained here suggest a definite line of future investigation, an intensive study of the inherent getter action of the vacuum switch when augmented by some sort of arcing contacts of metal more favorable than copper and by more active metallic wall deposits or adsorbtion surfaces, thus leading toward the ultimate goal, namely operation independent of pumping equipment.

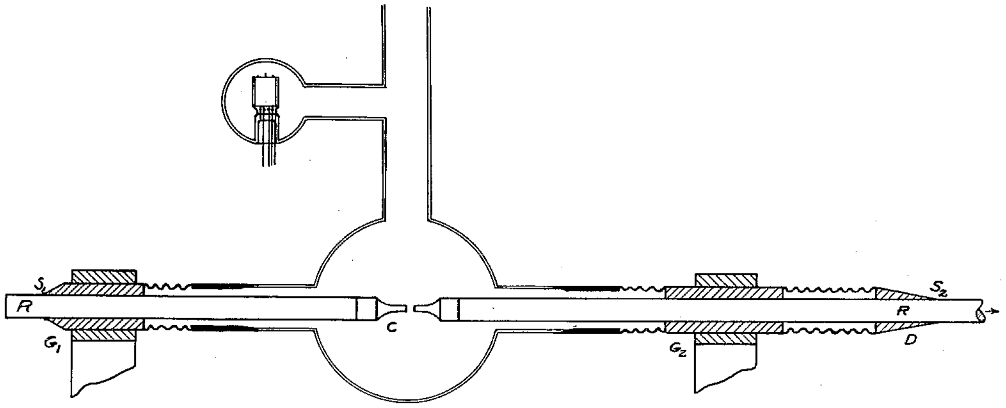


Figure 1

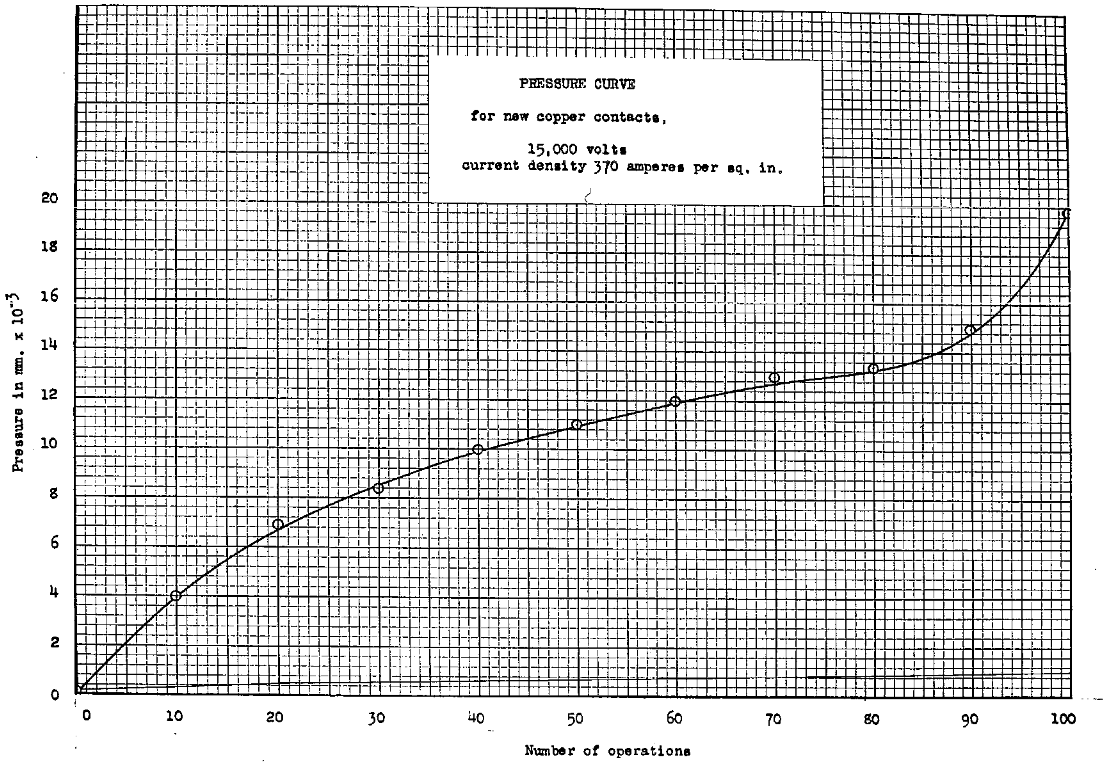
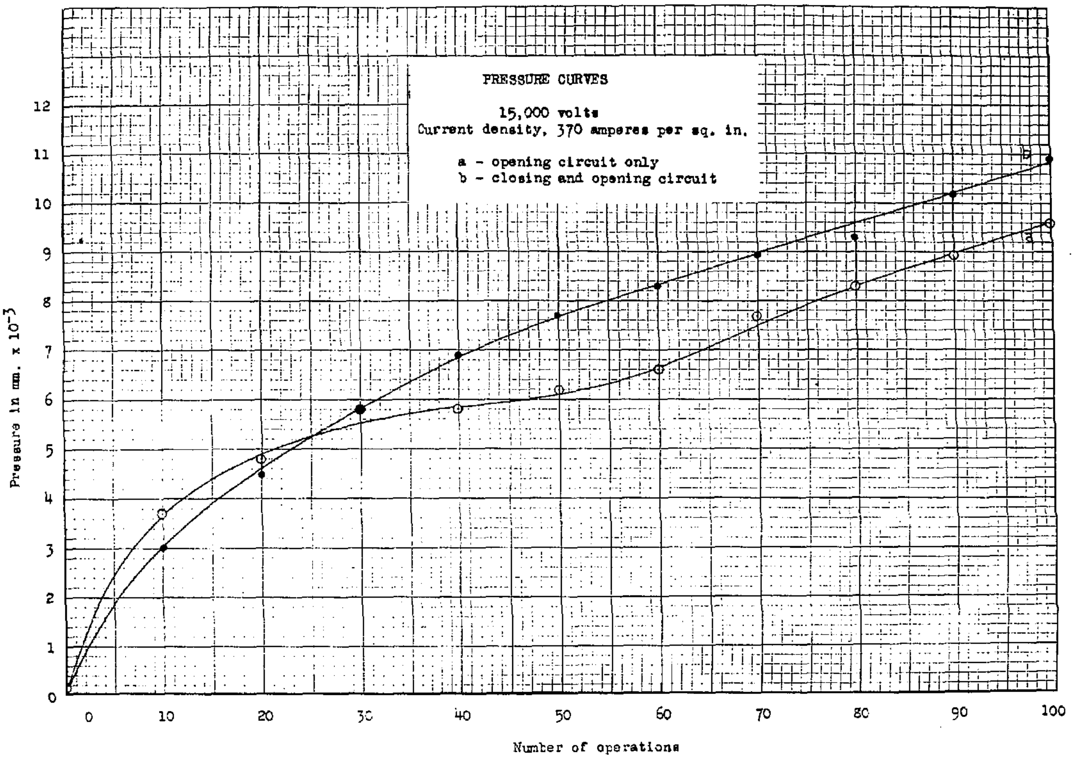


Figure 2



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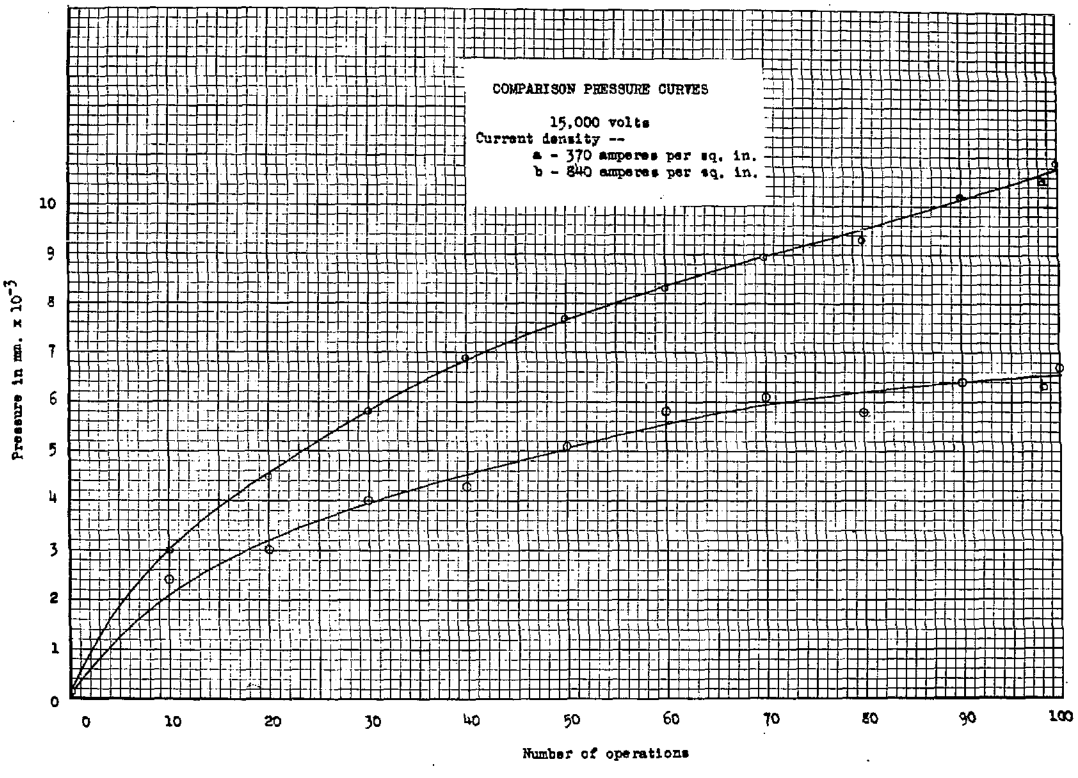

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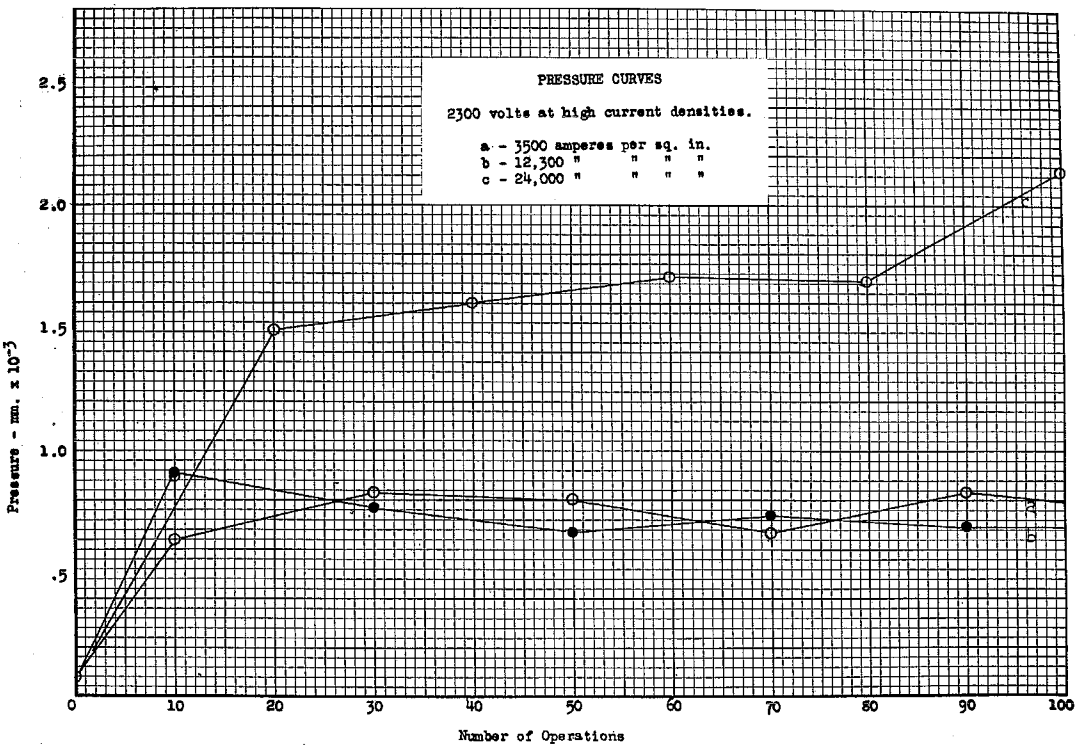

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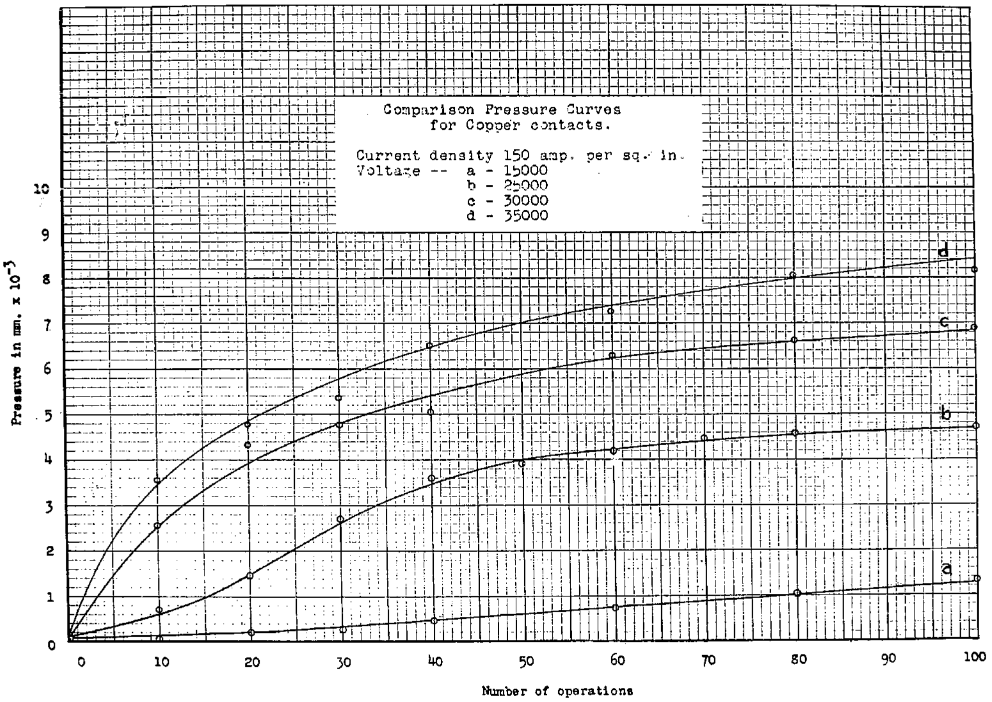

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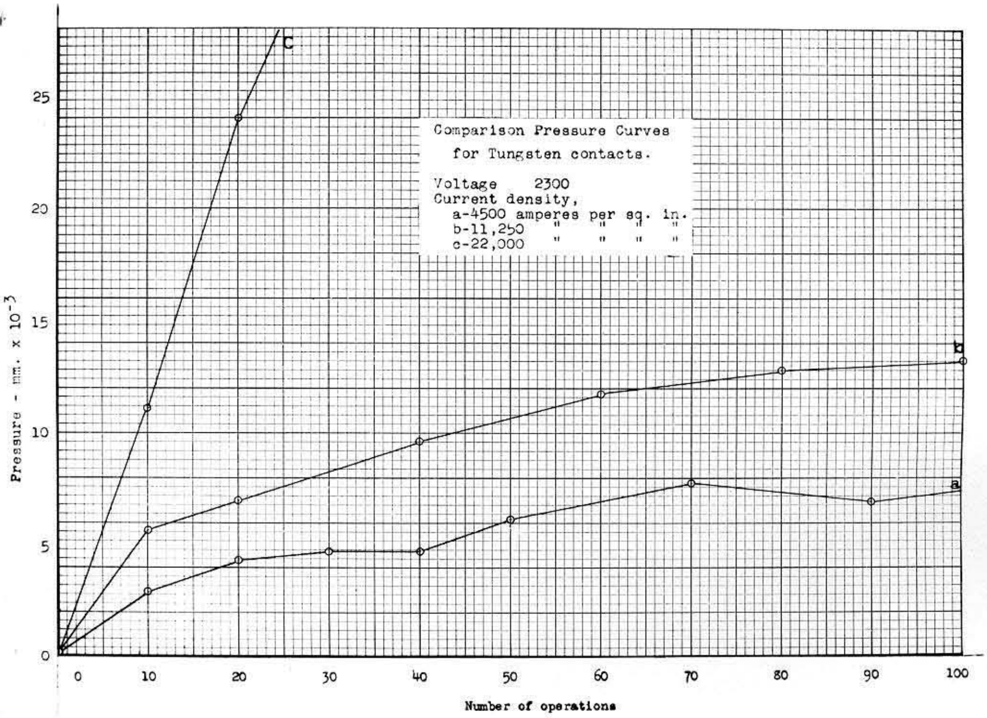

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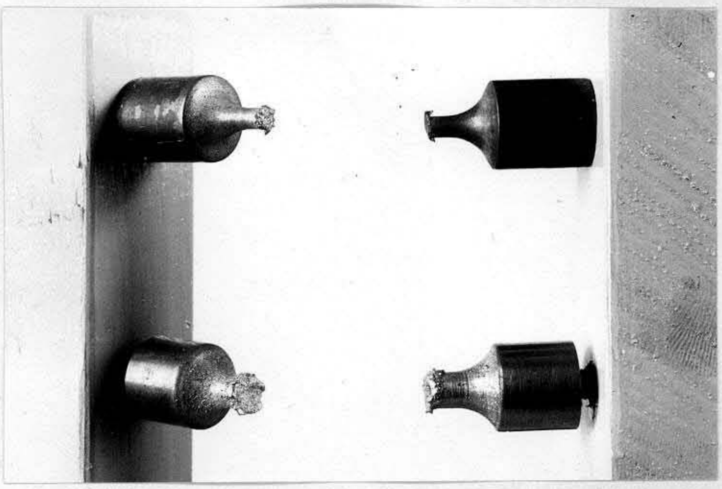
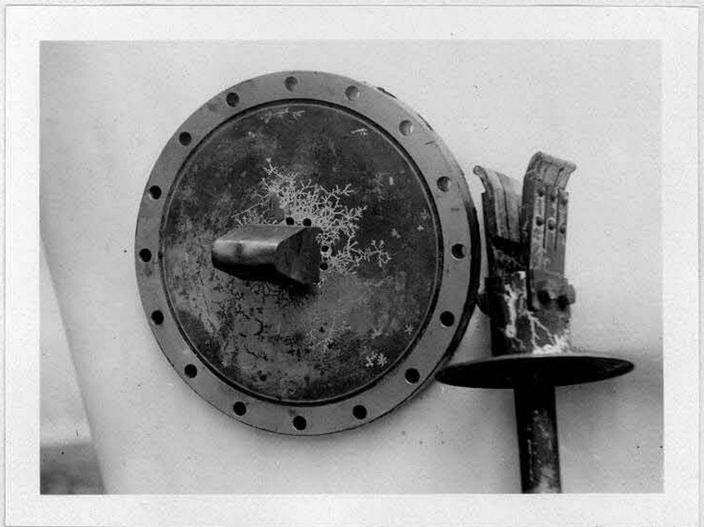


Figure 7

Figure 9



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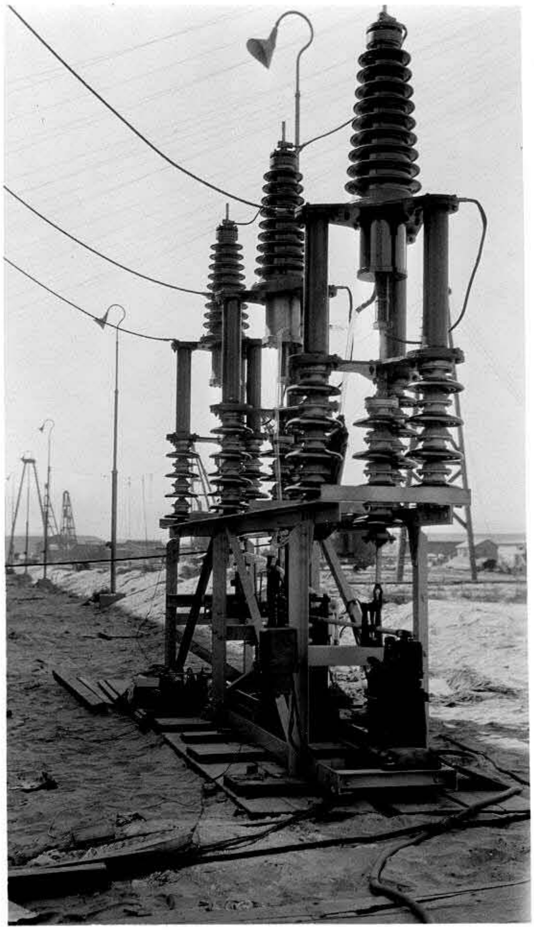

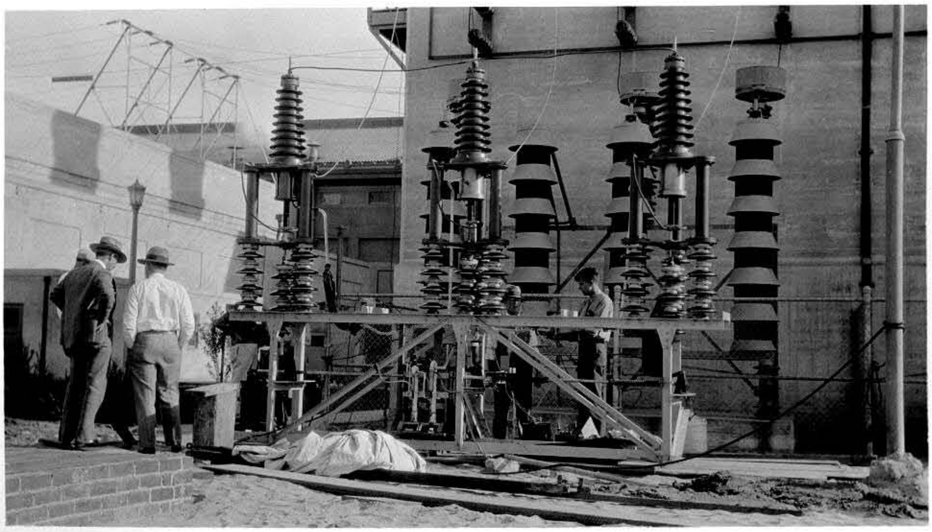

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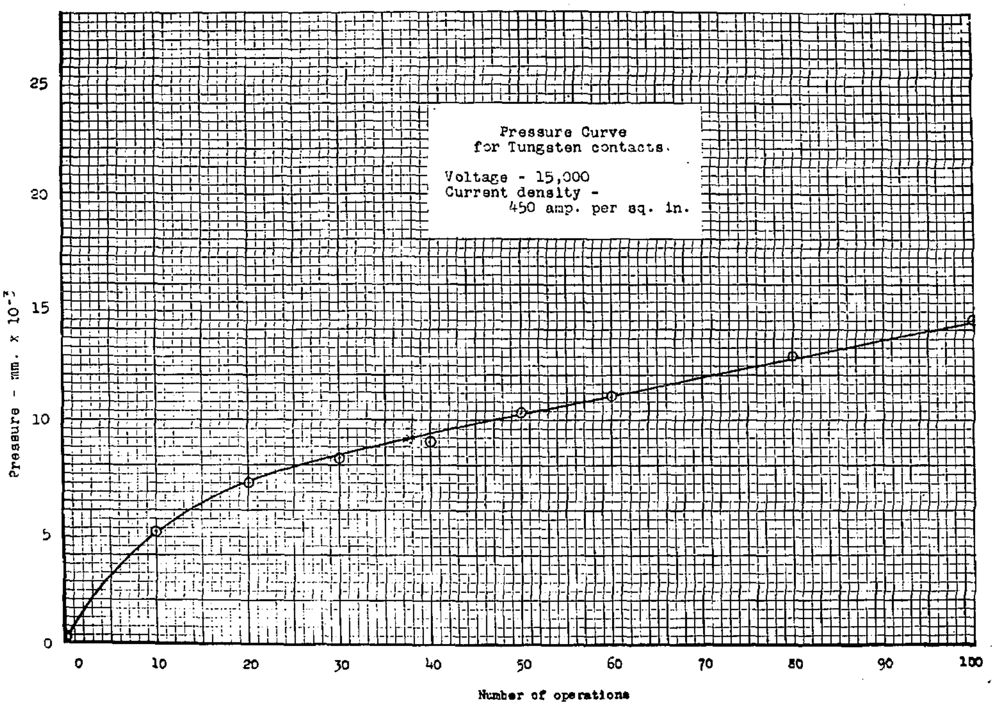

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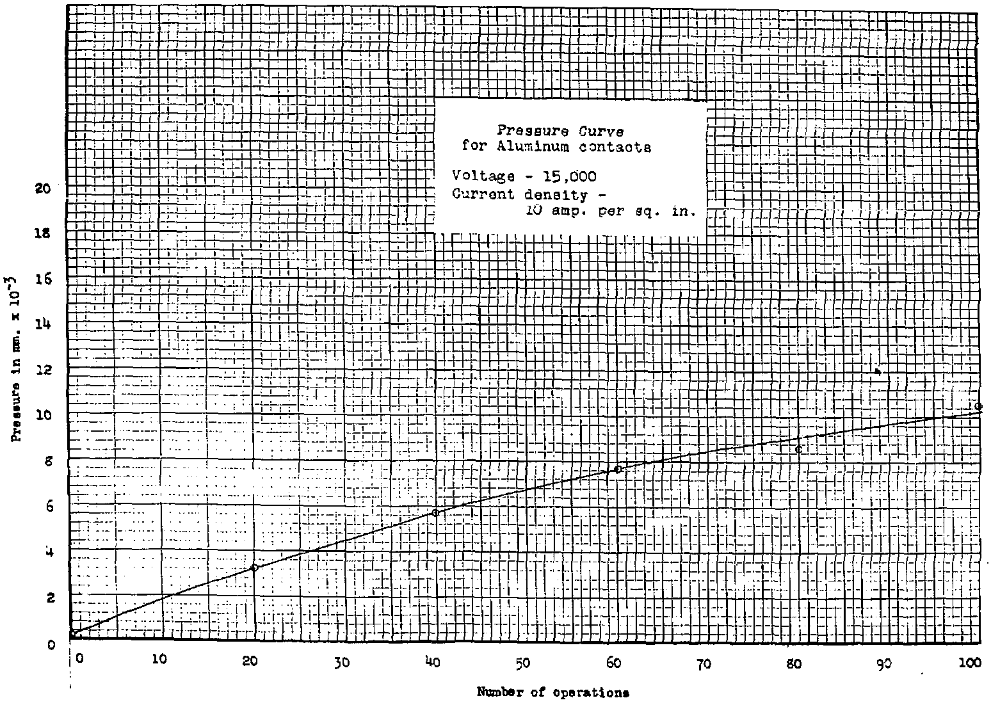

Figure 13