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VACUUM CIRCUIT BREAKER FOR POWER SYSTEM APPLICATION*

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ABSTRACT

The application of vacuum circuit breaker to the power system for switching on-off a large load and/or a large power supply plus the need of short circuit protection by the same circuit breaker requires a better understanding of the high-current vacuum arcs, electrode phenomenon and power system circuit constants under which the vacuum circuit breaker is applied.

This thesis is devoted to the following areas: 1) History of Vacuum Circuit Breaker Development, 2) Major Electric Characteristics of Vacuum Circuit Breaker such as Spark-over Voltage Levels vs. Contact Spacing, Spark-over Voltage vs. Vacuum Pressure, Cold Field Emission, Temperature Rise from Field Emission, Vacuum Pump Action in Vacuum Switches, Vacuum Pressure Maintained Over Long Time Periods, Switching and Recovery Voltage Characteristics, 3) Contact Materials, the Physical Mechanism of Current Chopping and How it is Influenced by the Physical Properties of the Contact Material, 4) Better Understanding of High Current Vacuum Arcs, and 5) The Initial and Operating Experiences of Vacuum Circuit Breakers Used on Eight 15kv Large Solid State Power Supplies Ranging from 1.5MW to 5.8MW. Final design and the selection of vacuum circuit breaker for six 567KW 4160 volt solid state power supplies is presented in this paper.

Vacuum circuit breakers used at Stanford Linear Accelerator Center are well coordinated to suit the duties that a circuit breaker must perform. Reasonable care must be taken under certain circumstances when applying these breakers. Such applications are identified and simple corrective measures are proposed.

CONTENTS

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I. INTRODUCTION

A. SEARCH FOR IDEAL ELECTRIC CIRCUIT BREAKER

After more than 70 years of engineering effort the best way to tame a plasma arc in an electric breaker circuit remains a subject of technical debate. As the voltage used in the power transmission has risen from 230 KV to 550 KV and most recently to 735 KV, the problem of designing a reliable circuit breaker has steadily intensified and the debate continues.

The problem is how to interrupt a high voltage current quickly but not too quickly. The answer lies in cultivating and then quickly dousing the arc that forms when the circuit is broken. The interruption of current--under normal load conditions, starting inrush, overloads and short circuits--places severe demands on electric switches, contactors and protective devices. Current interruption involves separating the contacts, usually at high speed, and then extinguishing the arc that is formed as the contacts part. Depending on the magnitude of the current interrupted and the operating voltage, considerable mechanical force may be required to perform the interruption--and a great amount of energy may be released by the arc. On the other hand, the interruption of current in vacuum minimizes both of these factors; therefore vacuum interrupters are attractive for many electric devices.

Regardless of type, there is a common fundamental principle of operation. Normally closed contacts through which the current passes are parted mechanically at a relatively high speed. This in itself does not cut off the current, for the contact gap is at once bridged by an intense electric arc which burns until the alternating current comes to zero, as it does twice each cycle. At the instant of current zero, vigorous means are applied by the interrupters to quickly cool the arc and remove the arc products from the vicinity of the contacts, so transforming that region into an insulating medium capable of withstanding the high voltages which are momentarily impressed across it by the power system. In an oil circuit breaker, for example, the arc burns within a bubble of hydrogen beneath the oil, and is quenched by a strong cross-blast of cool oil.

When the arc is formed the space between the contacts is filled with a high temperature plasma, a term first introduced by the late Dr. Langmuir of the General Electric Research Laboratory to describe an ionized gas in which there are approximately equal numbers of positively charged ions and negative electrons. The temperature of the plasma in some power circuit interrupters may be as high as 50,000°K. This is about four times the temperature of the sun's corona and seven times the temperature of which the air is heated in front of the nose cone as it re-enters the atmosphere. It is similar in character to the very high temperature plasma which has been under intensive study in the past several years for controlled thermonuclear fusion reactions, because at 50,000°K practically all the atoms are ionized. The conductivity of the plasma in a power circuit interrupter is as high as some metals. A very rapid rate of heat transfer is needed to convert such a conductor into an insulator within a few microseconds after the natural current zero.

As power systems have grown, in terms of capacity, voltage, and distance of transmission, the requirements placed on circuit protective devices have become more and more severe. In order to prepare themselves for the needs of both the present and the future, switchgear engineers have been continuously searching for new and better means of performing the interrupting functions. Consider, for the moment, some of the requirements in the functional specification of an ideal circuit interrupter, which might be considered the ultimate goal of this quest.

An ideal interrupter should effect a more rapid and a quieter interruption of large and small currents than existing devices, have long life and be operated by a simple mechanism with no auxiliary equipment. It should also present no fire hazard and be insensitive to its surrounding ambient condition. It is against this background the research and development work is required for the successful construction of a power circuit breaker in which the arc is quenched in vacuum.

Thirty-five years ago, Professor Sorenson and H. E. Mendenhal of the California Institute of Technology disclosed experiments made by them and their colleagues for the purpose of evaluating vacuum as a switching ambient for power circuit interrupters. Shortly afterwards, as a result of Professor Sorenson's work, an extensive development program was initiated in the General Electric Company and Jenning Company here in San Jose. However, problems encountered required many major technical breakthroughs before success could be assured.[1), 2)]

B. TECHNOLOGIES NEEDED FOR VACUUM CIRCUIT BREAKER DEVELOPMENT PROGRAMS

The vacuum technology advancements of recent years in the related fields of space science, semiconductors and in the electronic industry have provided the following needed breakthroughs and cost cross-over points that were the problems to produce a successful and economical vacuum circuit breaker in the earlier years.

a. Develop glass-to-metal seal technology to the extent that larger reliable vacuum-tight seals could be made.

Although some of these problems belonged only to vacuum interrupters, others were common to many other fields. These latter problems were solved when the technologies of the related fields made significant advances.

Making large glass-to-metal seals was a problem common to many devices. While small seals can be made between metals and glasses having large differences in coefficients of thermal expansion, it is very difficult to make large, mechanically strong seals between such a pair. The first major advance in this subject was made when Fernico, an iron-nickel-cobalt alloy, was developed. This has a coefficient of expansion that matches perfectly that of certain borosilicate glasses. Today a number of companies manufacture glass having the required characteristics.

Satisfactory joining to metal is not the only consideration as far as glass is concerned. Equally important in this application is its impermeability to helium. There is in the atmosphere a partial pressure of helium of approximately four microns. Helium can permeate through some glasses at a considerable rate; pyrex is an example, so that if such a glass were used in a vacuum interrupter, the vacuum would quickly deteriorate, and its life would be seriously affected. Today there are a number of glasses having such low permeation rate that gas permeation presents no problem.

Since the development of Fernico, other matching pairs have been found in the past several years, including the use of high purity ceramics. With these developments we have now at our disposal a large number of choices for the envelopes of vacuum interrupters.

In order to realize the intrinsic high dielectric strength of vacuum, one must make use of the best vacuum techniques known. Again, this is a subject in which major advances have been made in the past decade. For many years, it was thought to be impossible to achieve a vacuum better than 10^{-8} mm of Hg. It was subsequently discovered that this limit was actually set by the measuring equipment and was not a good indication of the actual degree of vacuum. Once this error was corrected, it became immediately possible to obtain vacua of 10^{-9} mm or better. By this means it became possible to produce atomically clean surfaces which are required to study the fundamental physics of surface effects, vacuum breakdowns being one of them.

Due to the diversified interest of this organization, many scientists in research laboratories have been actively engaged in ultra-high vacuum research. This effort has resulted in the development of new principles in ion pumping, the use of a hot cathode magnetron gauge, and a compact mass spectrometer tube, which are capable of measuring total and partial pressures as low as 10^{-15} Torr. These advances have been very valuable, directly and indirectly, in the development of power vacuum interrupters.

As pointed out previously, one of the major problems which plagued early investigators in vacuum interruption research was the emission of gases from solids during arcing. Calculations indicated that if, after arcing, the ungettered gas left in the envelope amounted to one part per 10 million of evaporated metal, the interrupter would not function properly. Yet, the solubilities of most gases in metals are many orders of magnitude higher. If these gases cannot be removed, the metals are unsuitable for contacts for vacuum interrupters.

b. Method of Gas Removal

It was found that the electrodes gave off a large amount of gas during arcing, thus destroying the vacuum.

With refractory metals dissolved gases can be removed by prolonged heating in a vacuum at an elevated temperature. For example, it is possible to de-gas tungsten in vacuum at 2300°K. With lower boiling point metals such as copper, this is impossible. Even at the melting point, the diffusion of gases out of such metals can be so low that the metal still retains a considerable amount of gas.

Advances in semiconductor technology have helped in leading to a solution to this problem. The behavior of semiconductors depends primarily on their impurity content. In order to produce semiconductors whose properties can be controlled, it is necessary to first refine the material to an extremely high degree of purity, and then add known amounts of impurities. It was found that with special modifications the techniques which were developed to refine semiconductors could be adapted to the removal of gases from metals. The ungettered gas, after arcing of materials so refined, was measured by several methods, and all results indicated that a solution to this major problem had been found.

c. Contact Materials

Up to 1962, the most successful experience had been with contact materials of pure tungsten, both sintered and single crystal, or pure molybdenum, since they are more easily purified. Work was also done with pure copper, pure beryllium, pure carbon, and other metals and alloys such as stainless steel, tantalum, titanium, and others. Pure copper has been interesting and could be advantageous for higher momentary and continuous currents, but so far we have found that in high vacuum it has a tendency to weld easily even at low currents, and its higher vapor pressure and lower melting point allows a comparatively large amount of contact vaporization at much lower arc temperatures. In high vacuum, pure ultra-clean copper also has a tendency to cold weld from mechanical pressure alone. Less cohesive alloys are now solving this problem.

Recent research of the use of binary alloys as vacuum switch contacts to meet the following conditions has been successfully tested:3)

1) The major constituent of the binary alloy is a non-refractory metal, preferably of good electrical conductivity, having a boiling point less than 3500°K.
1) The minor constituent, or the eutectic it forms, has the following properties:
    a) an effective freezing temperature below that of the major constituent
    b) substantial solubility in the major constituent in the liquid state and
    c) little or no solubility in the major constituent in the *solid* state.

The minor constituent, in addition to meeting these requirements, must be highly dispersed throughout the alloy. The maximum percentage of the minor constituent in these alloys must be limited to a relatively low value in order to preserve the high dielectric strength required within the container. The minimum percentage of the minor constituent should be substantially above a value corresponding to the solid state solubility of this minor constituent in the major constituent.

Alloys that meet the above stated requirements include copper-bismuth, copper-lead, copper-tellurium, copper-thallium, silver-bismuth, silver-lead, and silver-tellurium. Representative phase diagrams for such binary alloys are illustrated in Figs. 1 and 2.

Since the two constituents are mutually soluble in the liquid phase, these alloys are readily formed by casting. As the homogeneous liquid cools below the freezing temperature of the primary constituent, it begins to solidify in a granular structure. Since the two constituents are essentially not mutually soluble in the solid phase, the liquid becomes increasingly rich in secondary constituent during this initial cooling period. Finally, when the temperature of the mix has dropped sufficiently, the secondary constituent solidifies in the grain boundaries of the primary grains.

The extensiveness and thickness of the secondary constituents around the primary grain varies according to the relative quantities of two constituents. This is illustrated in Fig. 3 showing a series of 500X micrographs of bismuth copper alloys in which the bismuth content varies from 0.5% to 20%. Note particularly that, at the higher percentages of bismuth (11% - 20%), the grain boundary deposit is quite thick and continuous, whereas at lower percentages, the bismuth deposits are in very thin films and small, discrete islands on the grain boundary.

Test results on various alloys used as contact materials are summarized in Table I.

TABLE I. SUMMARY OF CONTACT WELD DATA FOR SEVERAL ALLOYS

CLOSING TESTS

Weld Strength Observations of Various Alloys	Peak Current Range	Weld Breaking Force
4% Pb - Al	29-30 KA	0-400#
4% Sn - Al	30 KA	10-400#
Copper-Bi 1-10%	14-32 KA	10-40#
Cu-Te 5%	30-40 KA	50-170#
Cu-Te (.5%)	22-28 KA	0-870#
Cu-Tl (3%)	22-30 KA	45-900#
Cu-Pb (1%)	21-34 KA	130-990#
Ag-Bi (3%)	34 KA	0-100#
Ag-Pb (6%)	33-36 KA	0-45#
Ag-Te (1%)	29-34 KA	0-550#

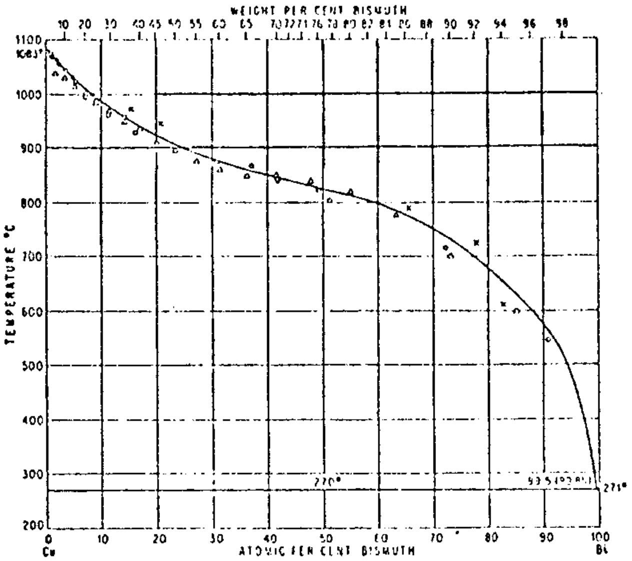


Fig. 1. Phase diagram for copper-bismuth alloys

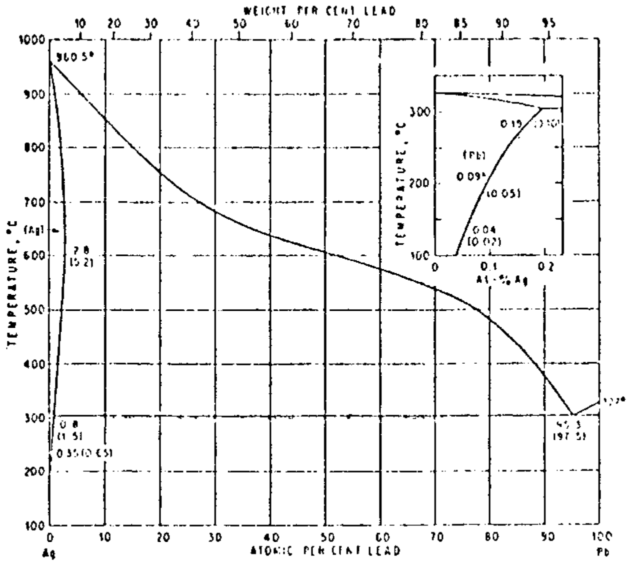


Fig. 2. Phase diagram for silver-lead alloys

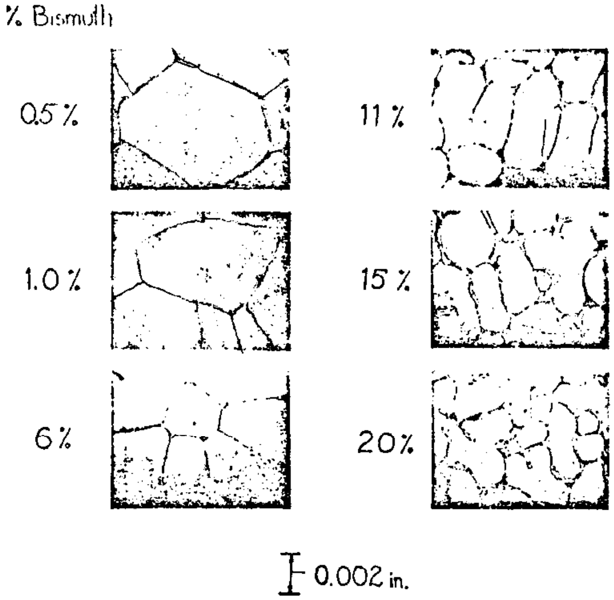


Fig. 3. Metallographic sections showing effect on grain structure of copper-bismuth alloys of specified concentrations of bismuth

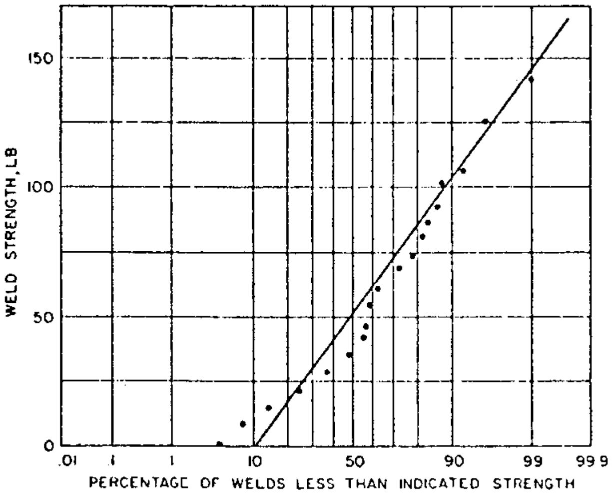


Fig. 4. Statistical plot of weld strength for copper bismuth contacts in a vacuum interrupter

II. THEORETICAL UNDERSTANDING OF VACUUM INSULATION AND ELECTRODE PERFORMANCES

A. Breakdown Strength of Insulation

The major insulating mediums of present-day electric power equipment are essentially atmospheric air, oil, paper, rubber-like compound and porcelain. Although appreciable voltages can be withstood by these dielectric materials, they are minute to what a corresponding gap in vacuum can withstand. Fig. 5 gives the breakdown voltage of a 3/8-inch-diameter rod gap, both for air and vacuum. As can be seen from Fig 5, a vacuum gap of 1/10 inch has a breakdown strength of 175 kv and a corresponding gradient of 1,750 kv per inch.

The reason for this high breakdown strength is the absence of air molecules between the electrodes. With electrodes in air, ionized molecules are probably the main carriers of electric charges and responsible for the low breakdown value. At atmospheric pressure and room temperature there are about 6×10^{23} molecules of air constituents in a volume of 22.4 liters. The mean free path for an air molecule is about 7×10^{-6} cm (centimeters) and for an electron about 40×10^{-6} cm. However, if the vacuum is better than 10^{-6} Torr, the mean free path of the molecule is more than 5,000 cm and that of the electron is more than 30,000 cm. It can be seen that with a gap distance of 1 cm only a few electrons in a million will collide with molecules and therefore have opportunities to form ions (as shown in Table II). It is primarily this fact which is responsible for the high breakdown strength in vacuum compared to the low breakdown strength in air.4)

TABLE II. COMPARISON OF MOLECULAR DENSITY AND MEAN FREE PATH AT VARIOUS PRESSURES

Pressure (Torr)	Molecules per Cubic Cm	Mean Free Path (Cm)
760	2.46×10^{19}	6.69×10^{-6}
1	3.24×10^{16}	5.09×10^{-3}
10^{-3}	3.24×10^{13}	5.09×10^{0}
10^{-6}	3.24×10^{10}	5.09×10^{3}
10^{-9}	3.24×10^{7}	5.09×10^{6}
10^{-12}	3.24×10^{4}	5.09×10^{9}
10^{-5}	3.24×10^{1}	5.09×10^{12}

If the voltage between electrodes is raised to or above the values indicated in Fig. 5, a breakdown of the gap occurs. The current during this breakdown is limited only by external impedance of the circuit, similar to the case of circuit breakers. The mechanism of this breakdown is not fully understood. It appears to be started by field emission of electrons at the cathode. The impact at the anode causes vaporization of the anode film and anode metal, the latter shooting at high velocity to the cathode, causing electron ionization in the gas, capable of supporting the high current. The voltage drop across the contacts during the current-carrying period is extremely small, in the order of voltage drops in air.

Upon termination of the discharge and after a deionization time of not more than 10 microseconds, even after current values of several thousand amperes, the original dielectric strength is established. This quick return of high dielectric strength is, of course, due to the fact that the vaporized metal which is localized between the contacts diffuses rapidly due to the absence of gas molecules. The metal molecules go at high speeds to the insulating walls and to the metal surfaces, and there condense.

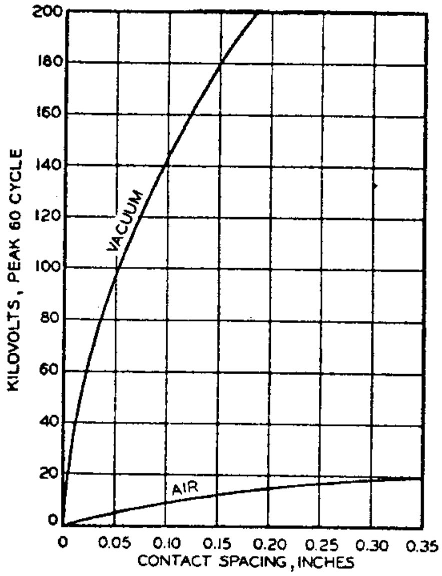


Fig. 5. Breakdown voltage of vacuum compared with air for one pair of 3/8-inch diameter tungsten contacts

B. Spark-over Voltage Levels vs. Contact Spacing

In general, it has been found that the maximum breakdown (spark-over) voltages in vacuum with particular methods of processing follow the contact spacing curve, Fig. 6 at the same vacuum level of 10^{-7} Torr (existing in outer space). In this graph, impulse, ac and dc levels are compared. The 300-kc voltage line was found also to lie close to the 60 cycle ac curve for maximum values for half-inch diameter contacts.

The graph shows highest for 1-1/2 x 40μsec standard impulse voltages (standard impulse test voltage, 1-1/2 x 40, mean peak voltage at 1μsec, reduced to 1/2 value at 40μsec), and is somewhat similar for high frequencies found in switching surges. We have found that for these higher frequencies the withstand level is much more dependent on vacuum level and remaining adsorbed gases, particularly on insulating surfaces, than for steady state 60 cycle or dc voltages.

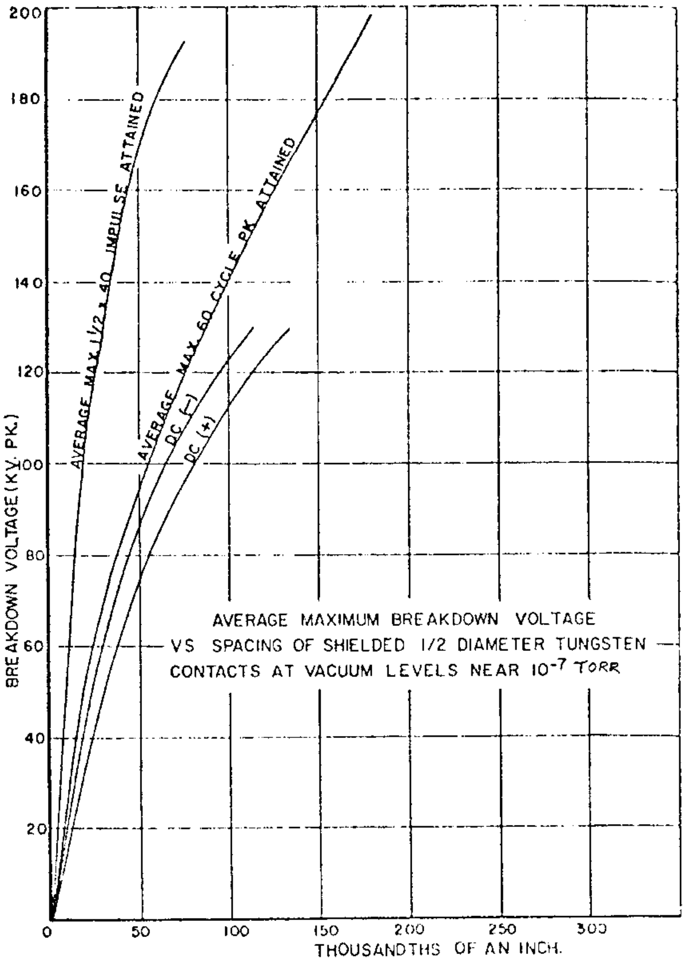


Fig. 6. Variation of breakdown voltage
for various contact spacings.

The curves in this graph show the areas of reasonably constant continuing breakdown. Occasional short-burst type breakdowns (called "barnacles" by popular use) may occur at considerably lower voltages, again depending on residual gases and loose contact material. It is typical of vacuum components that these intermittent breakdowns can be aged out by high voltage application so that operating levels can actually be forced upward by application of this high voltage.

C. Spark-over Voltage vs. Vacuum Level

For a fixed type and configuration of contacts, the maximum steady-state 60 Hz spark-over voltage follows the pressure curve as shown in Fig. 7. These particular curves were presented by Ross as early as 1955 and 1956.4) The specific type switch and its difference in voltage gradient are considerably dependent on processing, materials, and contact configuration. Variations as much as 70 percent can occur in commercial switches and still be satisfactory for some applications.

At the 1/32-inch spacing, the graph indicates a 10^{-4} to 10^{-7} Torr or better range in vacuum at useable values for the average maximum spark-over voltage levels of one of the more widely used types of 1/2-inch diameter tungsten contacts.

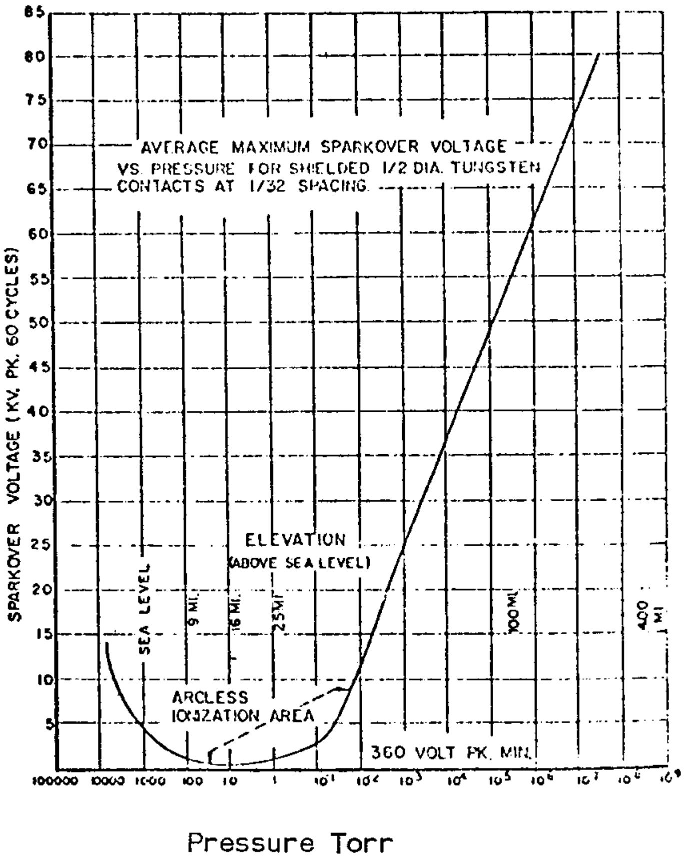


Fig. 7. Variation of spark-over voltage at different pressures.

This static analysis will vary according to the type and positioning of residual gases and high vapor pressure materials remaining in the enclosure, large quantities of which can be adsorbed on both conductive surfaces and insulating surfaces. Care must be taken in metering applied voltage and current since wave shape distortion may be caused by rectifying field emission currents and external corona which can be prominent at the extreme voltage levels. This is especially true when one uses high impedance hipot voltage sources.

D. Cold Field Emission

Graphs, Figs. 8 and 9, show some of the characteristics which may concern post-interrupting properties as well as statis characteristics. These graphs indicate a general average in field emission levels. Wide variations may occur which do not appear to have effect on switch performance during operation and, for rated steady-state operating voltages, emission effects are usually negligible. However, for short-time test voltages, which are usually considerably higher, or for moderately elevated long-time operating voltages, or close spacings, emission heating and possibly X-ray radiation must be considered. Emission may also have effect on voltage distribution when vacuum units are used in a series.

These graphs of cold-field emission current vs. spacing and applied voltage (ac and dc), also illustrate why ordinary dc leakage current checkers do not tell a true condition for ac operating capabilities; a high leakage reading from field emission current alone does not necessarily indicate inability to interrupt current, or hold off voltage.

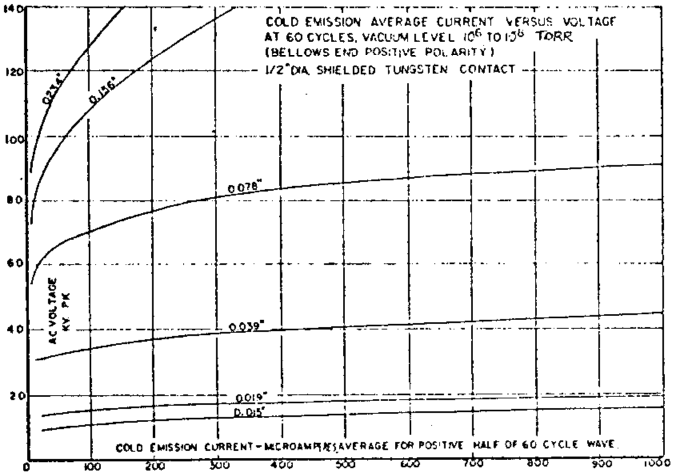


Fig. 9. dc voltage for different cold-emission average currents at various contact spacings in vacuum.

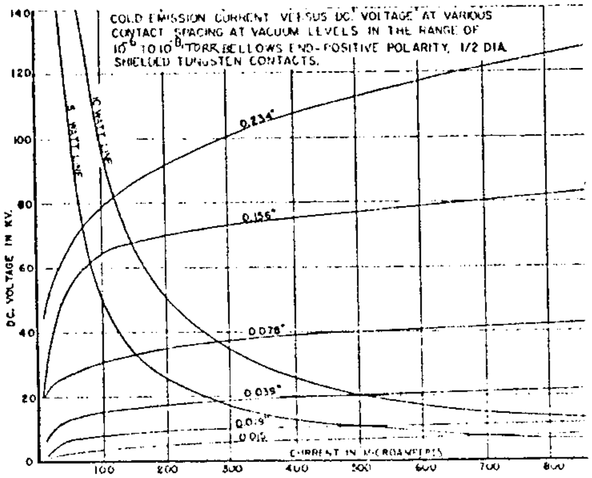


Fig. 8. dc voltage for different cold-emission currents at various contact spacings in vacuum.

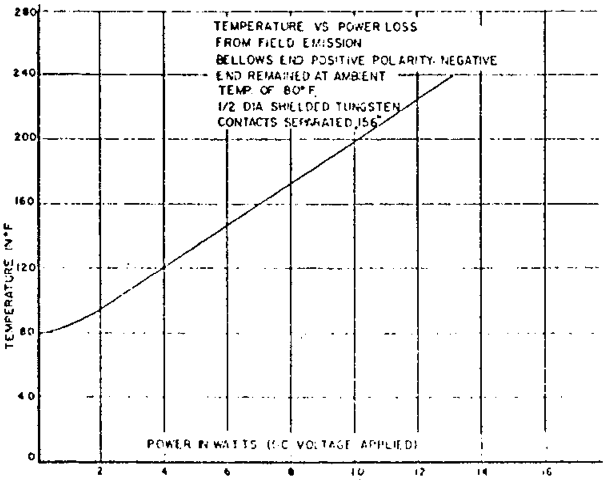


Fig. 10. Temperature rise caused by the typical "cold" field-emission bombardment energy.

E. Temperature Rise from Field Emission

In relationship to emission current the graph of Fig. 10 is shown to indicate the typical "cold" field emission bombardment energy vs. the temperature rise it causes. It shows that about 8 watts is the maximum recommended operating level for the particular contact studied. For dc only, the positive contact is heated. Emission current will be different for the different polarities. This is very evident on ac where the positive half of the cycle will have different emission than the negative half.

In all of these curves the average maximum values found for 1/2-inch diameter tungsten contacts have been shown. Over-all production values and ratings are necessarily lower to allow reasonably economical and safe variations.

F. Vacuum Pump Action in Vacuum Switches

Another fundamental which has been established within the past 10 years is the self-correcting vacuum pump action the properly outgassed tungsten contact provides. High-speed commercial vacuum pumps which use the metal vapor ion principle are on the market today. The vacuum contact, when interrupting, is in itself a metallic vapor ion pump which has a relatively high speed action for all of its possible contaminating gases. The graph of Fig. 11 illustrates this high speed action. This shows that the metallic vapor pumping action can improve a 10^{-4} Torr vacuum to a 10^{-6} Torr level or better within a few hundred operations. If tungsten contact material is used, the very large and heavy tungsten molecule easily plasters this inert atom or any other inert atom against the container walls in a tightly held

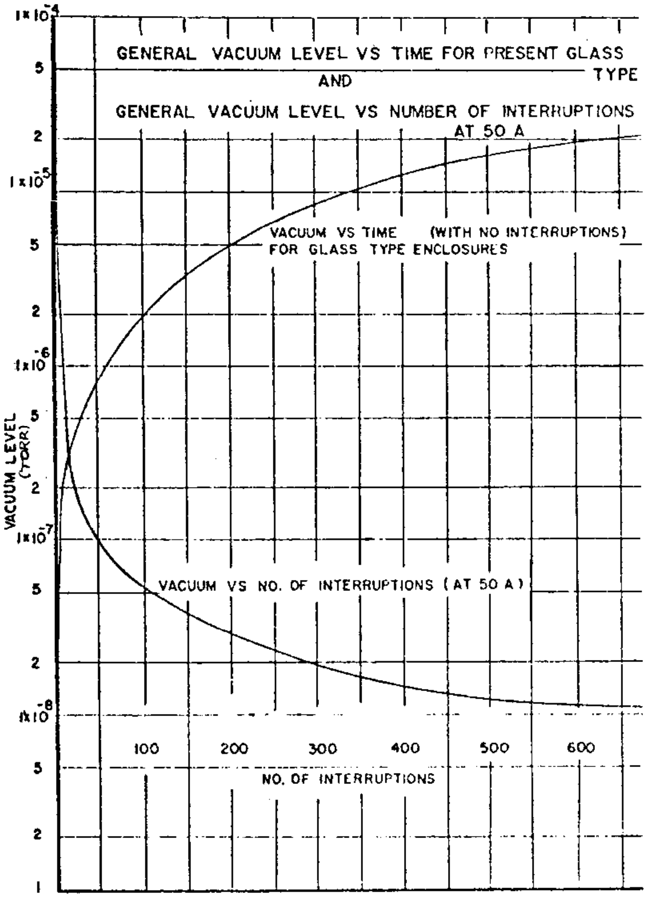


Fig. 11. The effects of number of interruptions and time on the vacuum level.

mechanical layer. For oxygen and other non-inert materials, the tungsten vapor reacts chemically and electrostatically as well as mechanically, thus effectively removing them from active circulation.

III. HIGH-CURRENT VACUUM ARCS

A. Observation of Vacuum Arcs

Most of the existing literature on the fundamental properties of vacuum arcs deals with discharges of less than a few thousand amperes. However, the present resurgence of interest in the vacuum circuit breaker has necessitated a fundamental study of the vacuum art at much higher currents. During faults on high-power interconnected distribution systems, circuit breakers may be required to interrupt currents of up to about 60kA r.m.s., and thus it is desirable that a vacuum circuit breaker may satisfactorily control arcs of up to this current range.

At currents up to about 1000A, vacuum arcs of a few centimeters long, between butt copper electrodes of a few centimeters diameter, conform to the description given in the literature; the vacuum arc is sustained from the cathode through highly mobile cathode spots which move continually over the cathode surface, filling the interelectrode gap with streams of vapor and charged particles. The voltage developed across the electrodes is about 20V and is independent of electrode geometry and separation. The anode plays little part in the discharge, and forms only a condensing surface for the charged particles and cathode vapor.5),6),7),8),9)

The experimental work reported by others10),11),12) shows that the voltage of the copper-vapor arc is a function of arc current, contact separation and contact geometry, and that these relationships are readily apparent for arcs of the dimensions examined at currents in excess of about 1000A. Moreover, the appearance of the copper-vapor arc is also affected by the total arc current, and a constructed or confined form of the arc may develop, rooted to large molten anode and cathode spots of about 10mm in area, if the current during power-frequency loops exceeds about 10kA.

The performance of practical vacuum circuit breakers will be adversely affected in two major ways if these large high-temperature spots develop:

(a) Excessive contact erosion or wear will be produced.

(b) A high density of vapor will be maintained, making arc re-ignition more likely.

These problems have been recognized for some time, and practical circuit-breaker designs have demonstrated that undue electrode melting may be prevented at currents in excess of about 10kA peak by magnetically moving the arc, and thus preventing localized overheating of the contacts.

A volume of literature exists on the behavior of cathode spots on a variety of metal electrodes.13),14) Much work has been carried out on mercury cathodes, and it may be concluded that the motion of the cathode spot in the absence of an external magnetic field is random. However, if a transverse magnetic field is applied to the cathode, the spot develops a component of velocity opposite to the normal Amperean direction, which has been designated retrograde motion, and has been observed on a variety of metal cathodes by Cobine and Gallacher and Reece. The order of this velocity may be 100m/s in the presence of a transverse magnetic field of the order of 1Wb/m.

As the current in the vacuum arc is increased, additional spots form and are repelled from one another; the mean current at which spots divide on copper cathodes is shown by Reece to be 100-200A per spot. On copper cathodes, these spots repel one another and move apart with mean directed velocities of up to 10m/s and tend to extinguish once they move over the edge of butt electrodes. In addition to the process of spot fission, Froome has reported spontaneous formation of cathode spots on mercury cathodes when the current is increasing by more than 10A/s; spontaneous formation of cathode spots has also been reported by Reece15) on copper cathodes.

The rate at which metal is evaporated from the cathode spots has been investigated by many workers, including Cobine and Vanderslice, Reece, Plyutto et al., and it is concluded that, during the vacuum arc at currents up to a few hundred amperes, only the cathode is eroded, and that the mean evaporation rate for copper cathodes is of the order of 100 g/C.

Appearance of the vacuum arc:

During practically all the discharges of less than about 10kA peak, between copper electrodes of more than 100mm in diameter, high-speed cine photographs show that the general appearance of the arc follows the descriptions given in the literature. The discharge is supported through a number of cathode spots which move constantly over the surface, and these spots emit a green plasma which extends to the anode. The mean-current cathode spot is 100-200A.

Summary of arcing-voltage characteristics:

The three forms of arcing voltage associated with vacuum arcs are shown in Fig. 12. They were obtained during three consecutive tests on 75mm-diameter electrodes of o.f.h.c. copper, at 5mm separation. Fig. 13 shows the linear portion of the voltage/current characteristic up to 40V; i.e. up to the starvation current. Fig. 14 shows the subsequent oscillogram obtained when the current is increased by about 25%. Gross instabilities occur in excess of 40V; i.e. the arc current exceeds the starvation current. Fig. 15 was the third test and shows the effect of increases in the current by a further 50%; gross electrode melting results in a reduced arcing voltage for most of the high-current period, and the extent of the instabilities are considerably reduced by the onset of melting. This oscillogram clearly indicates the asymmetrical disposition of the arcing voltage with respect to the current during the gross-melting form of the discharge.

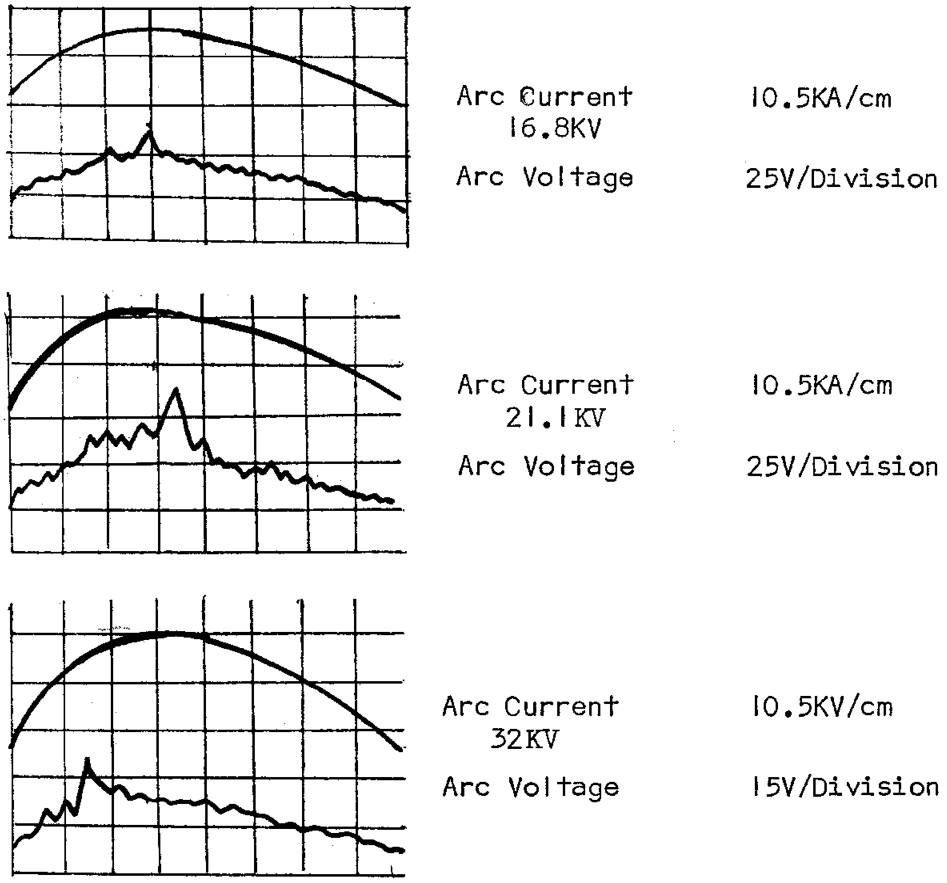


Fig. 12. Arcing-voltage/current characteristics during three consecutive tests on 75 mm-diameter o.f.h.c.copper electrodes at 5 mm separation

B. High Current Vacuum Arc Stabilized by Magnetically Induced Field

High current vacuum arcs stabilized by axial magnetically induced fields have important characteristics as follows:

(a) So far as constant gap arcs (such as triggered arcs) go, melting of the anode does not take place. If energy input to the anode caused by radiation of arc plasma is neglected, the anode melting can be prevented at the desired current, when the electrode dimensions are designed so as to enable the current density to be controlled by the magnetically induced field which will not exceed the threshold current density.

(b) The stabilized arcs, as the name indicates, compared with that of other types have the better reproducibilities. It is important to have a stabilized arc in vacuum circuit breakers for proper operation.

In the actual circuit breakers, arcs are initiated by the contact separation and the arc length becomes longer in line with electrode movement. The initial stage of the contact separation arcs is not the same as the constant gap arcs. However, when electrode spacing becomes longer than about 5 mm, the arc characteristics change to that of constant gap arcs. Thereby, an attempt to clear up the vacuum arcs stabilized by axial magnetic fields on constant electrode spacing was carried out in this study.

Recently, literature concerning the properties of high current vacuum arcs is increasing gradually, but less information with respect to magnetically stabilized vacuum arcs is available. The voltage-current data and the experimental outline of magnetically stabilized vacuum arcs are reported by Ito et al.8) The various quantities of magnetically stabilized arcs are calculated, according to authors, by the aid of the data on axial electric field of arc column and arc radius obtained through application of the Kruskal-Shafranov9) limit.

C. Critical Axial Magnetic Flux Density to Stabilize the Arcs

Arcing voltage measurement carried out with a pair of asymmetric copper electrodes in a dc magnetic field is shown in Fig. 13. The arcing voltage represented in Fig. 13 indicates the value at the instant when the current reaches peak value. The change of arcing voltage wave form corresponding to three axial magnetic flux densities is shown in Fig. 14. The wave form of arcing voltage in a relatively weak magnetic field has irregular vibration, while the wave form of arcing voltage in a strong magnetic field has no vibration, but has good reproducibility of wave form. The photographic observation confirms that the arcing voltage over-shoot in a strong magnetic field is caused by expansion of arc column toward the radial direction.

The diminishing parts of the arc voltage in Fig. 13 are considered to be the transition region from diffused arcs to column arcs; the fact is that the energy loss by diffusion is being decreased through the axial magnetic field applied across the arc voltage which exists between the contacts.

The reason for the increasing voltage in line with magnetic fields is explained as follows. Helical magnetic fields brought by the tangential field B_o and the axial field B_z are being enlarged in the peripheral region of column arcs. For this reason, the plasmas having long discharging paths along these helical magnetic fields are easily extinguished, leading to the decrease of actual radius of arcs.

The effect of axial magnetic fields of low current vacuum arcs has been reported by C. W. Kimblin.10) According to this report the arc voltage is being increased in pace with the increase of magnetic fields. The reason for this may also be the same as the above one, otherwise it may be due to the helical instability of the thinly column arcs.

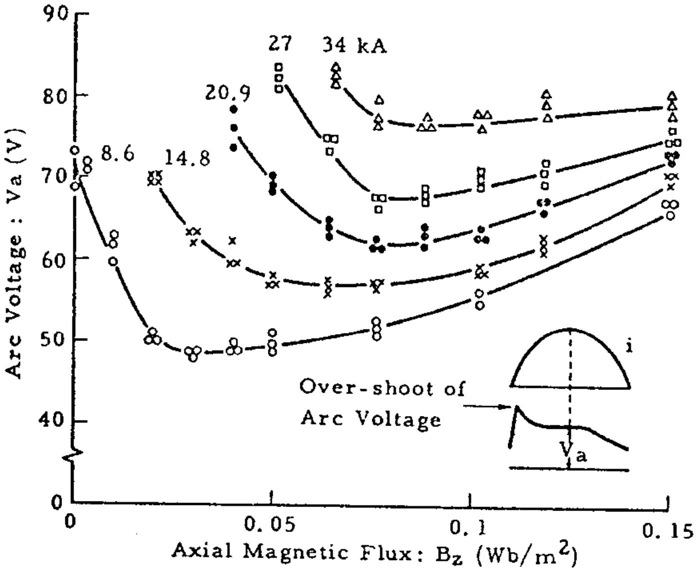
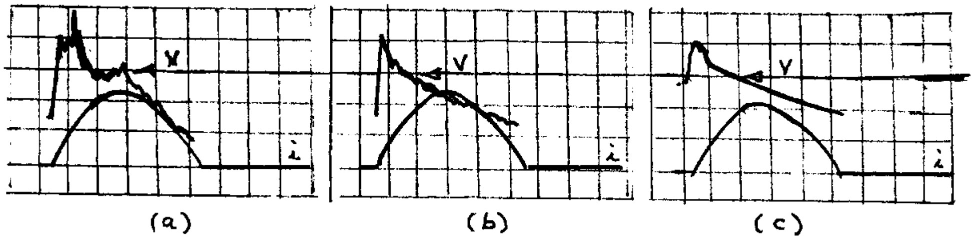


Fig. 13. Arc voltage versus axial magnetic flux for various arc currents 30mm electrode spacing



Arcing voltages 25 V/div sweep 2 mS/div

(a) (b) (c)

Fig. 14. Arcing voltage wave form in various magnetic flux densities at 18.4 kA. Zero lines of arcing voltages are the same as for currents
(a) $B_z = 0.02$ Wb/m^2 (b) $B_z = 0.064$
(c) $B_z = 0.12$

IV. VACUUM CIRCUIT BREAKERS USED ON REPETITIVE LOAD SWITCHING

A. Operating Experience

Since 1965, the Stanford Linear Accelerator Center has used eight 15 kV, 3-pole vacuum circuit breakers for all of the large solid-state power supplies operating at 12.47 kV, 60 Hz, ranging from 1.5 to 5.8 MW.

In 1970, six 4160 volt vacuum circuit breakers were added to replace the existing air circuit breakers for the six 4160 volt, 567 KW solid-state power supply a.c. power switching circuits. These vacuum circuit breakers provide the needs of repetitive operations which are beyond the present air circuit breaker (ACB) and oil circuit breaker (OCB mechanical duty cycles.

Operating counters have been installed on all the above 15 kV and 5 kV vacuum circuit breakers. An annual range of 2000 to 4000 operations has been recorded for each of these breakers; these records prove that the vacuum breakers far exceed the normal operating life of air circuit breakers and oil circuit breakers which were used previously.

Records indicate that in the earlier stage there were only two mechanical operating mechanism failures either due to thread wear on the fibre-glass rods or the long delayed closing due to sticky anti-bouncing material used on the tripping mechanism. These difficulties have been properly corrected and no further operating difficulties were reported.

There were two 15 kV, 2 MVA rectifier transformer failures throughout the operating history. Each time the vacuum circuit breakers, complete with their power fuses, operated properly to sustain the short circuit current of 20,000 amp at 12.47 kV. The vacuum breakers are inhibited from opening during periods of excessive currents. The fuses and a back-up air circuit breaker clear the short circuit currents.

During the initial operation period of the 5 kV vacuum circuit breakers, there were two 5 kV, 750 KVA rectifier transformer failures. It was suspected that the transformer failures were due to chopping current of the vacuum circuit breakers. Oscilloscope pictures were taken to compare the transient voltages generated by vacuum breaker versus the existing air circuit breaker due to current chopping. Fig. 15 shows the power supply rectifier transformer voltage while the circuit was switched off by vacuum circuit breaker. Fig. 16 shows that the similar power supply rectifier transformer voltage was switched off by conventional air circuit breaker. It is noted that the voltage rise due to air circuit breaker current chopping is about 200%, whereas the questioned vacuum circuit breaker generated less than 10% overvoltage.

Figs. 17 and 18 show the voltage conditions of the same transformers during the turn-on period to examine the contact bouncing in the closed position. It is noted that there are no essential differences in the vacuum breaker closing as shown on Fig. 17 compared with the air circuit breaker closing as shown on Fig. 18.

Fig. 19 shows a typical moveable vacuum circuit breaker contact travel curve. This curve defines the travel requirements on contact motions in order to assure proper contact closing force and wipe spring to be used to provide an impact force to the contacts to assist in their initial opening. The life of the vacuum circuit breaker is determined in general by the erosion life of the contact surfaces. Therefore, an initial external reference dimension mark is provided on each container against which the wear of the contact is measured to assure the serviceable life of the vacuum breakers. It is noted that there may be a change of 3/64 of an inch during initial 50 operations, especially if the closing motion contains a slight radial displacement. Any subsequent change in this dimension then can be attributed to contact wear.

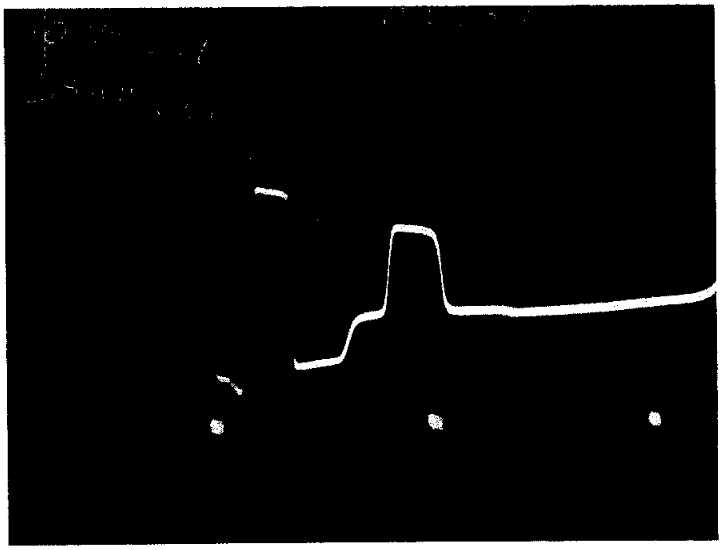
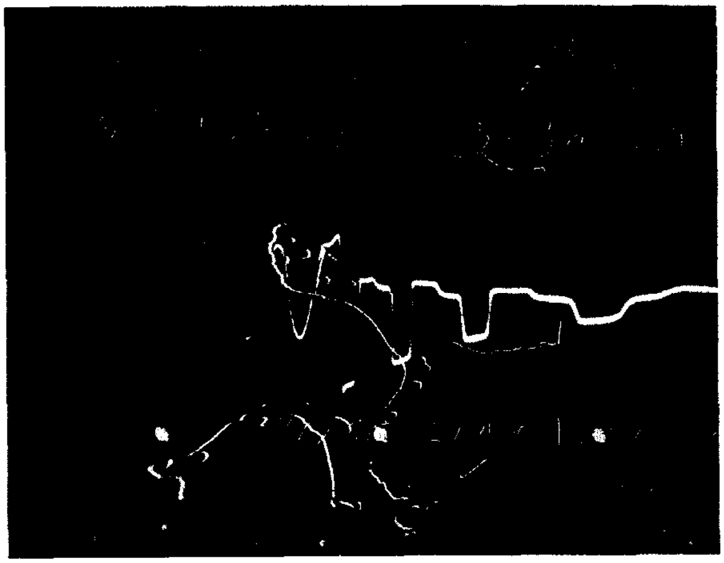
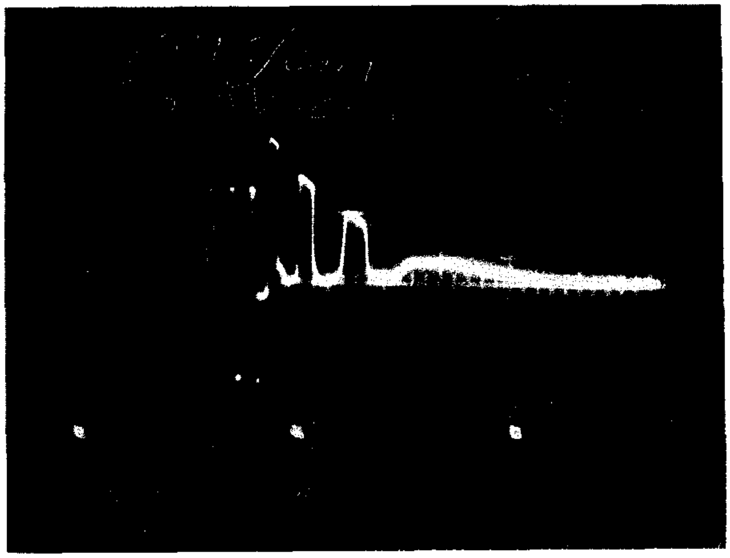


Fig. 15. Transient voltage rise on vacuum breaker "switched-off". Load-567KW, 4160V power supply PB20. Horizontal scale 10ms/cm; vertical scale 2.5 kV/cm



a) Vertical scale 5 kV/cm Horizontal scale 20 ms/cm



b) Vertical scale 2.5 kV/cm Horizontal scale 50 ms/cm

Fig. 16. Transient voltage rise on air circuit breaker during "switched-off". Load - 567 KW 4160 V power supply PQ 204.

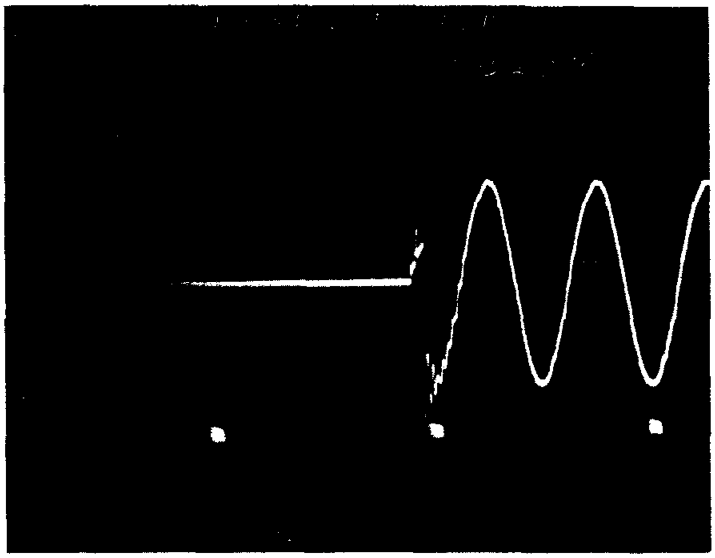


Fig. 17. Voltage condition in vacuum breaker during "turn-on". Load 567 KW 4160 V power supply PB-204. Horizontal scale 10 MS/cm; vertical scale 2.5 kV/cm

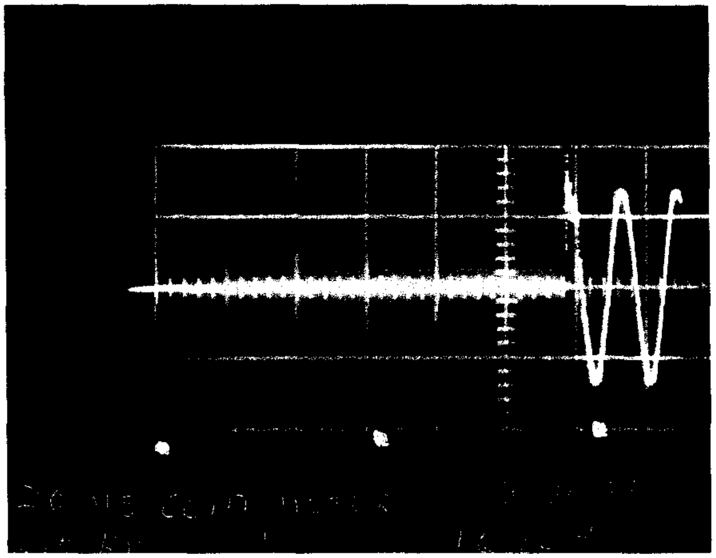


Fig. 18. Voltage condition, air current breaker "turn-on". Load 567 KW 4160 V power supply PQ-204; horizontal scale 20 MS/cm; vertical scale 2.5 kV/cm

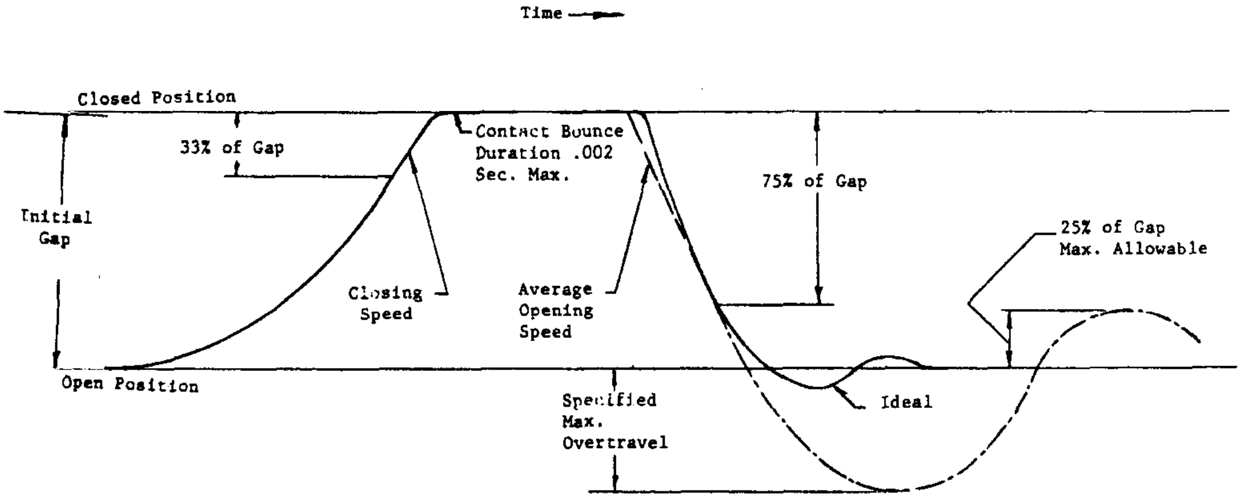


Fig. 19. Typical moving contact travel curve

B. Typical Construction of a Vacuum Circuit Breaker

The vacuum circuit breakers selected for the project use consist of the following main components:

1) Vacuum interrupter unit:

As shown in Fig. 20, the unit appears deceptively simple. The major components are described below:

a. Envelope: This provides mechanical support for the other components as well as electrical insulation when the contacts are in the open position. It may be made of high alumina ceramic, glass or glass-ceramic. It must be capable of maintaining the vacuum over the long life of the interrupter.

b. End cups or plates and center shell: Usually made of stainless steel or Monel. These provide support to various other components and must match the thermal expansion of the envelope if a direct seal is made.

c. Stationary and Moveable Rods: Normally oxygen-free, high conductivity (OFHC) copper. These are the main electrical conductors. One is fixed while the other moves to separate the contacts.

d. Metal vapor condensing shields: These are normally made from OFHC copper, nickel or stainless steel. They serve as a condensing surface for the metal vaporized by the arc.

It prevents the metal from condensing on the insulating portion of the envelope.

e. Flexible metallic bellows: Permits the motion to be transferred into the interrupter without a loss of vacuum. The usual materials are stainless steel or Monel.

f. Electrical contacts: These are perhaps the most critical components of the entire interrupter; their failure may destroy the interrupter. The most common material used is copper-bismuth. This is one exception to the rule of using only low vapor pressure materials, as bismuth has a relatively high vapor pressure. Bismuth is one of the few elements which will modify the copper so that welding of the contacts will not occur. It also is easily vaporized by the arc and thus reduces the current chopping level of copper to only a few amps. It is normally present in quantities of less than 1% of contact material. The contacts must exhibit a number of diverse and sometimes contradictory, properties (see section on contact materials). They must have good electrical conductivity. This normally means a copper alloy. They must exhibit good anti-welding properties. This eliminates pure copper. They must not chop the current at high values. Ideally, the current would go to zero following the sinusoidal wave, but normally the current goes to zero directly from a few amps. Thus, it may be noted that any voltage derived from chopping is a function of only the line impedance and the chop current and is independent of the system voltage. The various components are welded or silver-alloy brazed forming an airtight package. The interrupter is then evacuated to a pressure of about 10^{-9}T. A copper tube is usually attached to the interrupter for evacuation. When the desired pressure is reached, the tube is "pinched off", actually a cold weld sealing the tube.

The interrupter is then checked for dielectric properties. When the unit is found to be good, it is retained for several weeks. This time is such that succeeding tests will reveal leaks much smaller than are detectable with standard helium leak testing equipment.

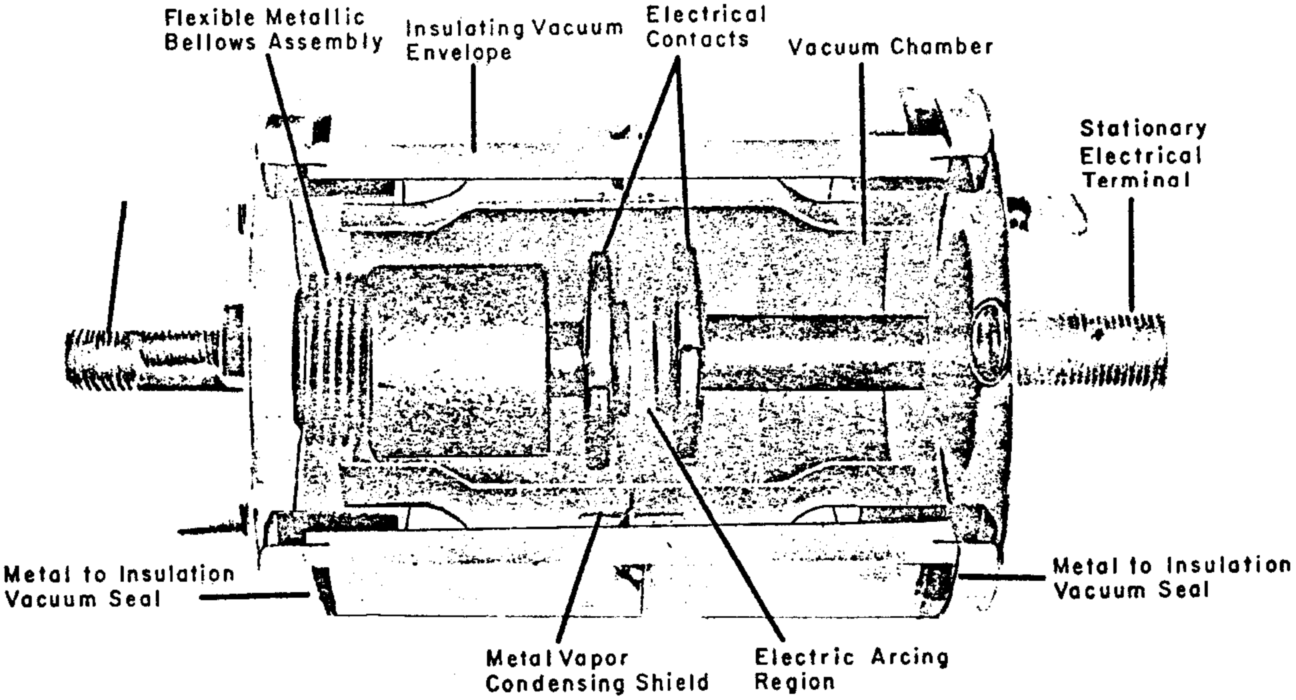


Fig. 20. Cutaway view of typical 15.5 kV, 12,000 ampere interrupter 600/800 ampere load current interrupter.

2) Three-pole control mechanism assembly:

As shown on Fig. 21, the three vacuum interrupter units for use on each of three phase 15 kV systems are mounted on the top of the control mechanism assembly. The movement of closing and tripping linkage, as shown on the lower portion of the picture, provides the contact travel movement as described previously.

3) Final Assembly:

The interrupter units, 3-phase control mechanism assembly, complete with power fuses, safety manual-operated disconnecting switch and protective relays are housed in a No. 11 gauge steel housing as shown on Fig. 22. The final assembly provides the over-all coordinated vacuum circuit breaker to be served as the switching medium.

C. Vacuum Circuit Breaker Specification and its Application

In order to procure the vacuum circuit breakers from commercial sources the following specifications were used for the 15 kV 600 Amp vacuum circuit breakers:

a. Rating: Each vacuum circuit breaker shall be rated at 13.2 (15L) kV, 60 Hz ac, maximum design voltage 14.5 kV, operating voltage 12.5 kV, 3 phase, wye connected, grounded system. The continuous current capacity shall be 400 amperes. The interrupting capacity shall be 4000 amperes at 80 percent power factor. The switch assembled in its housing for normal operation shall be capable of closing into a fault of 40,000 amps asymmetrical and subsequently be capable of carrying and interrupting its rated continuous current. The impulse withstand voltage rating shall be 95 kV BIL. The vacuum breaker shall have a close and latch rating of 20,000 amperes with minimum 40 operations at interrupting rating and maximum fault clearing time of 2-1/2 cycles. At rated current (400/600 amp), the breaker shall have a minimum operating life of 40,000 operations.

b. Design: Each 3-pole switch shall be designed for local and remote 125 volt dc electrical operation as shown on the drawing. Breakers shall be long life, minimum maintenance with minimum

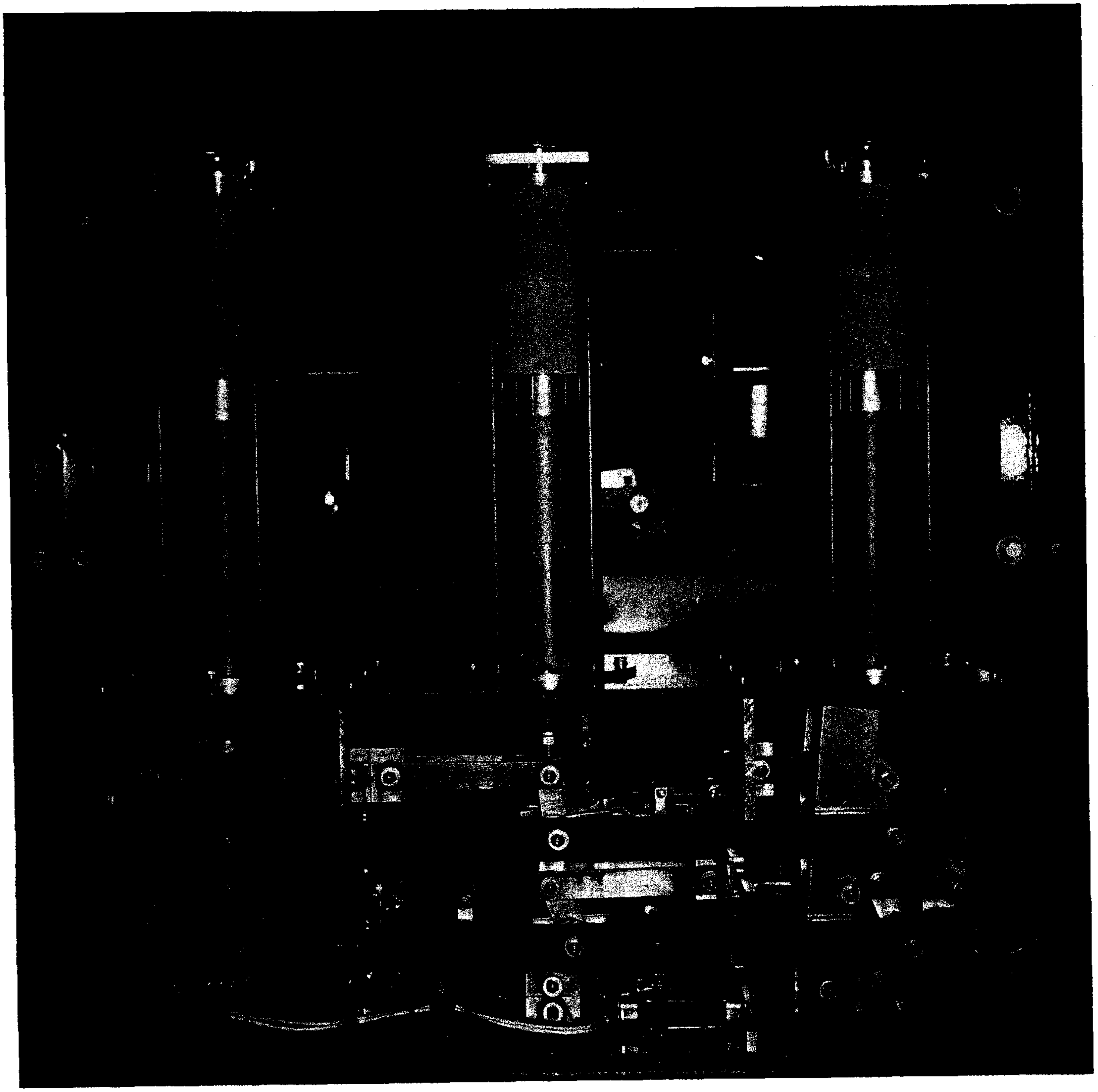
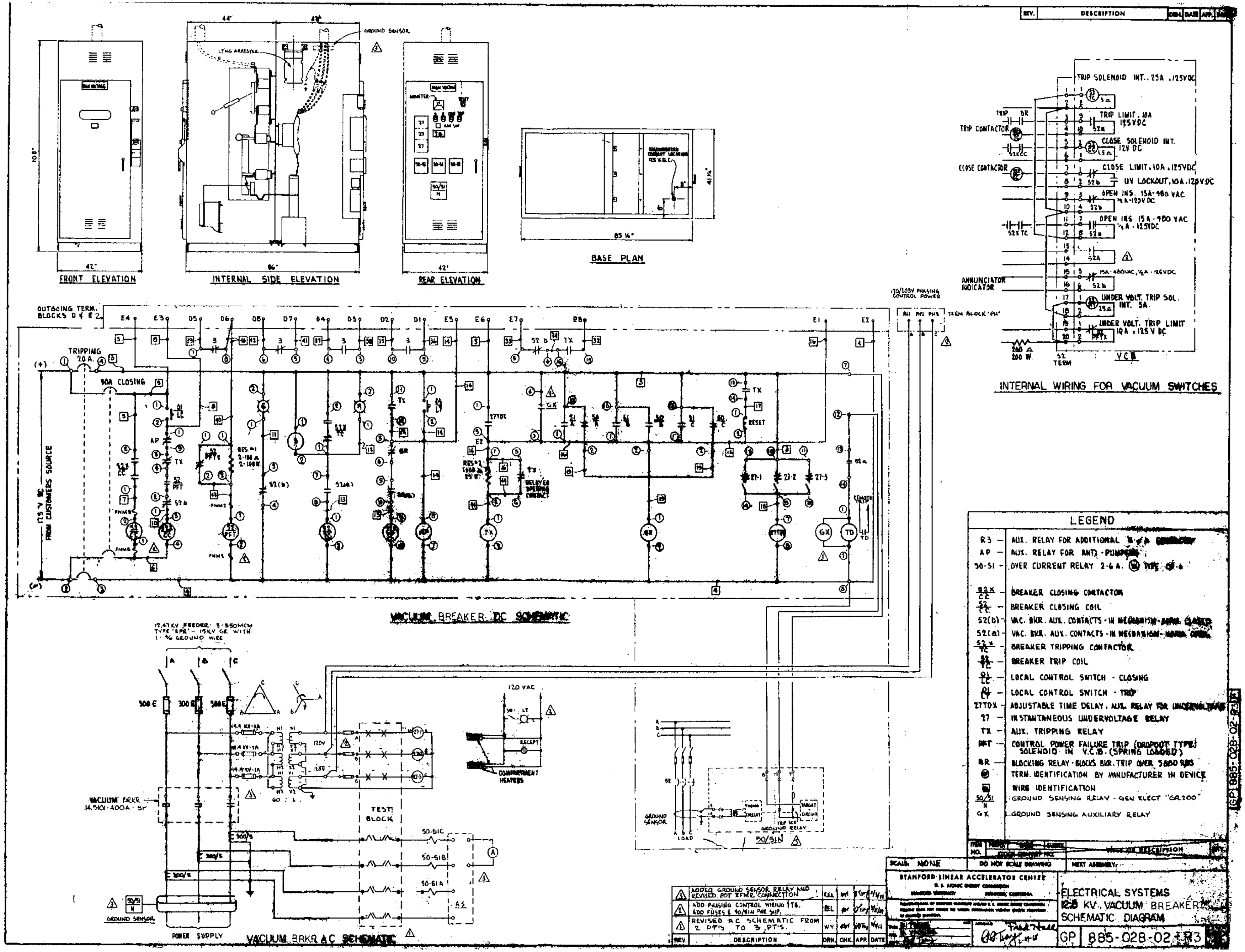


Fig. 21. 15.5 kV 600/800 Amp 3 pole control mechanism assembly



LEGEND

R3 —	AUX. RELAY FOR ADDITIONAL [illegible]
AP —	AUX. RELAY FOR ANTI-PUMPING
50-51 —	OVER CURRENT RELAY 2-6 A. Ⓦ TYPE CO-6
$\frac{52X}{CC}$ —	BREAKER CLOSING CONTACTOR
$\frac{52}{CC}$ —	BREAKER CLOSING COIL
52(b) —	VAC. BKR. AUX. CONTACTS - IN MECHANISM - NORM. CLOSED
52(a) —	VAC. BKR. AUX. CONTACTS - IN MECHANISM - NORM. OPEN
$\frac{52X}{TC}$ —	BREAKER TRIPPING CONTACTOR
$\frac{52}{TC}$ —	BREAKER TRIP COIL
$\frac{01}{LC}$ —	LOCAL CONTROL SWITCH - CLOSING
$\frac{01}{LT}$ —	LOCAL CONTROL SWITCH - TRIP
27TDX —	ADJUSTABLE TIME DELAY, AUX. RELAY FOR UNDERVOLTAGE
27 —	INSTANTANEOUS UNDERVOLTAGE RELAY
TX —	AUX. TRIPPING RELAY
PFT —	CONTROL POWER FAILURE TRIP (DROPOUT TYPE) SOLENOID IN V.C.B. (SPRING LOADED)
BR —	BLOCKING RELAY - BLOCKS BKR. TRIP OVER 5000 RMS
●	TERM. IDENTIFICATION BY MANUFACTURER IN DEVICE
▪	WIRE IDENTIFICATION
$\frac{50/51}{N}$	GROUND SENSING RELAY - GEN ELECT "GR200"
GX	GROUND SENSING AUXILIARY RELAY

REV.	DESCRIPTION	DRN.	CHK.	APP.	DATE
3	ADDED GROUND SENSOR RELAY AND REVISED POT XFMR CONNECTION	EEL			3/4/71
1	ADD PHASING CONTROL WIRING TB. ADD FUSES & 50/51N PWR SUP.	EEL			
	REVISED AC SCHEMATIC FROM 2 PT'S TO 3 PT'S.	WY.			

SCALE: NONE
DO NOT SCALE DRAWING
NEXT ASSEMBLY:

STANFORD LINEAR ACCELERATOR CENTER
U. S. ATOMIC ENERGY COMMISSION
STANFORD UNIVERSITY STANFORD, CALIFORNIA

Fred Hall

ELECTRICAL SYSTEMS
12.5 KV. VACUUM BREAKER
SCHEMATIC DIAGRAM

GP 885-028-02 R3

Fig. 22

interrupting rating to 4000 amps RMS, 2 cycle maximum interrupt time with one cycle or less preferable.

c. Trip free mechanism: Trip mechanism shall be equipped with 125 volt dc undervoltage trip device to trip out the vacuum breaker in case 125 volt dc control circuit loses voltage.

d. Interlocks: Shall be provided to prevent the closing of a switch while the fuse compartment is open.

e. Vacuum switch contactor position indicators to indicate the switch position and contact erosion for each individual pole shall be provided.

Typical SLAC vacuum circuit breaker installations are shown in Figs. 23, 24, 25 and 26.

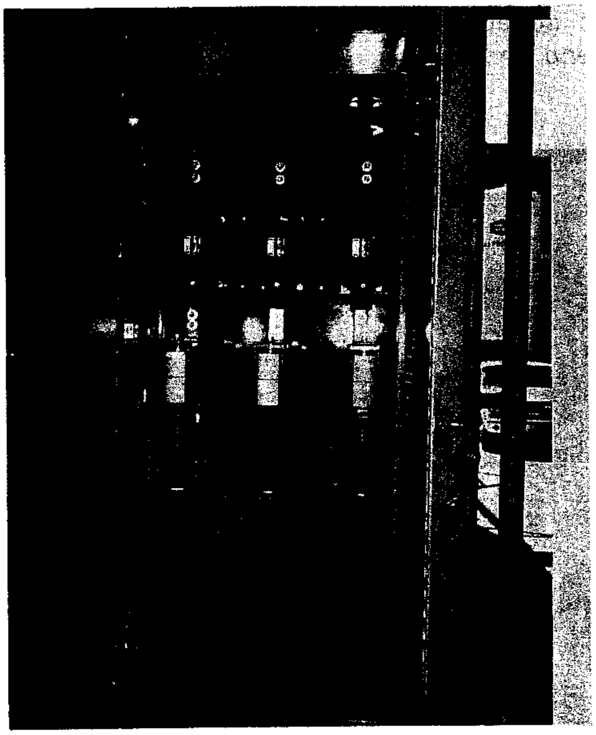


Fig. 23. 15 kV 600A vacuum circuit breaker assembly complete with current transformers and potential transformers for use on 5.8 MW 12.47 kV solid state power supply.

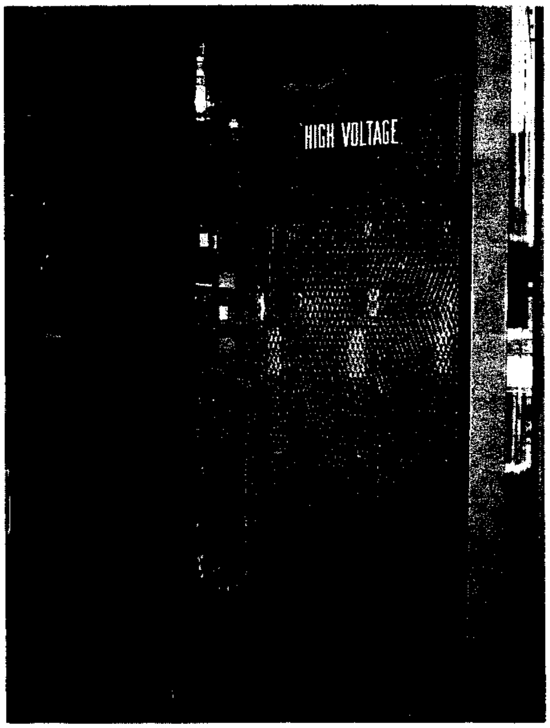


Fig. 24. Same 15 kV 600 Amp vacuum circuit breaker as shown in Fig.23, covered with metallic screen to comply with California Safety Code for hot maintenance and inspection.

Fig. 25. 600 Amp 15 kV vacuum circuit breaker back side power fuses and manual disconnect switch assembly for use on 5.8 MW power supply.

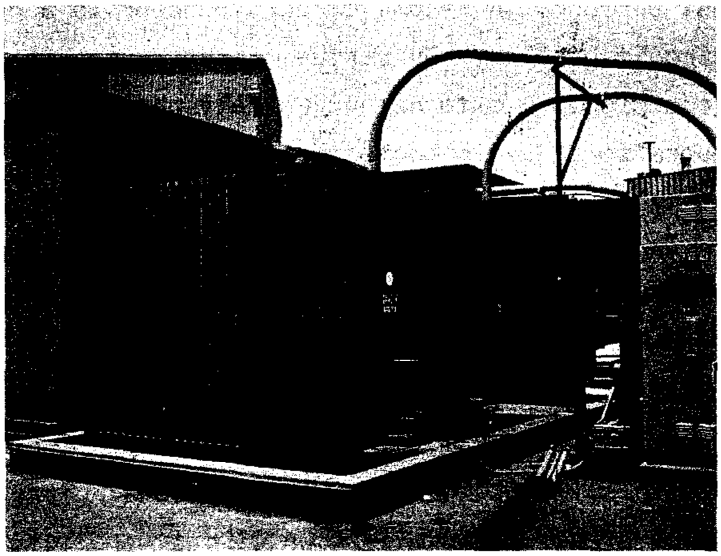


Fig. 26. 600 Amp 15 kV outdoor circuit breaker installation for use on 3.4 MW rectifier transformers.

After eight years of successful operating experience at SLAC, vacuum circuit breakers are now being accepted by SLAC for 5 kV and 15 kV power circuit switching applications. A fully rated 15 kV, 500 MVA vacuum circuit breaker is now being built for SPEAR (Stanford Positron Electron Assymetric Ring) 15 kV main feeder circuir breaker. Two additional 5 kV 3.0 MW vacuum circuit breakers are being built for SPEAR detector magnet power supply use.

V. CONCLUSION

Vacuum circuit breakers are well suited for the duties that a circuit breaker must perform. A vacuum circuit breaker is a quiet, fast and efficient circuit breaker. By virtue of its design it is non-maintainable except occasionally external adjustments have to be made after thousands of operations due to contact erosions. The contacts have to be capable of interrupting all of the normal operations and fault duties normally encountered in a lifetime of power distribution services. The long operating life and low maintenance of vacuum switches has already been proven to be a fact. These attributes, and the absence of any exhaust, make them ideally suited for such highly repetitive switching operations, especially under hazardous conditions. As an applications electrical engineer or switchgear manufacturer, one must know the importance of selecting all known circuit protective devices, including the special characteristics of vacuum breakers. Reasonable care must be taken in the application of vacuum breakers under specific electrical network.

The state of the art of the vacuum technology and material science is continuing to surge ahead. Vacuum circuit breakers should bring it much closer in cost to the conventional bulk-oil switchgear now used on 34.5 kV, 69 kV and 115 kV circuits. A greatly expanded application of vacuum breakers in the industrial and power systems is definitely on the horizon.

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