Determination of Electrical Clearances for Permissible Equipment Operating in Gassy Mines and Tunnels

John M. Mesina

Abstract—A design algorithm is derived, for calculating minimum allowable electrical clearances in alternating and direct current “permissible” equipments, which are authorized to operate in gassy mines and tunnels under Part 18 of Title 30, Code of Federal Regulations [1]. The calculated clearances apply to operations at altitudes ranging up to 12 000 ft (3658 m) above sea level. The minimum allowable clearance values are tabulated for typical nominal mining machine voltages and maximum operating temperatures within explosion-proof enclosures. An equation is provided for increasing the clearances when the listed maximum temperatures are exceeded.

I. INTRODUCTION

PARKS and arcs are disruptive impulse-type and continuous electric discharges, respectively [2]. Both are of concern within explosion-proof enclosures operating in gassy locations. The discharges emit ultra-violet radiation, which promotes the formation of ozone and acids capable of eroding critical components. Electric discharges may ignite enclosed methane. Furthermore, the heat of arcing raises “an enclosure”s internal air temperature-and pressure, which, left to build unchecked, might rupture the enclosure. Flames would be fed to the mine atmosphere if enclosed methane ignited simultaneously. Dangerous pressure levels can build rapidly from high-power phase-to-phase arcing, or gradually, e.g., when ground fault arc current is limited by a neutral-grounding resistor. Insulation is “punctured” when disruptive discharge current passes through and permanently increases the insulator’s localized conductivity. High-power arcing close to bare casing or arcing to the casing itself may weaken or “burn through” the casing if not detected and cleared quickly. Heat from nearby arcs or from current, through punctured insulation may decompose the insulation, possibly releasing explosive and toxic gases. Such gas may negate the enclosure’s pressure and flamepath protective limits, which are based on methane. Federal Regulation 30 CFR 18.25r prohibits use of such insulation, but identification is difficult in the field.

For the reasons cited, sparks and arcs must be minimized within explosion-proof enclosures. This paper focuses on only one limiting means-assigning minimum allowable electrical clearances, i.e., the allowable distance through air (gas) between oppositely charged live parts.

II. TECHNICAL BACKGROUND

The references reveal that arcing is initiated by sparking [2]. Sparking usually occurs between live parts through air (or other gas) when a voltage difference results in electric field intensity (strength) that exceeds the dielectric strength of the gas [3]. For a typical live part configuration in mining equipment, the instantaneous average electric intensity is proportional to the voltage between live parts and inversely proportional to their separation distance. When the average field strength exceeds the dielectric strength of insulation between live parts, “breakdown” (sparking through gas or puncture of solid insulation) occurs.

Due to response time considerations, breakdown voltage varies with the voltage type (dc, ac, pulse) and timing (duration, frequency, rise time). When solid insulation intersects the gas space between live parts, the respective average electric field strengths are inversely proportional to the permittivities of the gaseous and solid insulators [4]. Should both the air and insulation break down, sparking may appear to occur between a live part and a solid insulation surface.

The gas in the spark path is partially ionized. If the live parts are connected across a power source, and the gas is sufficiently ionized, the power source may supply “follow-through” arc current. When physical and electrical parameters are favorably valued, the arc will become “self-sustained” and may continue indefinitely if not cleared.

Since sparking occurs when the average electric field intensity exceeds the gas dielectric strength, and average electric field intensity diminishes as the distance increases...
between live parts, sparking events, and therefore, arcing
events can be minimized by specifying minimum allowable
electrical clearances.

A. Breakdown Voltage Data-Plain Air

The International Electrotechnical Commission (IEC)
Publication 664 [5] lists breakdown voltages \( V \), for im-
 pulse types (1.2 \( \times \) 50\( \mu \)s) [61 and 50/60 Hz waveforms,
-versus electrode separation distances \( S \) in plain air at
both sea level \( S_0 \) and at a 2000 m altitude \( S_{2k} \). The sea
level data, which are duplicated in Table I, were actually
measured. The 2000 m data, which are duplicated, in
Table II, were calculated by the IEC from worst-case sea
level data, adjusting for the altitude difference. A means
to adjust the electrode separation distances for altitude
will be explained. (The symbols \( V_b \), \( S_0 \), and \( S_{2k} \), are not
used by the IEC.) Table I data were ‘measured under
“normal conditions of temperature, and relative
humidity.” The tables include data from tests using sphere
to plane electrodes (“homogeneous field”) and point-to-
TABLE II

<table>
<thead>
<tr>
<th>&quot;S&quot;</th>
<th>&quot;Vb&quot;</th>
<th>Peak Breakdown Voltage, Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>0.02</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>0.03</td>
<td>470</td>
<td>470</td>
</tr>
<tr>
<td>0.04</td>
<td>520</td>
<td>520</td>
</tr>
<tr>
<td>0.05</td>
<td>560</td>
<td>560</td>
</tr>
<tr>
<td>0.08</td>
<td>650</td>
<td>700</td>
</tr>
<tr>
<td>0.1</td>
<td>700</td>
<td>810</td>
</tr>
<tr>
<td>0.15</td>
<td>800</td>
<td>1,040</td>
</tr>
<tr>
<td>0.2</td>
<td>880</td>
<td>1,150</td>
</tr>
<tr>
<td>0.3</td>
<td>1,010</td>
<td>1,310</td>
</tr>
<tr>
<td>0.4</td>
<td>1,110</td>
<td>1,440</td>
</tr>
<tr>
<td>0.5</td>
<td>1,190</td>
<td>1,550</td>
</tr>
<tr>
<td>0.6</td>
<td>1,270</td>
<td>1,650</td>
</tr>
<tr>
<td>0.8</td>
<td>1,390</td>
<td>1,810</td>
</tr>
<tr>
<td>1.0</td>
<td>1,500</td>
<td>1,950</td>
</tr>
<tr>
<td>1.2</td>
<td>1,700</td>
<td>2,200</td>
</tr>
<tr>
<td>1.5</td>
<td>1,970</td>
<td>2,560</td>
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<tr>
<td>2.0</td>
<td>2,380</td>
<td>3,090</td>
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<td>2.5</td>
<td>2,770</td>
<td>3,600</td>
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<td>3.0</td>
<td>3,130</td>
<td>4,070</td>
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<tr>
<td>4.0</td>
<td>3,790</td>
<td>4,930</td>
</tr>
<tr>
<td>5.0</td>
<td>4,490</td>
<td>5,720</td>
</tr>
<tr>
<td>6.0</td>
<td>4,970</td>
<td>6,460</td>
</tr>
<tr>
<td>8.0</td>
<td>6,030</td>
<td>7,840</td>
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<tr>
<td>10.0</td>
<td>7,000</td>
<td>9,100</td>
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<tr>
<td>12.0</td>
<td>8,180</td>
<td>10,600</td>
</tr>
<tr>
<td>15.0</td>
<td>9,900</td>
<td>12,900</td>
</tr>
<tr>
<td>20.0</td>
<td>12,700</td>
<td>16,400</td>
</tr>
<tr>
<td>25.0</td>
<td>15,300</td>
<td>19,900</td>
</tr>
<tr>
<td>30.0</td>
<td>17,900</td>
<td>23,300</td>
</tr>
<tr>
<td>40.0</td>
<td>22,900</td>
<td>29,800</td>
</tr>
<tr>
<td>50.0</td>
<td>27,700</td>
<td>36,000</td>
</tr>
<tr>
<td>60.0</td>
<td>32,300</td>
<td>42,000</td>
</tr>
<tr>
<td>80.0</td>
<td>41,300</td>
<td>53,700</td>
</tr>
</tbody>
</table>

plane electrodes ("inhomogeneous field"). Table I includes data from tests with and without ultraviolet radiation (UV) of the electrodes and interspersed air. It should be noted that although IEC Publication 664 does not stipulate UV for the data of Table II, the data were in fact calculated from UV data of Table I per the head of Table II.

Tables I and II reveal that worst-case data are from point-to-plane electrodes. With or without UV, less of the same type voltage is required to break down the air between these electrodes at any given separation distance exceeding 0.2 mm (0.008 in). The tables also show that less peak 50/60 Hz voltage than "112 X 50" impulse voltage is required to break down the air between any same-type electrode pair at separation distances exceeding 0.1 mm (0.004 in), except for homogeneous fields with UV (column G, Table I). In this case, breakdown occurs across the same clearance at the same peak voltage of either waveform. Additionally, Table I data demonstrate that UV reduces the breakdown voltage of either waveform, for both point to plane and sphere to plane electrodes. In summary, the IEC sparking data reveal that the condition for which sparking occurs most readily for either the 60 Hz or 1.2 X 50 impulse waveform, is the inhomogeneous field (point-to-plane electrodes) under UV, i.e., the data of Table I, columns C and D.

B: Breakdown Voltage Data-Methane Flamefront

The flamefront of a methane deflagration can also be sufficiently ionized to trigger follow-through arcing as the flamefront bridges live parts. This was demonstrated in tests conducted at the Canadian Explosive Atmospheres Laboratory (CEAL) in 1973 [7] and at the U. S. Bureau of Mines (USBM) Pittsburgh Research Center in 1982 [8]. Although not specified in the reports, the tests were conducted between 500 and 1050 feet above sea level and at approximately 68°F (20°C) ambient temperature. Exact sea level will be assumed as the altitude for these measurements, as a safety factor. Critical electrode spacings $S_0$, which just preclude initiation of sustained arcing at sea level were correlated with the applied power supply voltages, $V_p$. Low-impedance power supplies with large inductance to resistance ratios were used to encourage follow-through alternating current arcing. The test results were presented in graph form only and are duplicated in Fig. 1 (CEAL) and Fig. 2 (USBM). Equations (1) and (2), in Fig. 2 were added.

Calculations from (1) and (2) demonstrate how much the flamefront reduces the breakdown strength of plain
air at various spacings. For example, at a 1 in (25.4 mm) spacing the average breakdown strength, \( V_a/S_0 \) is 53 924 V (rms)/in for plain air while only 4722 V (rms/inch) for the flamefront-ionized gas.

Fig. 1 reveals that flamefront initiation of sustained arcing is precluded at any electrode separation distance for power supply voltages less than the indicated minimums, 1.15\( \text{in} \). It is not known, but for this report it is assumed that these minimums remain constant for any internal enclosure atmosphere. Regulation 30 CFR, 18.47 limits permissible mining machine maximum voltages to 550 V dc and 4160 V ac. Therefore, the flamefront effect is of concern only on ac mining machines with nominal (typical) rms voltages of 2400 and 4160 V ac. Accordingly, curves C in Fig. 1 and D in Fig. 2 do not apply to permissible mining equipment. Also, regarding phase-to-ground arcing, it should be recognized that mining three-phase power supplies are resistance-grounded and the relatively large-ohm neutral ground resistors used represent a large departure from the CEAL and USBM test power sources. Those sources comprised low resistance to encourage follow-through arcing. Phase-to-ground clearances are therefore less critical than are phase-to-phase clearances regarding flamefront-induced arcing-especially on nominal 2400 V machines since the nominal phase-to-ground voltage is only 1386 V (rms).

The curves pertinent to mining equipment, A and B in Fig. 1 and curve E in Fig. 2, are plotted simultaneously in Fig. 3. CEAL curve A and USBM curve E (both 12.5 mm sphere tests) should be, but are not in agreement; reasons have not been determined. Comparing curve B (point-to-point electrodes) to curves A and E (sphere electrodes) reveals that curve B is the worst-case recorded data for methane flamefront consideration. Equations -defining Curve B data are

\[
V_a = 80S_0 + 852 \text{ V (rms)} \quad (3)
\]

\[
S_0 = \text{ELECTRODE SEPARATION, mm (12.5 mm Spheres)}
\]

**C. Timing Features of Transient Voltages**

A study of references teaches that for sparking to occur the peak voltage must be larger for short duration transient voltages-than for long duration voltages [2], [4], [9], [10]. As an example of this data of Tables I and II reveal that for sparking to occur between point-to-plane electrodes separated 0.15 mm (5.9 \(10^{-3} \text{ in} \)) or more, peak voltage of a 1.2 X 50 impulse must be 1.3 times the crest voltage of the corresponding 50/60 Hz waveform.

For spacings that are large relative to electrode dimensions, another timing factor is the time interval during which the transient voltage exceeds the static breakdown voltage \( S_b \), of the electrodes. Sparking will not occur unless this "over-\( S_b \)" interval exceeds the sparking response (or "lag") time of the particular live part pair. The response time appears to vary in a statistical manner and is affected by the condition of the live part material (oxides, grease), the material's work function, the transient wave shape, the transient "overvoltage" (voltage in excess of the \( S_b \)), and the level of irradiation. Although continuous high-frequency cyclic waveforms can cause
breakdown at peak voltages considerably less than the 
SBV, the crest voltage of a 60 Hz wave is essentially the SBV 
[2].

III. MINIMUM ALLOWABLE CLEARANCE DESIGN
Criteria

The primary criterion for designing electrical clearances 
in permissible 2400 and 4160 V mining equipment is to 
prevent the initiation of sustained arcing by a methane 
flamefront. It follows that the clearances on these equip-
ments should also be large enough to minimize the occur-
rence of sparks that might ignite methane. Since the 
flamefront has no effect on permissible dc mining equipment 
or on permissible ac equipment with typical nominal 
machine voltages less than 2400 V (rms), the only design 
criterion for these equipments is the minimization of 
sparks from transient voltages. Finally, the clearance de-
sign shall accommodate the normal steady-state air densi-
ties in the enclosure.

IV. CLEARANCE DESIGN APPROACH

The design of electrical clearances requires base break-
down voltage data, i.e., worst-case data measured at a 
base altitude and temperature. Assigning sea level and 
68°F (20°C) as the base, columns C and D in Table I, are 
accepted as the “base plain air data,” and the points on 
curve B, Fig. 3 are accepted as the “base flamefront 
data.” Clearance design also requires a means for extrap-
olating the base data to other altitudes and temperatures. 
Additionally, the worst-case transient voltages to be 
“blocked” (rendered incapable of generating a spark) 
must be determined. The influence of altitude and tem-
perature on breakdown behavior will be defined next. 
Then, the transients to be blocked will be specified. 
Thereafter, the clearance design method may be detailed.

A. Altitude and Temperature Effects on Plain Air Breakdown Voltages

According to Paschen’s law for homogeneous (uniform) 
electric fields in gas at a fixed temperature, the product of 
the absolute gas pressure P and the spacing between 
electrodes S (i.e., PSI determines the gas breakdown 
voltages [2], [4], [10]. It should be noted that since explo-
sion-proof enclosures are not airtight, the steady-state internal air pressure equals the ambient mine air pres-
sure, which varies with the mining altitude. Peck demon-
strated that gas density, not simply pressure, along with 
electrode spacing determines the breakdown voltage [9].

Accepting that air near atmospheric conditions may be 
considered a perfect gas [II], it follows that the equation 
of state [3]

\[ P(\text{vol}) = \frac{m}{M} RT \]  

(5)

applies to the air in the enclosure, where 
\( P = \text{absolute pressure, atmospheres (atm)} \)
\( \text{vol} = \text{volume, liters (L)} \)
\( m = \text{mass, grams (g)} \)
\( M = \text{molecular weight of air (constant) (29 gm/mol)} \)
\( R = \text{universal gas constant (0.08207 L atm/Mol °K)} \)
\( T = \text{absolute temperature K.} \)

Note: The dimensional units cited are for example only. 
Since density \( d \) is defined as mass per unit volume, \( d = \frac{m}{\text{vol}} \), \( \frac{M}{P} \frac{P}{T} \left( \frac{S}{L} \right) \) \( \frac{\text{g}}{\text{L}} \) (8) 
which shows that the gas density is proportional to its pressure-temperature ratio. Treating the quantity \( dS \) (in 
lieu of \( PS \) in Paschen’s law) as the constant for a given 
breakdown voltage, gas, states 0 and 1 are related as 
\( dS_0 = dS_1 \); therefore,

\[ S_1 = \frac{dS_0}{dS_1} S_0. \]  

(7)

Conditions:
1) plain air,
2) uniform electric field,
3) constant breakdown voltage,
4) near atmospheric conditions.

Assuming that (7) applies to any electric field, combining 
(6) and (7), which deletes the constants \( M \) and \( R \), and 
dimensioning results in the general equation (8)

\[ S_1 = \frac{(H_g)_0 460 + F_1}{(H_g)_1 460 + F_0} S_0 \]  

(8)

\( (\text{length units}) \)

where \( F \) is the internal enclosure temperature (°F), and 
\( H_g \) is the absolute air pressure (in Hg). 
An equation from Smithsonian Meteorological Table 
51, 5th Revision, 1939 relates pressure (in Hg) to altitude 
\( h \) (ft) as

\[ H_g = 10^{4.7567 - 1.59766(10^{-5}M)} \]  

(9)

(in Hg); 
Condition: \(-8000 \text{ ft.} \leq h \text{ (altitude)} \leq 15000 \text{ ft.} \)
Combining (8) and (9) yields

\[ S_1 = S_0 \frac{460 + F_1}{460 + F_0} 10^{4.7567 - 1.59766(10^{-5}(h - h_0))} \]  

(10)

\( (\text{length units}) \)

A general clearance factor \( f \) may be defined as

\[ f = \frac{460 + F_1}{460 + F_0} 10^{4.7567 - 1.59766(10^{-5}(h - h_0))} \]  

(11)
TABLE III.
CLEARANCE CORRECTION FACTORS VERSUS ALTITUDE AND TEMPERATURE

<table>
<thead>
<tr>
<th>Altitude (ft)</th>
<th>Clearance Factor Referenced to Sea Level - 68°F (20°C) for Enclosure Internal Temperature, <em>F 0</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ft</td>
<td>B</td>
</tr>
<tr>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>2000</td>
<td>1.08</td>
</tr>
<tr>
<td>4000</td>
<td>1.16</td>
</tr>
<tr>
<td>6000</td>
<td>1.25</td>
</tr>
<tr>
<td>6562</td>
<td>1.27</td>
</tr>
<tr>
<td>8000</td>
<td>1.34</td>
</tr>
<tr>
<td>10000</td>
<td>1.44</td>
</tr>
<tr>
<td>12000</td>
<td>1.56</td>
</tr>
</tbody>
</table>

TABLE IV
(\(f_{0}\)) \(H\) VERSUS IEC CLEARANCE FACTORS

<table>
<thead>
<tr>
<th>Altitude (ft)</th>
<th>Normal Barometric Clearance Factor</th>
<th>IEC Clearance Factor Referenced to 2000 m</th>
<th>IEC Clearance Factor Referenced to Sea Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ft</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>0</td>
<td>101.3</td>
<td>0.79</td>
<td>1.00</td>
</tr>
<tr>
<td>1640</td>
<td>95.0</td>
<td>0.84</td>
<td>1.06</td>
</tr>
<tr>
<td>3281</td>
<td>90.0</td>
<td>0.89</td>
<td>1.13</td>
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<tr>
<td>6562</td>
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<td>1.27</td>
</tr>
<tr>
<td>9843</td>
<td>70.0</td>
<td>1.14</td>
<td>1.44</td>
</tr>
<tr>
<td>13123</td>
<td>62.0</td>
<td>1.29</td>
<td>1.63</td>
</tr>
</tbody>
</table>

since then \(S_1 = fS_0\). Ascribing 0 conditions to sea level at 68°F (20°C) defines the specific clearance correction factor \(f_0\) to be used for correcting base clearances for 1 state conditions:

\[
f_0 = \frac{460 + F_0}{528} \times 10^{-5} \text{m}(68°F),
\]

(12) Condition of Use: Relative to sea level (at which \(h_0 = 0\)) and \(F_0 = 68°F\) (20°C).

Table III lists \(f_0\) values from (12) for various altitudes and internal enclosure temperatures. The 12,000 ft altitude limit accommodates the estimated maximum altitude at which coal is mined in the United States [12].

The clearance factor \(f_0\) can be broken into altitude
Fig. 4. Calculated voltage breakdown behavior at 2000 m altitude, homogeneous field.

\[(f_0)_h = 10^{1.5786(10^{-7}) h} \]  \hspace{1cm} (13)

\[(f_0)_T = \frac{460 + F_1}{528}. \]  \hspace{1cm} (14)

Condition: Relative to sea level at 68°F (20°C).

Combining (12), (13), and (14) gives the alternate form of (12):

\[f_0 = (f_0)_h (f_0)_T \]  \hspace{1cm} (15)

Note that since \((f_0)_T\) is unity when \(F_1\) is 68°F (20°C), \((f_0)_h\) values are listed in the 68°F (20°C) column of Table III.

B. Comparing \((f_0)_h\) to the IEC Clearance Altitude Correction Factors

Clearance, factors and pressures versus altitudes listed in Appendix A of IEC Publication 664 [5] are repeated here as columns A, B, and C in Table IV. The IEC clearance factors, column C, are referenced to 2000 m (6562 ft) altitude, dividing these by 0.79 references the IEC factors to sea level, per column D. Comparing column D factors and \((f_0)_h\) values in column E indicates excellent agreement (+0 percent, -0.6 percent).

It should be noted that the IEC Publication 664 does not provide correction factors for temperature [5].

Figs. 4-6 also confirm the excellent agreement between columns D and E in Table IV. Each of the curves in Figs. 4-6 is identified by the column number in Table I or Table II. The voltage data for the Table I curves are IEC measurements taken with electrodes and air exposed to UV. The voltage data for Table II curves were interpolated by the IEC from curves generated from the sea level data. Each figure demonstrates that for the same breakdown voltages, the IEC 2000 m electrode separation distances \(S_{2k}\) are predicted, either exactly or with a slight safety margin, from multiplying the sea level electrode clearances \(S_0\) by \((f_0)_h\).

C. Specifying Transients to be Blocked

Because volt-time characteristics of transients vary from one to another combination of power system-, machine activity, electrical clearances should ideally be custom tailored. The estimated quantity of such combinations dictates a more general design approach. Study establishes that a general design from theoretical consideration alone is precluded by the many complex electrical phenomena involved in the development and transmission of transients (see [18]-1351). A rigorous general design would require measuring all transients on all machines and categorizing these according to volt-time characteristics and frequency of occurrence. Then, using circuits to simulate the transients, sparking tests would be performed to...
TABLE V

<table>
<thead>
<tr>
<th>DC UTILIZATION</th>
<th>AC UTILIZATION</th>
<th>DISTRIBUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vt Transient Voltage Peak</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Amplitude, per unit*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FASTEST RISE TIME, ms</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td>LONGEST TRANSIENT TIME, ms</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>REPETITION RATE</td>
<td>10/pulses per hour</td>
<td>1 to 2 pulses per shift</td>
</tr>
</tbody>
</table>

*Referenced to the nominal system phase-to-phase voltage \( V \) for ac systems and \( V_{dc} \) for dc systems.

TABLE VI

<table>
<thead>
<tr>
<th>DC</th>
<th>AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase to Ground</td>
<td>Phase to Phase</td>
</tr>
<tr>
<td>Vt Transient Peak Voltage</td>
<td>5.64 Vdc</td>
</tr>
</tbody>
</table>

D. Equating 1.2\( \times \)50 \( \mu \)s Impulses to the Mine Transients

To facilitate clearance design, the worst-casemine transients should be correlated to the base plain-air breakdown voltage data in Table I. However, due to timing considerations, rigorous correlation is not possible without extensive testing. Fortunately, a safe-side approximate...
correlation is possible without testing, as will be explained next.

The form of the transients specified in Table V are not rectangular, which is the worst-case form considering the spark lag-time criterion. Sparking cannot occur unless the voltage exceeds the static breakdown voltage (sbut) for a time in excess of the electrode pair’s lag time. Recalling that the 60 Hz waveform crest equals the sbut, a simple safe-side relationship is forced by assuming only rectangular-waveform mine transients and zero lag time for all electrode pairs. In this way the crest of the equivalent 60 Hz wave becomes exactly equal to \( V_t \), the peak voltage of the mine transient to be blocked. Accordingly, the peak voltage of the equivalent 1.2 \( x \) \( 50 \) impulse becomes 1.3 \( V_t \).

Finally, applying additional safety factors equal to 1.03 to allow for 3 percent increase in the nominal power supply voltage and then 1.05 to allow for 5 percent statistical variation in breakdown voltage.

\[ \text{[(V)_{1.2x50}]_{equivalent} = 1.41V_t} \]  

(16).

Table VI calculated from (16), summarizes the worst-case mine transients to be blocked in terms of IEC worst case base plain air data, the algorithm for calculating minimum allowable clearances may now be detailed.

1) Table I, column D data or the equations of Table VII shall be used to determine base plain air clearances \( S_0 \). The 1.2 \( x \) \( 50 \) impulse voltage value \( V_{bo} \) to enter in Table I or Table VII shall be the value calculated for \( V_t \) from Table VI.

2) Equation (4), which describes curve B in Fig. 3, shall be used to determine base flamefront clearances, both phase-to-neutral and phase-to-phase, for (typically) 2400 V (rms) and 4160 V (rms) systems only [strictly speaking, for any voltage exceeding 1386 KV (rms)]. The \( V_a \) value to be entered in (4) shall be 1.03 times the nominal voltage \( V \) (rms). \( S_0 \) calculated from (4) shall be the base flamefront clearance.

3) For nominal 2400 and 4160 V systems, the base clearance shall be the larger of the base plain-air and flamefront clearances calculated from 1) and 2). For all other nominal system voltages, the base clearance shall be the base plain-air clearance from 1).

4) Table III shall be used to correct the base clearances for use at mine face altitudes up to 12 000 ft (3658 m) above sea level and for a specified maximum air temperature in the enclosure. Sea level clearances shall be specified for equipment operating below sea level altitude.

5) Additional factors shall also be applied as follows.

a) To guard against bolted or arcing faults involving loosened terminal connections, no clearances shall be less than 0.25 in (6.35 mm).

b) The clearance between an on-board step-down transformer’s secondary terminal and electrical ground...
TABLE VIII

<table>
<thead>
<tr>
<th>Nominal Machine Voltage (V (rms))</th>
<th>Temperature Maximum**</th>
<th>Enclosure Internal Clearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-550</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum 120 V (rms) Control Transformer Secondary Terminals</td>
<td>302 150</td>
<td>6.35 0.25 6.35 0.25</td>
</tr>
<tr>
<td>601-1001 V (rms)</td>
<td>302 150</td>
<td>7.12 0.28 6.35 0.25</td>
</tr>
<tr>
<td>2500 V (rms)</td>
<td>302 150</td>
<td>15.3 0.61 6.35 0.25</td>
</tr>
<tr>
<td>4160 V (rms)</td>
<td>135 51.2</td>
<td>35.4 1.40 15.3 0.60</td>
</tr>
</tbody>
</table>

* Altitude maximum of 12000 feet (3658 meters).

** To calculate clearance for higher than the listed maximum temperature, multiply the listed clearance by (460 + higher maximum temperature, °F)/(460 + listed maximum temperature, °F).

NOTE 1: Clearance between machine voltage and control voltage live parts shall not be less than C pn listed for the machine voltage.

NOTE 2: All on-board transformers shall comprise grounded Faraday shielding between primary and secondary windings.

shall not be less than the clearance between its secondary terminals.

c) The clearance between live parts of separate voltage sources shall not be less than the phase-to-ground clearance calculated by using for Vpp in Table VI the voltage equal to the sum of the separate phase-to-ground voltages.

d) The clearance shall equal the larger of the direct-sight electrode separation distance dictated by the minimum allowable creepage distance and the electrical clearance determined from Steps 1 through 53).

e) To attenuate the transmission of high-frequency-content transient voltages from transformer primary to secondary terminals, grounded electrostatic (Faraday) shielding shall be used in all on-board step-down transformers [16].

f) Where sparking occurs frequently *even though the equipment electrical clearances are designed as specified, or severe *transients (however infrequent) are known to occur, measures shall be taken to reduce the voltage levels of the transients. Alternatively, larger base plain-air clearances shall be calculated using voltages in Step 1) larger than the values normally calculated from Table VI.

g) All interior surfaces shall be kept as clean and dry as is practicable.

VI. PERMISSIBLE EQUIPMENT ELECTRICAL CLEARANCES

Table VIII lists the minimum allowable electrical clearances calculated from the algorithm that were recommended for use in all permissible mining equipment operating at altitudes up to 12000 ft (3658 m) above sea level. A maximum internal enclosure operating temperature is listed for each voltage. The lowest maximum temperature, 135°F (57.2°C) for the 2400 and 4160 V systems, is based on measurements of temperatures taken inside longwall control enclosures at six different mines in 1987, as recorded by an ad hoc committee of the American Mining
The clearances listed in Table VIII are the bases for the minimum clearances specified in a table under 30 CFR, 18.24 [I]. Table IX is a duplication of the table. The clearances apply to every machine for which an MSHA approval was requested after February 21, 1993. Table IX does not include the footnotes of Table VIII. Nor does Table IX categorize direct current clearances as such; clearances for the 0-550 V dc range are included in the first two rows of the phase to ground or control circuit column. Also, Table IX does not specify the maximum control voltage, which is 120 V rms. Additionally, the 2.96 in clearance for 4160 V rms on Table VIII was rounded up to 3.0 in for Table IX. The other significant differences between Tables VIII and IX are the voltage range specifications:

601-1001 was changed to “601 to 1000;”
2400 was changed to “1001 to 2400;” and
4160 was changed to “2401 to 4160.”

VII. CONCLUSION

Electrical clearance design criteria and a design algorithm were derived to preclude initiation of sustained arcing from methane flamefronts and to minimize sparking within electrical-enclosures operating in gassy areas. The design utilizes plain-air breakdown voltage data from the IEC, data from CEAL, and the USBM regarding initiation of sustained arcing by methane flamefronts, and a specification of worst-case mine transients from research contracted by the USBM. The effects of altitude and internal enclosure temperature on breakdown voltages are compensated for by the clearance design. Assumptions relating the data and design equations to conditions not tested are stated. Calculated clearances are tabulated for equipment operating in altitudes above sea level up to 12,000 ft according to specified typical nominal, machine voltages and maximum internal enclosure temperatures. An equation is provided to adjust clearances for temperatures in excess of the listed maximums. Minimum allowable electrical clearances for -atypical equipment voltages may be calculated from the algorithm.

The minimum clearance values listed under 30 CFR, 18.24 (July 1, 1993) are based on the algorithm described.

Every machine for which an MSHA approval was requested after February 21, 1993 must comply with these clearances.

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REFERENCES

[17] W. M. Hart, “Revised temperature readings,” personal commun-
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