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

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***Abstract*-A design algorithm is derived, for a 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

SPARKS 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 difficulty 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 insulator 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

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[1] 30 CFR is the abbreviation for Title 30, Code of Federal Regulations; 'the numbers and letters following 30 CFR refer to the section number in Part 18 of 30 CFR.

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TABLE I
IEC SEA LEVEL VOLTAGE BREAKDOWN DATA WITH AND WITHOUT ULTRAVIOLET EXPOSURE: AIR (68°F, 20°C)

"S_o" Electrode Separation Distance, mm	"V_{bo}" - Peak Breakdown Voltage, Volts Peak						
	Inhomogeneous Field (Point to Plane)				Homogeneous Field (Sphere to Plane)		
	NO UV		UV - Exposed		NO UV		UV - Exposed
	50/60 Hz	1.2/50 Impulse	50/60 Hz	1.2/50 Impulse	50/60 Hz	1.2/50 Impulse	50/60 Hz and 1.2/50 Impulse
	A	B	C	D	E	F	G
0.01		360			360	360	
0.02		460			430	460	
0.03		560					
0.04		640			580	640	
0.05		720	600	600	650	720	600
0.06		800	631	674	700	800	674
0.08		930	701	809	820	930	809
0.1	780	1,030	754	932	980	1,030	932
0.15			863	1,121			1,207
0.2	990	1,500	949	1,234		1,530	1,449
0 . 3	1,200	1,670	1,085	1,410		2,030	1,876
0.4	1,370	1,750	1,193	1,551		2,410	2,250
0.5	1,440	1,900	1,284	1,669	2,700	2,810	2,600
0.6			1,364	1,773			2,910
0.8			1,500	1,950			3,500
1.0	1,940	2,500	1,742	2,265	4,500	4,640	4,230
1.2	2,300	2,650	1,967	2,560		5,370	4,950
1.5	2,660	3,140	2,280	2,960	6,000	6,360	5,990
2	3,150	3,600	2,770	3,600	7,500	7,820	7,650
2.5			3,210	4,170			9,260
3	3,680	5,100	3,630	4,720	11,200		10,820
4		6,700	4,400	5,720			13,830
5	5,370		5,110	6,640	16,800		16,740
6			5,770	7,500			19,560
8	7,920		7,000	9,100	26,000		25,000
10	9,480		8,470	11,010	31,700		30,700
12	10,900		9,900	12,870			36,400
15	12,690		11,970	15,560	45,500		44,700
20	15,600		15,310	19,900	59,000		58,300
25	22,000		18,520	24,100			71,700
30	27,600		21,600	28,100	86,000		84,800
40	33,900		27,700	36,000	112,000		116,700
50	38,900		33,500	43,600	138,000		136,000
60	43,100		39,100	50,800	164,000		161,000
80	52,300		50,000	65,000	215,000		210,000

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 impulse ,types (1.2 X, 50µs) [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_{sk} , 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
IEC 2000 M VOLTAGE BREAKDOWN DATA, ULTRAVIOLET EXPOSURE; AIR (68°F, 20°0,

"S_{2k}" Electrode Separation Distance, mm	"V_{b2k}" - Peak Breakdown Voltage, Volts		
	Inhomogeneous Field (Point to Plane)		Homogeneous Field (Sphere to Plane)
	50/60 Hz	1.2/50 Impulse	50/60 and 1.2/50 -Hz Impulse
	H	I	J
0.01	330	330	330
0.02	400	400	400
0.03	470	470	470
0.04	5.20	520	520
0.05	560	560	560
0.08	650	700	700
0.1	700	810	810
0.15	800	1,040	1,040
0.2	880	1,150	1,266
0.3	1,010	1,310	1,620
0.4	1,110	1,440	1,950
0.5	1,190	1,550	2,250
0.6	1,270	1,650	2,530
0.8	1,390	1,810	3,040
1.0	1,500	1,950	3,500
1.2	1,700	2,200	4,090
1.5	1,970	2,560	4,950
2	2,380	3,090	6,330
2.5	2,770	3,600	7,650
3	3,130	4,070	8,940
4	3,790	4,930	11,400
5	4,400	5,720	13,800
6	4,970	6,460	16,200
8	6,030	7,840	20,700
10	7,000	9,100	25,000
12	8,180	10,600	29,600
15	9,900	12,900	36,400
20	12,700	16,400	47,400
25	15,300	19,900	58,300
30	17,900	23,300	69,000
40	22,900	29,800	90,000
50	27,700	36,000	11,000
60	32,300	42,000	31,000
80	41,300	53,700	71,000

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.

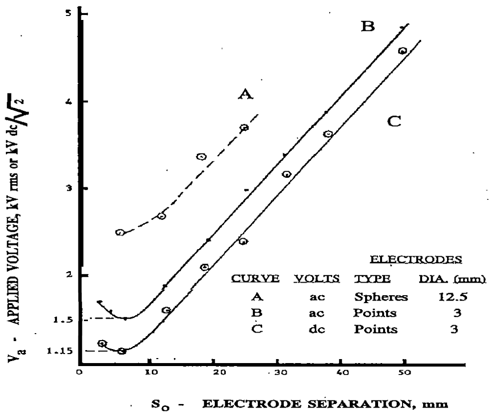

Fig. 1. CEAL flamefront trial results.

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 [S]. 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_a. 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

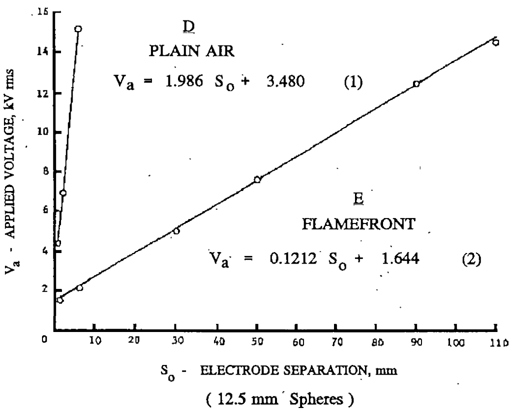

Fig. 2. USBM flamefront and air tests.

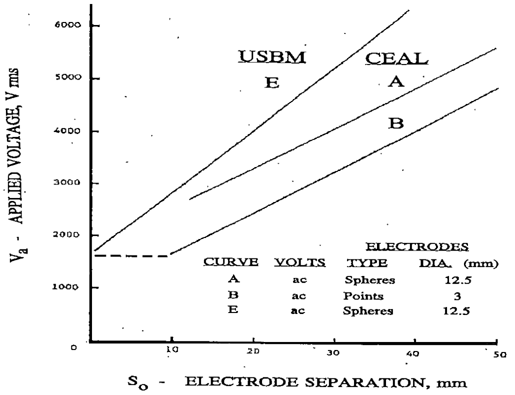

Fig. 3. CEAL and USBM flamefront trial results.

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, $1.15\sqrt{2} = 1.63$ kV (dc) and 1.5 kV (rms) (ac). 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. 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

$$V_a = 80S_0 + 852 \text{ V (rms)} \tag{3}$$

flamefront breakdown voltage, and

$$S_0 = \frac{V_a - 852}{80} \text{ mm} \tag{4}$$

base flamefront clearance.

1) Qualifications: It must be acknowledged that since point-to-plane electrodes are worst case according to the IEC and others [9], it is questionable whether the CEAL curve B point-to-point electrode data represent worst-case flamefront behavior. Also, data of Tables I and II imply, and as will be supported, that larger clearances are required to preclude sparking from a given voltage for lesser air densities (higher altitudes and/or temperatures). It is not known whether air density alters flamefront breakdown voltage values. For the purpose of this paper, it is assumed that flamefront and plain air clearance requirements are equally affected by the normal steady-state air density in the enclosure.

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}) 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 sbv, of the. electrodes. Sparking will not occur unless this "over-sbv" 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 sbv), 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 equipments should also be large enough to minimize the occurrence 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 densities in the enclosure.

IV. CLEARANCE DESIGN APPROACH

The design of electrical clearances requires base breakdown 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 extrapolating 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 temperature' 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], [l0]. It should be noted that since explosion-proof enclosures are not airtight, the steady-state internal air pressure equals the ambient mine air pressure, which varies with the mining altitude. Peek demonstrated 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 [ll], it follows that the equation of state [3]

$$P(\text{vol}) = \frac{m}{M}RT \tag{5}$$

applies to 'the air in the enclosure,. where

P = absolute pressure, atmospheres (atm)

vol = volume, liters *(L)*

m = mass, grams (g)

M = molecular weight of air (constant) (29 gm/mol)

R = universal gas constant (0.08207 L atm/Mol °K)

T = absolute temperature *K*.

Note: The dimensional units cited are for example only.

Since density d is defined as mass per unit volume, (5) yields

$$d = \frac{m}{\text{vol}} = \frac{M}{P}\frac{P}{T} \quad \left(\frac{\text{g}}{\text{L}}\right) \tag{8}$$

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 $d_0 s_0 = d_1 S_1$; therefore;

$$S_1 = \frac{d_0}{d_1} S_0. \tag{7}$$

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)

$$S_1 = \frac{(H_g)_0}{(H_g)_1}\frac{460 + F_1}{460 + F_0} S_0 \tag{8}$$

(length units)

where F is the internal enclosure temperature (°F), and Hg 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

$$H_g = 10^{1.47567 - 1.59786(10^{-5})h} \tag{9}$$

(in Hg);

Condition: -8000 ft. $\leq h$ (altitude) $\leq$ 15 000 ft.

Combining (8) and (9) yields

$$S_1 = S_0 \frac{460 + F_1}{460 + F_0} 10^{1.59786(10^{-5})(h_1 - h_0)}. \tag{10}$$

(length units)

A general clearance factor f may be defined as

$$f = \frac{460 + F_1}{460 + F_0} 10^{1.59786(10^{-5})(h_1 - h_0)} \tag{11}$$

TABLE III.
CLEARANCE CORRECTION FACTORS VERSUS ALTITUDE AND TEMPERATURE

"h_1" Altitude		f_o Clearance Factor Referenced to Sea Level - 68°F (20°C) for Enclosure Internal Temperature, "F_1"					
	°F	68	135	150	180	220	302
ft	m °C	20	57.2	65.6	82.2	104.4	150.0
0	0	1.00	1.13	1.16	1.22	1.29	1.45
2000	610	1.08	1.21	1.24	1.31	1.39	1.56
4000	1219	1.16	1.31	1.34	1.41	1.50	1.68
6000	1829	1.25	1.41	1.44	1.52	1.61	1.80
6562	2000	1.27	1.43	1.47	1.55	1.64	1.84
8000	2438	1.34	1.51	1.55	1.63	1.73	1.94
10000	3046	1.44	1.63	1.67	1.77	1.87	2.09
12000	3658	1.56	1.75	1.80	1.89	2.01	2.25

TABLE IV
$(f_0)_H$ VERSUS IEC CLEARANCE FACTORS

A Altitude		B Normal Barometric Pressure	C IEC Clearance Factor Referenced to 2000 m	D IEC Clearance Factor Referenced to sea level	E Clearance Factor $(f_o)_h$
ft	m	kPa			
0	0	101.3	0.79	1.00	1.00
1640	500	95.0	0.84	1.06	1.06
3281	1000	90.0	0.89	1.13	1.13
6562	2000	80.0	1.00	1.27	1.27
9843	3000	70.0	1.14	1.44	1.44
13123	4000	62.0	1.29	1.63	1.62

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:

$$f_0 = \frac{460 + F_1}{528} 10^{1.59786(10^{-5})h_1}. \qquad (12)$$

Condition of Use: Relative to sea level (at which h_0 = zero) 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

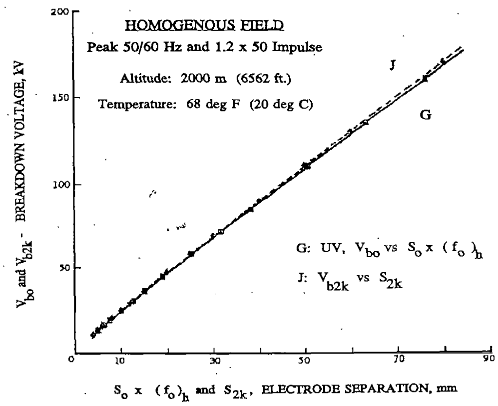

Fig. 4. Calculated voltage breakdown behavior at 2000 m altitude, homogeneous field.

(subnotation *h)* and temperature (subnotation *T)* components; from (12):

$$(f_0)_h = 10^{1.59786(10^{-5})h_1} \tag{13}$$

$$(f_0)_T = \frac{460 + F_1}{528}. \tag{14}$$

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

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

$$f_0 = (f_0)_h (f_0)_T \tag{15}$$

Note that since $(f_0)_T$ is unity when F_l is 68°F (20°C), $(f_O)_h$ 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 $(f_O)_h$ 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_o) by $(f_o)h$.

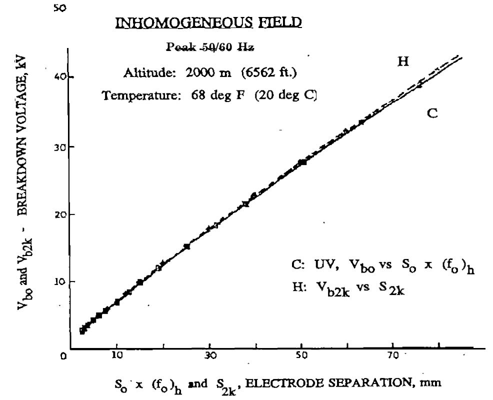

Fig. 5. Calculated voltage breakdown behavior at 2000 m altitude, inhomogeneous field.

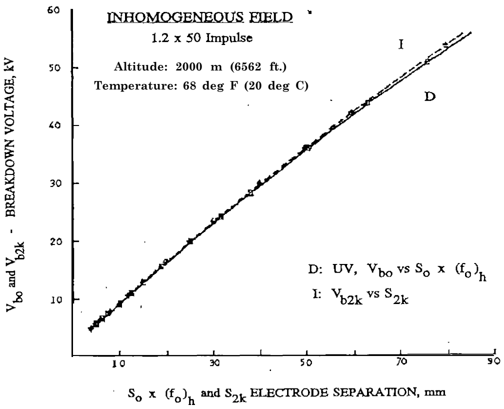

Fig. 6. Calculated voltage breakdown behavior at 2000 m altitude, inhomogeneous field.

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
RECOMMENDED SPECIFICATION OF WORST-CASE MINE TRANSIENTS FROM USBM-CONTRACTED RESEARCH

	dc UTILIZATION	ac UTILIZATION	ac DISTRIBUTION
V_t Transient Voltage Peak Aplitude, per unit*	4	5	7
FASTEST RISE TIME, ms	0.01	1	0.001
LONGEST TRANSIENT TIME, ms	2	5	0.005
REPETITION PATE	10/pulses per hour	1 to 2 pulses per shift	1 to 2 pulses per shift

*Referenced to the nominal system phase-to-phase voltage V_{PP} for ac systems and V_{dc} for dc systems.

TABLE VI
WORST-CASE MINE TRANSIENT AMPLITUDES REFERENCED TO 1.2 x 50 μs IMPULSE

	dc	ac	
		Phase to Ground	Phase to Phase
V_t, Transient Peak Voltage	5.64 V_{dc}	4.07 V_{PP}	8.14 V_{PP}

determine their relative spark generating capabilities. A general clearance could then be determined that precludes all sparking or, e.g., 9.5 percent of sparking. The time and cost for this procedure is obviously prohibitive.

Mining transients research, funded by the USBM, was conducted between 1974 and 1978 in joint efforts of West Virginia University, Pennsylvania State University, and the Westinghouse Electric Corporation. The research included computer modeling of mining power systems and transient measurements at 25 mines and produced a specification, for design purposes, of estimated worst-case mining transients; see Table V [13], [14], [15]. Table V lists V_t, the transients' per unit maximum peak voltages, fastest rise times, longest "transient time," and repetition rates, according to the location in the electrical system. Permissible equipment is part of the utilization system. Therefore, for permissible three-phase ac equipment, Table V interprets to transient peak voltages of $5\ V_{pp}/\sqrt{3}$ across phase-to-ground live parts and $5\ V_{pp}$ across phase-to-phase parts. The listed worst-case dc system peak transient voltage is $4\ V_{dc}$.

The utilization per unit voltage magnitudes listed in Table V were accepted as the worst case inby transient voltage magnitudes to be blocked, with one exception. For phase-to-phase (ac) live parts, the per unit V_t value was changed to $(10/\sqrt{3})$—reasoning that the worst-case transient occurs when two oppositely polarized worst-case phase-to-ground transients coincide exactly in time on separate phases.

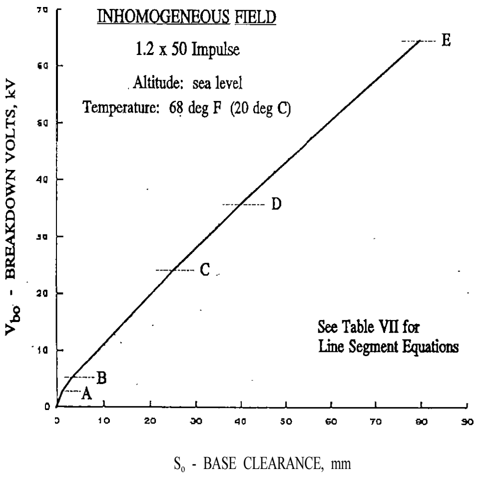

Fig. 7. Safe side approximation-Table I, column D data.

D. Equating 1.2 X 50 Impulses to the Mine Transients

To facilitate clearance design, the worst-case mine 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

TABLE VII
EQUATIONS FOR TABLE I-COLUMN D BASE AIR BREAKDOWN DATA

Line Segment On Figure 7	Equation No.	Equation: $s_0 =$ (mm)	V_{bo} Range (Volts Peak)	s_0 Range (mm)	(in)
O-A	(20)	$\frac{V_{bo}}{2265}$	0-2265	0-1	0-0.0394
A-B	(21)	$\frac{V_{bo}-1037.5}{1227.5}$	2265-4720	1-3	0.0394-0.118
B-C	(22)	$\frac{V_{bo}-2077.25}{880.91}$	4720-24100	3-25	0.118-0.984
C - D	(23)	$\frac{V_{bo}-4266.8}{793.33}$	24100-36000	25-40	0.984-1.575
D-E	(24)	$\frac{V_{bo}-7000}{725}$	36000-65000	40-80	1.575-3.150

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 (sbv) for a time in excess of the electrode pair's lag time. Recalling that the 60 Hz waveform crest equals the sbv, 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.

$$[(V)_{1.2\times 50}]_{\text{equivalent}} = 1.41V_t \qquad (16).$$

Table VI calculated from (16), summarizes the worst-case mine transients to be blocked in. terms of the worst-case 1.2 **X** 50 impulse amplitudes of column D, Table I.

To facilitate clearance calculations, Table **I,** column D data are presented as five connected (safe-side) -line segments in Fig. 7 and the equations that define the segments are listed in Table VII.

V. DETAILED DESIGN ALGORITHM

Having determined the base clearance data, the means for extrapolating base data to other altitude-temperature levels, and the inby 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_{b0} 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 1.386 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
RECOMMENDED ELECTRICAL CLEARANCE FOR PERMISSIBLE EQUIPMENT

Nominal Machine Voltage	Enclosure Internal Temperature Maximum**		MINIMUM CLEARANCES* C_{pp} Phase to Phase		C_{pn} Phase to Ground	
	F	C	mm	in	mm	in
0-550 V (rms)	302	150	6.35	0.25	6.35	0.25
Maximum 120 V (rms) Control Transformer Secondary Terminals	302	150	6.35	0.25	6.35	0.25
0-250 V (rms)	302	150	6.35	0.25	6.35	0.25
251-600 V (rms)	302	150	7.12	0.28	6.35	0.25
601-1001 V (rms)	302	150	15.5	0.61	6.35	0.25
2400 V (rms)	135	51.2	35.4	1.40	15.3	0.60
4160 V (rms)	135	51.2	15.1	2.96	35.5	1.40

* 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 V_{pp} 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 5 3).

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

TABLE IX
MINIMUM CLEARANCES BETWEEN UNINSULATED SURFACES

	Clearances (inches)	
Phase to Phase Voltage (rms)	Phase to Phase	Phase-to-Ground or Control Ckt.
0 to 250	0.25	0.25
251 to 600..	0.28	0.25
601 to 1000	0.61	0.25
1001 to 2400.4	1.4	0.6
2401 to 4160	3.0	1.4

Congress (AMC) [17]. A simple equation, based on (f_0), from (14) and included in the footnotes on Table VIII, may be used to calculate clearances that accommodate higher than. the specified maximum enclosure temperature.

The clearances listed in Table VIII are the bases for the minimum clearances specified in a table under 30 CFR, 18.24 [l]. Table IX is a duplication of the table. These 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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