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# AC Flashovers on Henan Power 500-kV Lines during Rain

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# PRODUCT DESCRIPTION

This report covers electrical breakdown of air gaps in the conductor/hardware-structure of Henan Power overhead lines and discusses the behaviour of wind parameters in areas where the lines are strung. Heavy rains in Henan Province, the People's Republic of China, combined with strong winds have produced unexpected outages on Henan Power's 500-kV line. Preliminary research concludes that the outages are due to unusual atmospheric conditions prevailing in the conductor/hardware-structure air gaps. This conclusion was reached because Henan's insulators do not show evidence of flashovers nor is there a record of switching events or lightning activity.

## Results & Findings

The report provides background and analysis on Henan Power's voltage sparkover phenomenon. Responses to other information requested by Henan Power are detailed: statistics on causes and effects of flashovers; structure and line design criteria, including wind speed and effect of humidity/moisture; possible effects of air pollution and airborne contaminants; data on results of wind tunnel tests on structures; recommendations for research and tests on full-scale structures; and mitigation measures. Recommendations for future research also are given.

## Challenges & Objective(s)

The study's objective is to determine the root causes of the breakdown of air gaps in the conductor/hardware-structure of Henan Power overhead lines.

## Applications, Values & Use

The possibility that strong winds can lead to significant reduction of the gap sparkover voltage in Henan's overhead lines requires detailed investigation. Several mitigation approaches are possible to reduce the unacceptable outage rate. Some general approaches include the following:

- Making appropriate changes to structural details to change the "gap factor." This approach is relatively inexpensive and is suitable for retrofitting exiting structures. However, it normally results in small improvements and is considered a secondary measure.
- Increasing clearances. This may require extensive structural modification and is usually expensive as a retrofit measure for existing structures. Review of the mechanical and structural design of the structures should be conducted.
- Controlling insulator swing. This may require addition of insulators and would require mechanical loading analysis of structures, and possibly structural modifications. In some cases, restraining insulator swing can allow reduction of phase-to-structure distances; however, electrical performance of the line should be reviewed in such cases.

## EPRI Perspective

EPRI recommends that special tests be set up first on small-scale models followed by larger more realistic models to investigate the effects of very strong winds on air gap sparkover. The test setup will have to include a strong wind generator and a high-voltage supply, suitably insulated for the test voltage. Since the test setup is expected to have large dimensions, it may be prudent to start with small-scale tests first.

## Approach

Henan Power contacted EPRI for assistance in analyzing and defining preventive and remedial actions for the unacceptable outage rate on their 500-kV lines. A two-step approach was planned:

- Study of conductor swing and galloping, followed by development of anti-galloping measures.
- Study of breakdown of air insulation under extreme rain, contamination, and wind conditions.

This report covers the second issue, electrical breakdown of air gaps. An initial conference call was held between Henan Power and EPRI experts to scope the study and discover vital information, and a draft presentation was prepared for a meeting with Henan Power. Following the meeting, Henan Power requested a written report to provide a preliminary assessment of the problem, eliminate unlikely causes, define a line of research, and scope out a series of laboratory tests to develop preventive and remedial approaches.


## Keywords

Transmission towers
Flashovers
Rain
Wind
Extreme weather

# ABSTRACT

Henan Power has experienced several unexpected outages on their 500-kV line during heavy rain combined with strong winds. Since insulators do not show evidence of flashovers and there is no record of switching events or lightning activity, it must be concluded that the outages are related to unusual atmospheric conditions prevailing in the conductor/hardware-structure air gaps. This report covers electrical breakdown of air gaps and discusses the behaviour of wind parameters in areas traversed by Henan Power overhead lines.

Analysis of information provided by Henan Power led to several important observations, mitigation suggestions, and recommendations for fundamental research:

- The very large difference between the expected electrical stress (318 $kV_{rms}$) imparted in the conductor-structure air gap (estimated to be 1.2 m in length), compared with the expected sparkover voltage (632 $kV_{rms}$) of any type of air gap 1.2 m in length, suggest that outages should not occur under usual conditions. The inescapable conclusion, therefore, is that **either** the air gap is in fact considerably shorter than 1.2 m **or** severe atmospheric conditions reduce the sparkover voltage of the gap very significantly.
- A comprehensive literature search conducted to discover useful data in other areas of research strongly suggests that strong wind and high humidity can have unusual effects on sparkover of air gaps and very large reduction in sparkover voltage.
- Making appropriate changes to structural details to change the “gap factor” is usually a relatively inexpensive mitigation approach that is suitable for retrofitting exiting structures. However, it normally results in small improvements and is considered a secondary measure.
- Increasing clearances is effective but may require extensive structural modification and is usually expensive as a retrofit measure for existing structures. Review of the structures’ mechanical and structural design should be conducted.
- Controlling insulator swing also is an effective approach, but it may require addition of insulators and would require mechanical loading analysis of structures, and possibly structural modifications. In some cases, restraining insulator swing can allow reduction of phase-to-structure distances, but electrical performance of the line should be reviewed in such cases.

## Recommendations for Further Research

The possibility that strong winds can lead to significant reduction of the gap sparkover voltage should be investigated in detail. It is recommended that special tests be set up first on small-scale models and then followed by larger more realistic models to investigate the effects of very strong winds on air gap sparkover. The test setup will have to include a strong wind generator (large air fans) and a high-voltage supply, suitably insulated for the test voltage. For these reasons, the test setup is expected to be of large dimensions, and it may be prudent to start with small-scale tests first.

Effects of severe atmospheric conditions on sparkover behavior of air gaps are not well understood and should be investigated. Existing test setups in the ultra high voltage (UHV) test chamber for insulators at the EPRI-Lenox laboratory can be used for this purpose. The chamber, which is 24 m in diameter and 24 m high, has a wall bushing rated in the 800-kV class and has standard rain spray systems that are capable of producing heavy rain conditions.

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# 1
# BACKGROUND

Henan Power has experienced several unexpected outages on their 500-kV line during heavy rain combined with strong winds. The lines are both single-circuit (Figure 1-1) and double-circuit (Figure 1-2), and are supported on steel lattice structures.

**Figure 1-1**
**Typical Henan Tangent Single-Circuit 500-kV Steel Lattice Structures**

**(Courtesy of Henan Power)**

**Figure 1-2**
**Typical Henan Dead-End and Tangent Double-Circuit 500-kV Steel Lattice Structures**

**(Courtesy of Henan Power)**

## Information Provided by Henan Power

The outages were caused by sparkovers through air between the steel lattice structure members and the energized conductors or hardware, i.e., by disruptive discharges through air, or breakdown of the conductor-structure air gap. This is confirmed by physical evidence (burn marks) on structure members and on conductors (Figure 1-3 and 1-4, and Appendix A, all courtesy Henan Power).

The outages occurred in inclement weather, namely, heavy rain and strong wind. However, the insulators do not show evidence of flashovers (i.e., of discharges along the insulator surface). Examples of insulators that flashed over on other lines are shown in Figures 1-5 and 1-6.

Also, information provided by Henan Power indicates that outages occurred in the absence of switching events or lightning activity in the area.

**Figure 1-3**
**Evidence of a Sparkover (Burn Mark) on a Steel Lattice Member**

**(Courtesy of Henan Power)**

**Figure 1-4**
**Evidence of a Sparkover (Burn Mark) on a Steel Lattice Member**

**(Courtesy of Henan Power)**


**Figure 1-5**
**Example of an Insulator that Flushed Over**

**(Note scorching of the surface glazing and damage to the metal cap due to large fault current resulting from the flashover.)**

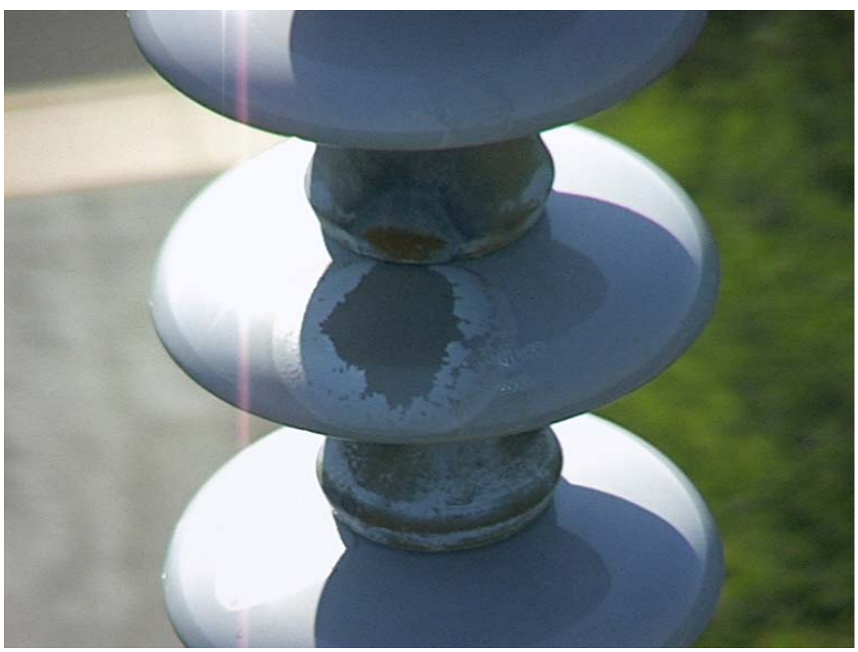


**Figure 1-6**
**Example of an Insulator String that Flashed Over**

**(Note scorching of the surface glazing and damage to the metal cap due to large fault current resulting from the flashover.)**

## Inquiry from Henan Power

In view of the unacceptable outage rate on the 500-kV lines involved in the outages, Henan Power contacted EPRI with a request for assistance in analyzing the problem and defining preventing and remedial actions. A two-prong approach was agreed upon:

- Study of conductor swing and galloping, followed by development of anti-galloping measures,
- Study of breakdown of air insulation under extreme rain, contamination and wind conditions.

This report covers the second issue, i.e., electrical breakdown of air gaps. In this area, Henan Power requested information on the following points:

- US/Canada/worldwide statistics on causes and effects of flashovers,
- US/Canada/worldwide structure and line design criteria, including wind speed, effect of humidity/moisture,
- Tests performed by EPRI on structures under various conditions, including possible effects of air pollution and airborne contaminants,
- Mitigation measures,
- Mathematical models for flashover phenomena,
- Data on results of wind tunnel tests on structures, if any,
- Tests on installed towers, performed in the field.

An initial conference call was held between Henan Power and EPRI experts to scope the study and discover vital information, and a draft presentation, covering some of the above topics, was prepared for a meeting with Henan Power. Following the meeting, additional details were provided and clarified, and Henan Power requested a written report with the view to provide a preliminary assessment of the problem, eliminate unlikely causes and solution, define a line of research, and scope out a series of laboratory tests to understand the problem and develop preventive and remedial approaches.

# 2
# ANALYSIS OF THE VOLTAGE SPARKOVER PHENOMENON

Based on the information form Henan Power that there is no evidence of insulator flashover of the type shown in Figure 1-5 and 1-6, the possibility of insulator contamination is not considered to be the cause of the outages.

Also, since there was no evidence of switching or lightning activity, the possibility of overvoltages on the lines is also not considered to be the cause of the outages.

Therefore, it must be concluded that the outages are related to unusual atmospheric conditions prevailing in the conductor/hardware-structure air gap.

## Analysis of Structure Clearances

A sketch of a typical structure, provided by Henan Power, is shown in Figure 2-1.

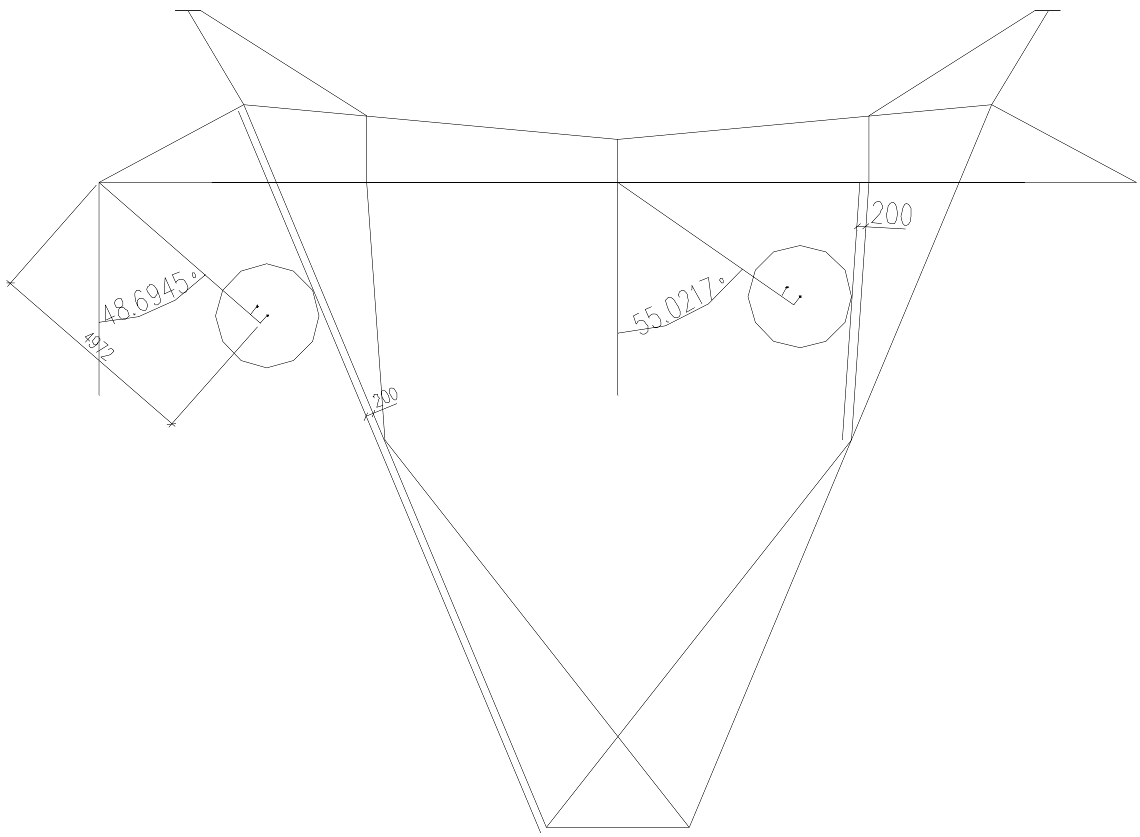



**Figure 2-1**
**Sketch of a Typical Henan Power 500-kV Tangent Structure**

Figure 2-2 shows a photograph, taken from below and looking upward, of a typical suspension structures.

The design swing angle of an I-string is 55° from vertical. Both the sketch and the photograph shows that the structure clearances (distances between the structure steel and the energized conductors) and quite tight for 500-kV lines.

Based on the sketch and subsequent information provided by Henan Power, the clearance at maximum observed swing angle (at maximum wind) is 1.2 m. This clearance is somewhat smaller that for other typical 500-kV lines.


**Figure 2-2**
**Photograph of a Henan Power 500-kV Tangent Structure**

## AC Sparkover Voltage of Air Gaps in the Range of 1 m

Sparkover under AC voltage conditions occurs usually in the positive half-cycle of the AC voltage wave, and usually at the (positive) peak of the wave. Development of the sparkover process is complicated and goes through several stages in a very short period of time. The sparkover process is schematically illustrated in Figure 2-3 [3].

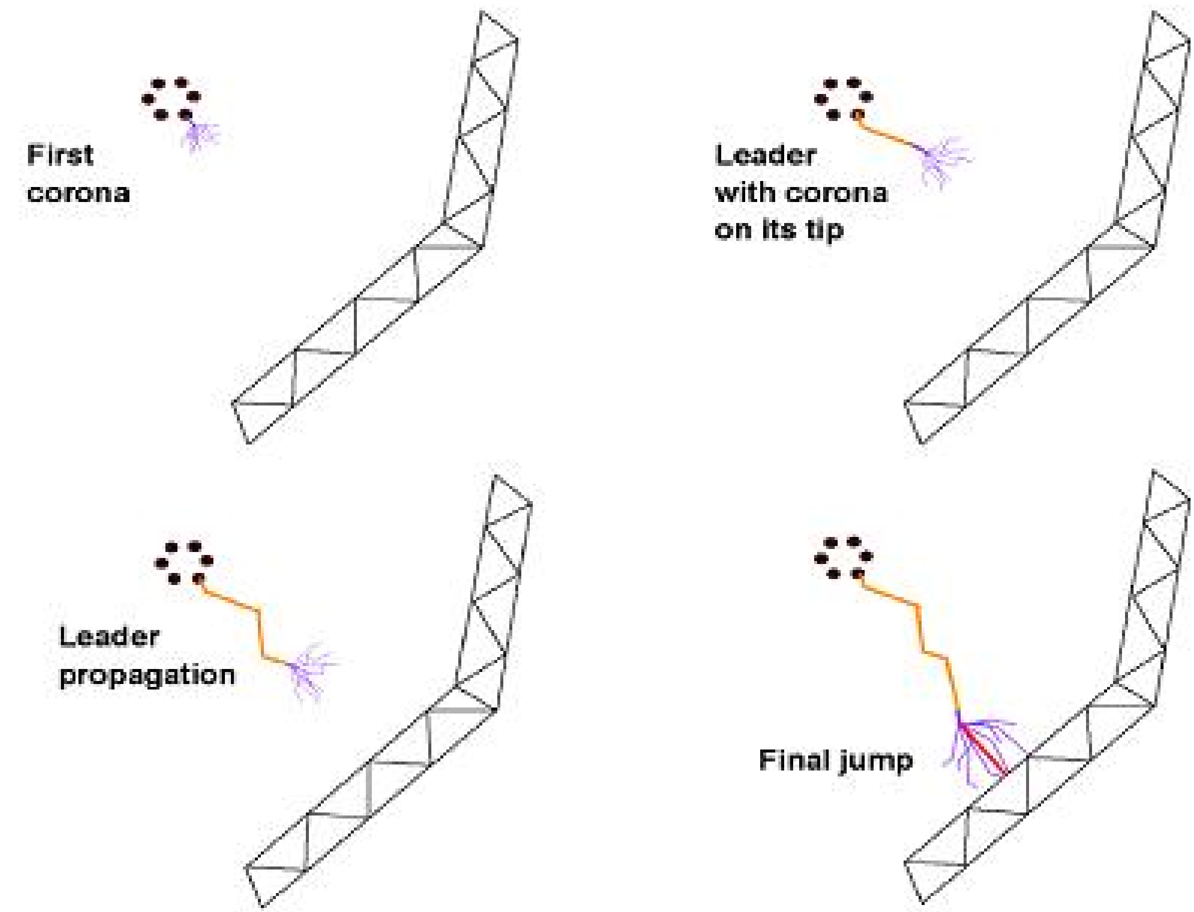



**Figure 2-3**
**Schematic Illustration of Development of Voltage Sparkover**

AC sparkover data for conductor-structure air gaps in the range of 1 m are scarce in the literature, but extrapolations from other results (air gap length, similar configurations) are possible [1, 2]. Examples of test data are listed in Table 2-1 (D is in m). Gap factor listed in Table 2-1 is defined as the ratio of the sparkover voltage of the gap under consideration to the sparkover voltage of a rod-to-plane gap with the same gap length:

$$GAP\ FACTOR = U_{(gap)} / U_{(rod-to-planegap)} \quad \textbf{Eq. 2-1}$$

The large spread in sparkover AC voltage values in Table 2-1 indicates that the details of the energized and grounded electrodes are very important and can significantly affect the sparkover performance of the gap. This is due to spatial distribution of the electric field at the energized and the grounded electrodes, and possible presence and effects of various modes of corona (onset discharges, glow, pre-breakdown streamers).

For this reason, it is very difficult to estimate the AC sparkover voltage of a conductor-structure air gap without detailed analysis of the configuration and electrode shapes.

**Table 2-1**
**Examples of Sparkover Data of Air Gaps in the Range of 1m**

| D (m) | $U_{sp}$ ($kV_{peak}$) | Gap Factor | Gap Electrode Configuration |
|---|---|---|---|
| 0.305 | 227 | 1.49 | **Conductor-to-plane gap:** energized 31.8 mm diameter metal pipe above grounded large rectangular metal plate |
| 0.508 | 253 | N/A | **Standard rod-to-plane gap:** energized 0.5 inch flat cut square metal rod above grounded large metal plate |
| 1.016 | 509 | N/A | **Rod-to-plane gap:** energized 0.5 inch flat cut square metal rod above grounded large metal plate |
| 0.508 | 274 | N/A | **Hemispherical rod-to-plane gap:** energized metal rod with 10 mm diameter hemispherical tip above grounded large metal plate; air density = 0.99, humidity = 4 g/m$^3$ |
| 1.016 | 481 | N/A | **Hemispherical rod-to-plane gap:** energized metal rod with 10 mm diameter hemispherical tip above grounded large metal plate; air density = 0.99, relative humidity = 4 g/m$^3$ |
| 0.90 | 473 | 1.06 | **Standard horizontal rod-to-rod air gap** [4] |
| 1.00 | 520 | 1.04 | **Standard horizontal rod-to-rod air gap** [4] |
| 1.20 | 625 | 1.05 | **Standard horizontal rod-to-rod air gap** [4] |
| 0.889 | 445 | 1.01 | **Sphere-to-plane gap:** energized 25 cm metal sphere above grounded large metal plate; temperature = 25°C, pressure = 760 mmHg, humidity = 0.5 gtrains/ft$^3$ |
| 1.016 | 480 | 0.95 | **Sphere-to-plane gap:** energized 25 cm metal sphere above grounded large metal plate; temperature = 25°C, pressure = 760 mmHg, humidity = 0.5 gtrains/ft$^3$ |
| 1.143 | 520 | 0.91 | **Sphere-to-plane gap:** energized 25 cm metal sphere above grounded large metal plate; temperature = 25°C, pressure = 760 mmHg, humidity = 0.5 gtrains/ft$^3$ |
| 1.00 | 1131 | 2.27 | **Vertical hoop-to-plane gap:** energized metal hoop of diameter 0.25 m made of metal pipe of diameter 0.0016 m, placed above grounded large metal plate |

**Table 2-1 (continued)**
**Examples of Sparkover Data of Air Gaps in the Range of 1m**

| D (m) | $U_{sp}$ (k$V_{peak}$) | Gap Factor | Gap Electrode Configuration |
|---|---|---|---|
| 1.00 | 1041 | 2.09 | **Vertical hoop-to-plane gap:** energized metal hoop of diameter 1.0 m made of metal pipe of diameter 0.0024 m, placed above grounded large metal plate |
| 1.00 | 761 | 1.53 | **Vertical hoop-to-plane gap:** energized metal hoop of diameter 1.0 m made of metal pipe of diameter 0.0032 m, placed above grounded large metal plate |
| 1.00 | 1206 | 2.42 | **Vertical hoop-to-plane gap:** energized metal hoop of diameter 1.0 m made of 1.6 mm thick metal ribbon on edge (i.e., a disk 1.6 mm thick), placed above grounded large metal plate |

### *Standard Rod-To-Plane Air Gap*

For a standard rod-to-plane air gap, the AC sparkover voltage is quite linear with gap length, D, in the range of D around 1 m, and may be approximated by Equation 2-2:

$$U_{sp,ac,peak} = 498 \times D \ \ \text{(kV, m)} \qquad \textbf{Eq. 2-2}$$

Equation 2-2 does not hold for very short air gaps due to local corona, and also does not hold for long air gaps (several meters), however, it is quite accurate around the 1 m range, as shown in Figure 2-4 [2].

Using Equation 2-2, the AC sparkover voltage of a 1.2 m gap would be 598 $kV_{peak}$ or 423 $kV_{rms}$.

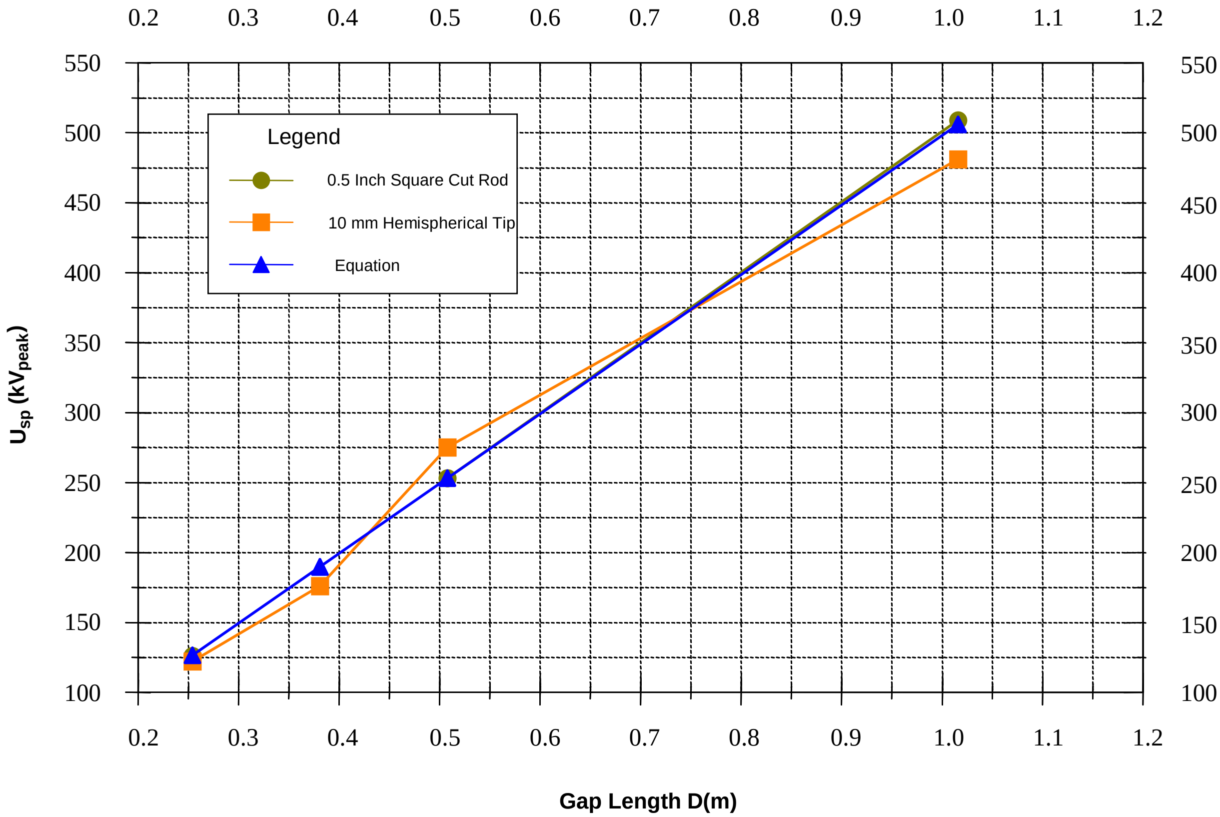



**Figure 2-4**
**Validation of Equation 2-2**

## *Conductor-To-Plane Air Gap*

Assuming that Equation 2-2 also holds for a conductor-to-plane air gap, and using the data from Table 2-1, the AC sparkover voltage of a 1.2 m conductor-to-plane gap would be 893 $kV_{peak}$ or 632 $kV_{rms}$.

On the 500-kV Henan Power line, the phase-to-structure voltage, which electrically stresses the conductor-to-structure air gap, is 318 $kV_{rms,phase\text{-}to\text{-}ground}$, assuming, as the worst case, that the line voltage is in fact equal to the maximum nominal voltage of 550 $kV_{rms,phase\text{-}to\text{-}phase}$ at the time of an outage. This stress (318 kV) is approximately half of the expected strength (632 kV) of the conductor-to-structure air gap at maximum expected insulator swing, under normal atmospheric conditions.

Therefore, outages should not occur.

The inescapable conclusion, therefore, is that **either** the air gap is in fact considerably shorted than 1.2 m, **or** severe atmospheric conditions reduce the sparkover voltage of the gap very significantly.

The first possibility – significant reduction of the gap due to very high winds that result is much greater insulator swing – should be investigated. Wind tunnel studies of reduced-scale models could provide answers to this issue. We are not aware of detailed wind tunnel data that would provide insight into this issue. Known data in this area are discussed later. It is recommended that special tests be set up first on small scale models, and then followed by larger more realistic models to investigate the effects of very strong winds on air gap sparkover. The test setup will have to include a strong wind generator (large air fans) and a high voltage supply, suitably insulated for the test voltage. For these reasons, the test setup is expected to be of large dimensions.

Effects of severe atmospheric conditions, such as heavy rain, on sparkover behavior of air gaps are not well understood. We re not aware of detailed data on air gap sparkovers in very heavy rain that could be used to explain the conditions observed by Henan. Known data on this topic are discussed later. Full-scale studies in high-voltage laboratories, possibly preceded by reduced-scale tests, should be conducted. Existing test setup in the UHV test chamber for insulators, see Figure 2-5, at the EPRI-Lenox laboratory can be used for this purpose. The chamber has dimensions of 24 m diameter and 24 m high, has a wall bushing rated for 800-kV class and has standard rain spray systems that are capable of producing heavy rain conditions.

Other known effects of atmospheric conditions are in the section titled *Effects of Atmospheric Conditions on AC Sparkover Voltage of Air Gaps*.

## Effects of Atmospheric Conditions on AC Sparkover Voltage of Air Gaps

The sparkover voltage of air gaps depends on atmospheric conditions that prevail in the gap at the instant of sparkover. In order to facilitate comparisons of test results from tests that may have been performed under different atmospheric conditions, normal industry practice allows the use of agreed-upon correction factors to adjust the test result, $U_{sp}$, to standard reference atmospheric conditions [4, 5]: temperature t0 = 20°C, pressure $p_0$ = 101.3 kPa (1013 mbar or 760 mmHg), and humidity $h_0$ = 11 g/m3. Two adjustments for atmospheric conditions are used: the air-density correction factor, kd, and the humidity-correction factor, $k_h$. The corrected sparkover (breakdown) voltage value, $U_{corr}$, which corresponds to the sparkover value at the standard reference atmospheric conditions, is then calculated as:

$$U_{corr} = U_{sp} / K_t \qquad \textbf{Eq. 2-3}$$

where:

$U_{corr}$ is the corrected sparkover voltage (corrected to reference atmospheric conditions),

$U_{sp}$ is the sparkover voltage obtained from a test under nonstandard atmospheric conditions,

$K_t$ is defined as:

$$K_t = k_d \times k_h \qquad \textbf{Eq. 2-4}$$

**Figure 2-5**
**UHV Test Chamber at the EPRI-Lenox Facility**

The adjustment procedure described above is used for AC voltage and positive-polarity impulse breakdown results. For negative polarity impulse, the correction factor Kt is taken as 1.000.

The correction factor, $k_d$, for air density is given as:

$$k_d = (\delta)^m$$ **Eq. 2-5**

where:

$$\delta = \frac{p}{p_0} \times \frac{273 + t_0}{273 + t}$$ **Eq. 2-6**

where:

*p* is the atmospheric pressure during the test, in the same units as $p_0$,

$p_0$ is the standard reference pressure corresponding to standard reference atmospheric conditions (for example, $p_0$ = 101.3 kPa or 760 mmHg)

$t_0$ is the standard reference temperature (for example, $t_0 = 20^{o}$C)

*t* is the temperature during the test, in the same units as $t_0$,

*m* is an exponent parameter obtained from curves [4, 5];

The humidity correction factor, $k_h$, is given as:

$$k_h = k^w$$ **Eq. 2-7**

where:

*k* is a function of the absolute humidity during the test (and the type of test voltage; the voltage is AC in this case),

*w* is an exponent parameter obtained from curves [4].

Absolute humidity, *h*, during the sparkover event should be measured (preferably in the air gap) using a meter that measures the absolute humidity directly, or a meter that measures relative humidity and temperature, or using the dry-bulb and wet-bulb temperatures (using, for example, a ventilated dry and wet bulb hygrometer). The curves in Figure 2-6 are used to calculate the absolute humidity from the dry-bulb and wet-bulb temperature data [4]. Of course, this method cannot be used below freezing temperatures for water.

For practical purposes, the value of *k* can be obtained as a function of the ratio of absolute humidity, *h*, during the sparkover event, to the relative air density, $\delta$, during the sparkover event. The curves in Figure 2-7 can be used for this purpose [4].

Note that, for values of $h/\delta$ greater than 15 g/$m^3$, humidity correction is still under investigation, and the curves in Figure 2-7 may be regarded as upper limits [4].

The exponents *m* and *w* can be read off from the curve in Figure 2-8, where the abscissa parameter *g* is [4]:

$$g = \frac{U_{sp}}{500 \times L \times \delta \times k} \quad \textbf{Eq. 2-8}$$

where:

$U_{sp}$ is the sparkover voltage (in $kV_{peak}$),

$L$ is the minimum sparkover path length (in m).

In this case, the value of *L* is 1.2 m, based on previous discussions.

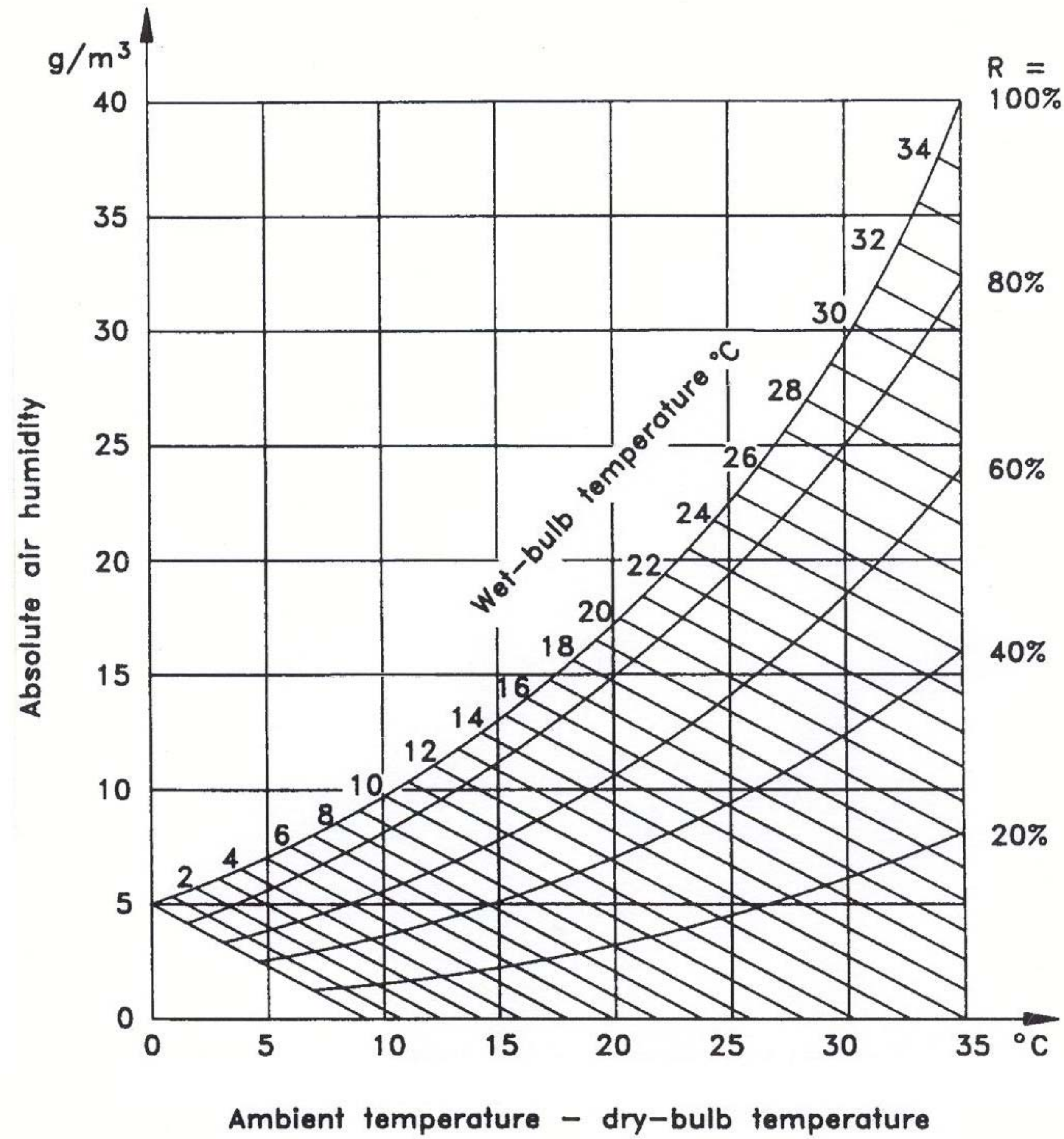
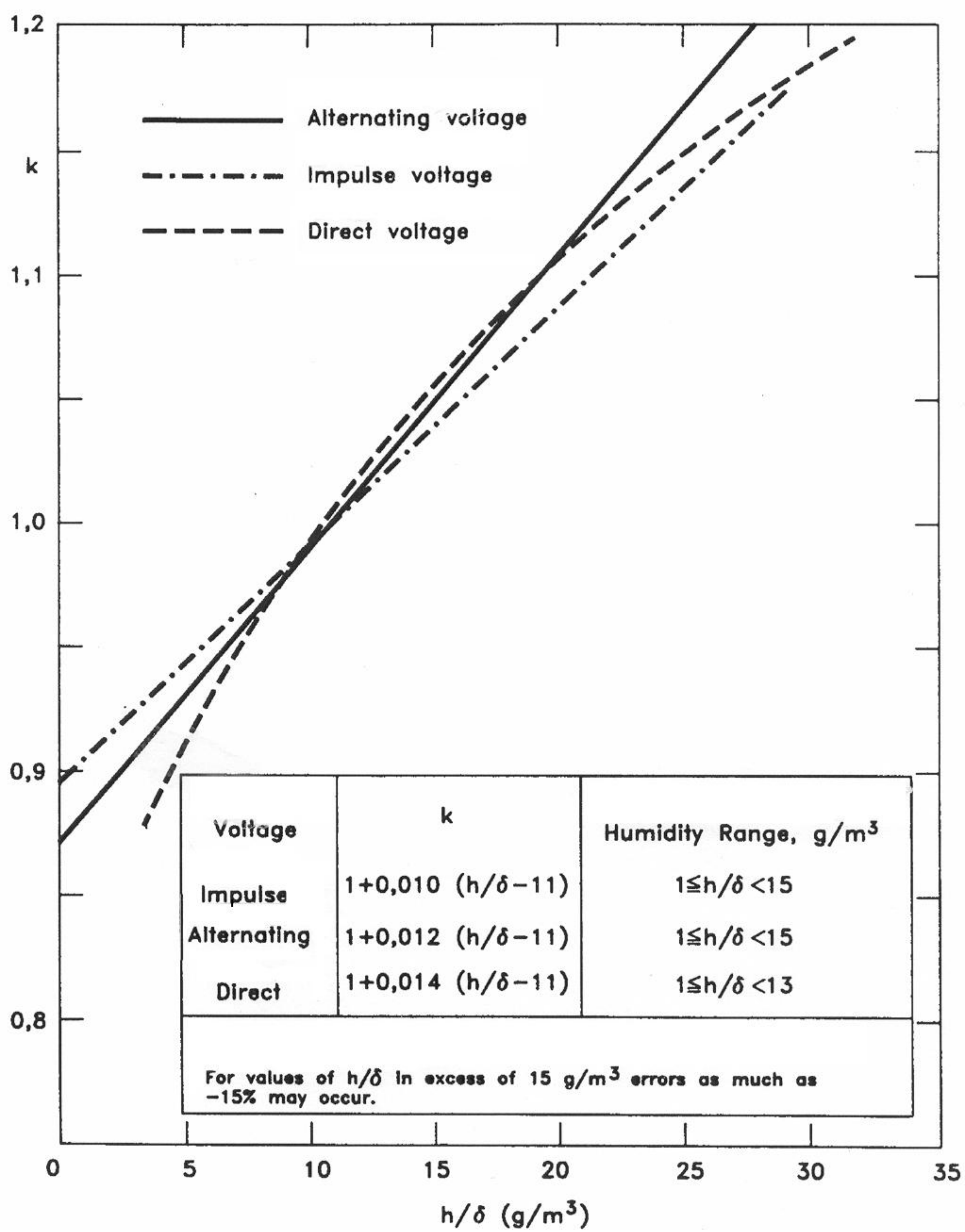



**Figure 2-6**
**Curves for Calculating the Absolute Humidity from Dry-Bulb and Wet-Bulb Temperature Measurements**




| Voltage | k | Humidity Range, g/m³ |
|---|---|---|
| Impulse | $1+0{,}010\ (h/\delta-11)$ | $1 \leq h/\delta < 15$ |
| Alternating | $1+0{,}012\ (h/\delta-11)$ | $1 \leq h/\delta < 15$ |
| Direct | $1+0{,}014\ (h/\delta-11)$ | $1 \leq h/\delta < 13$ |

**Figure 2-7**
**Curves for Calculation of Humidity Correction**

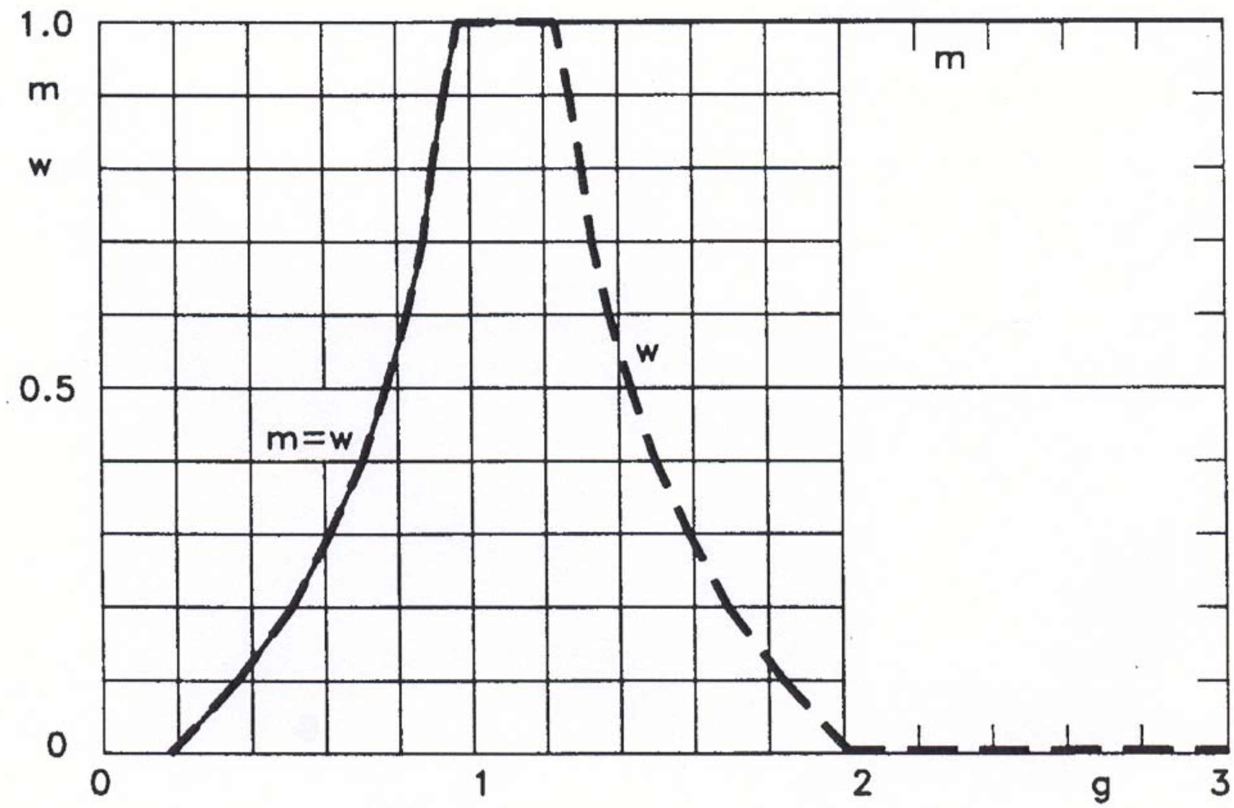



**Figure 2-8**
**Curves for Determination of Exponents *m* and *w***

## *Discussion of Correction Factors*

The correction for air density is explained by Paschen's Law, which states that the sparkover voltage for a uniform air gap (such as the parallel plate gap) is a function of the product of the pressure and gap length.

As temperature, *t*, in the air gap increases, the air-density, $\delta$, decreases as seen from Equation 2-6, the air density correction factor, $k_d$, decreases (see Equation 2-5) , the total correction factor, $K_t$, decreases (see Equation 2-4) and the corrected sparkover voltage, $U_{corr}$, increases, as seen from Equation 2-3. Conversely, if the sparkover voltage at standard reference atmospheric conditions, i.e., the corrected voltage, $U_{corr}$, is known, and the temperature increases, the actual sparkover voltage, $U_{sp}$, measured during a test, decreases.

The effect of increasing humidity is somewhat different and more difficult to analyze. Equation 2-7 and curves in Figures 2-7 and 2-8 are still under investigation.

## Application of Correction Factors to Outages on Henan Power 500-kV Lines

Recalling previous discussions, the AC sparkover voltage of a 1.2 m conductor-to-structure air gap under standard reference atmospheric conditions is estimated to be $U_{corr}$ = 632 $kV_{rms}$ or 894 $kV_{peak}$.

Assuming that the actual observed sparkovers occurred when the line voltage was at the maximum nominal value or 318 $kV_{rms,phase\text{-}to\text{-}ground}$, the actual sparkover voltage of the 1.2 m conductor-structure air gap was $U_{sp}$ = 318 $kV_{rms}$ or 450 $kV_{peak}$.

Then, from Equation 2-3, the total actual correction factor is $K_{t,\ actual}$ = 450 / 894 = 0.503.

Values of correction factor, $K_t$, typically observed in laboratory tests are within the range of 0.9 to 1.1 or so. Hence, the value of 0.503 is extremely low and unusual.

### *Calculations Assuming Maximum Value of k, w and m*

Using the largest value from Figure 2-7 for parameter, *k*, the maximum value of *k* is $k_{max}$ = 1.2.

Using the largest value from Figure 2-8 for exponent ,*w*, the maximum value of *w* is $w_{max}$ = 1.0.

Using Equation 2-7, the maximum value for the humidity correction factor, $k_h$, is $k_{h,max}$ = 1.2.

The, using Equation 2-4 and the value $K_{t,\ actual}$ = 318 / 632 = 0.503, the minimum air density correction factor, $k_d$, is $k_{d,min}$ = 0.503 / 1.2 = 0.419.

Using the largest value from Figure 2-8 for exponent, *m*, the maximum value of *m* is $m_{max}$ = 1.0.

Using Equation 2-5 and the above values of $k_{d,min}$ = 0.419 and $m_{max}$ = 1.0, the actual value of the air density, $\delta$, is calculated as $\delta_{actual,1}$ = 0.419.

### *Calculations Assuming Minimum Values of k, w and m*

Using the smallest value from Figure 2-7 for the parameter, *k*, the maximum value of *k* is $k_{min}$ = 0.87 approximately.

Using the smallest value from Figure 2-8 for exponent, *w*, the maximum value of *w* is $w_{min}$ = 0.0.

Using Equation 2-7, the minimum value for the humidity correction factor, $k_h$, is $k_{h,min}$ = 1.0.

The, using Equation 2-4 and the value $K_{t,\ actual}$ = 318 / 632 = 0.503, the maximum air density correction factor, $k_d$, is $k_{d,max}$ = 0.503 / 1.0 = 0.503.

Using the smallest value from Figure 2-8 for exponent, *m*, the maximum value of *m* is $m_{min}$ = 0.0.

Using Equation 2-5 and the above values of $k_{d,max}$ = 0.503 and $m_{min}$ = 0.0, the actual value of the air density, $\delta$, cannot be determined, indicating that the value $m_{min}$ = 0.0 is not valid.

If the maximum value for *m* is used, the actual $\delta_{actual,2}$ = 0.503.

### Other Combinations of Values of k, w and m

Other combinations of values for parameters *k*, *w* and *m* can also be considered as a mental exercise, however, the resulting values of $\delta$ would still fall near the above values.

### Check of Calculations

As a check on these calculations, the actual value of parameter, *g*, is, from Equation 2-8,

$$g_{actual} = 450/\left(500 \times L \times \delta_{actual,1} \times k_{\max}\right) = 450/\left(500 \times 1.2 \times 0.419 \times 1.2\right) = 1.05$$

This value of $g_{actual}$, and the previously calculated value of the parameter, *k*, together with Figure 2-7, gives the actual value for the parameter, *h/g*, of $h_{actual}/g_{actual}$ = 28, approximately. It must be noted that this value of *h/g* is outside the range of validity of Figure 2-7.

Nevertheless, the actual value of absolute humidity, $h_{actual}$, would be $h_{actual}$ = 28 × 1.05 = 29.4 g/m$^3$.

Other combinations of values for parameters *k*, *w*, and *m* would produce similar results.

This value of absolute humidity is very high. It is not known whether this corresponds to heavy rain conditions, since no data are available on this point.

## Atmospheric Conditions During Outages on Henan Power 500-kV Lines

The atmospheric conditions during the outages on the Henan Power 500-kV lines appear to be unusual and very extreme. For this reason, the correction factors discussed above may not be accurate or even altogether applicable. In fact, all indications suggest that the conditions during the outages are outside the range of applicability of these correction factors.

Considerable literature search was conducted to identify useful data in other areas of research [6 – 8]. While research reported in these references does not apply directly to the Henan Power outages, some interesting observations were found:

- There is some evidence suggesting that turbulence helps create charged water droplets. When relating this conclusion to the Henan Power outages, it should be noted that strong wind can create turbulence near a conductor.
- Preliminary tests conducted at the EPRI-Lenox laboratories on insulators in high humidity and fairly strong wind indicate that the insulator flashover voltage exhibits a strong decrease.

- Charge flow in humid conditions and strong wind seems to increase significantly. This observation applies to tests in the presence of high temperatures (steam).
- Wet steam shows very high conductivity. This also refers to high temperature conditions.

While above observations were made based on tests under different atmospheric conditions (notably, presence of high temperature), they point to possible unexpectedly large reductions in the sparkover voltage of air gaps.

Other research, relating to flashovers of insulating tools (hotsticks) [9 – 10], suggested that high wind can cause turbulence near the surface of the tool and thus reduce the flashover voltage significantly. While this mechanism was later put aside in favor of a light contamination mechanism, it is an interesting observation and some laboratory tests confirm the reduction in flashover voltage.

Also, in the case of DC overhead transmission lines, space charge transport on aerosols moved by wind is a known phenomenon, and its effect is observed at large distances from the line [11].

Hence, there is a significant body of evidence to suggest that strong wind and high humidity can have usual effects on sparkover of air gaps. Much more research and testing, however, needs to be conducted to quantify the effects and understand the phenomenon in detail.

# 3
# RESPONSES TO OTHER INFORMATION REQUESTED BY HENAN POWER

This Section addresses other information requested by Henan Power. Some responses were provided earlier in a meeting at Henan Power.

## Statistics on Causes and Effects of Flashovers

Normally, transmission lines in the 500-kV range are designed for:

- Not more than several (less than 1 to as many as 20) flashovers per 100 km-year due to LIGHTNING,
- Not more than a few (1 to not more than 10) flashovers per 100 operations due to SWITCHING,

More details can be found in Ref. [3] (the EPRI "Red Book").

Flashovers due to power frequency, in the absence of lightning and switching, are rare unless unusual conditions exist such as high or non-uniform contamination, or possibly high wind.

## Structure and Line Design Criteria, Including Wind Speed, Effect of Humidity/Moisture

The wind is the main effect on the conductor/insulator swing. A maximum wind is selected for the design of a transmission line. This maximum wind speed is generally based on historical data taken at 10 m above ground from nearby weather stations that are located in open areas such as an airport. While this design approach is adequate for determining structure loads, it could be inadequate for insulator swing calculations under unusual circumstances. Factors that affect the insulator swing angle are discussed below [11]. These factors must be considered in defining the length of the support arm and size of the tower window, for a given insulator string length.

### *Dynamic Wind Pressure, $q_0$*

The most commonly used equation in determining the dynamic wind pressure on a conductor and an insulator string, $q_0$ is:

$$q_0 = 0.5\ \rho\ V_T^2 \qquad \textbf{Eq. 3-1}$$

The units of this equation are Pa for $q_0$, kg/m$^3$ for ρ, and m/s for $V_T$. The air mass per unit volume, ρ, is taken equal to 1.293 kg/m$^3$ at a temperature of 0°C and an atmospheric pressure of 101.325 kPa.

In calculating insulator swing angles, the wind loads on both the conductor and the insulator string are considered. The load is the product of the wind pressure by the projected area. For the conductor, the area is the diameter of the conductor and its wind span. For the insulator, it is the area of the insulator string projected horizontally on a vertical plane parallel to the axis of the string. This area could be conservatively assumed to be equal to the product of the diameter of the insulator by the length of the string.

The wind speed, $V_T$, measured at a height of 10 m above ground must be converted to the proper height of the conductor/insulator above ground and the roughness of the terrain where the transmission line transverse must be taken into consideration as described in the following section.

### *Height Factor & Terrain Roughness*

Wind speed increases with increasing altitude in accordance with a generally accepted exponential law. The following equation provides the relationship between wind speed, $V_Z$, at an altitude, Z, and the gradient wind speed, $V_g$.

$$V_Z = V_g\ (Z/\ Z_g)^{1/n} \qquad \textbf{Eq. 3-2}$$

The wind speed $V_{10}$ at 10 m above ground can also be derived:

$$V_{10} = V_g\ (10/\ Z_g)^{1/n} \qquad \textbf{Eq. 3-3}$$

Combining both above equations, we have:

$$V_Z = V_{10}\ (Z/10)^{1/n} \qquad \textbf{Eq. 3-4}$$

The flow of wind is influenced by the surface roughness of the ground. The terrain roughness categories are based on the gradient wind theory, where the influence of surface roughness on flow of wind is limited to a given altitude, called gradient height, $V_g$. With higher terrain roughness, the gradient height increases.

The values of 1/n corresponding to various terrain categories are listed in Table 3-1.

**Table 3-1**
**Terrain Categories**

| Terrain Roughness | 1/n |
|---|---|
| A | 0.10 to 0.12 |
| B | 0.16 |
| C | 0.22 |
| D | 0.28 |

where:

A  is large stretch of water upwind, flat coastal areas

B  is open country with very few obstacles such as airports or cultivated fields with few trees or buildings

C  is terrain with numerous small obstacles of low height such as hedges, trees and buildings

D  is suburban areas or terrain with many tall trees

The 500-kV lines on the Henan Power system transverse mostly within the Category B areas.

It is seen from the above equations that wind speed increases with altitude depending on terrain roughness. The increase in wind speed is inversely proportional to roughness. Besides wind speed variation, the gustiness of wind is very important to line design. An indication of gustiness is the ratio of instantaneous wind speeds to average wind during a reference period (such as 10 minute duration). The higher this ratio the more gusty is the wind. Gustiness of wind increases with terrain roughness category, but decreases with height in all terrains.

For a Category B surface roughness, the combined effect of the height and wind gustiness could raise the equivalent wind speed by 10 to 20% for a 60 m span and increases with shorter spans [12]. Due to its shape, the gust factor will have a larger impact on the insulator string.

The wind is further influenced by local conditions as described in the following section.

### *Local Variations of Reference Wind Speed*

The reference wind speed values used in designs as pointed out earlier are representative of a flat, open terrain. Terrain features interact with the wind flow to produce significant changes in the basic wind speed.

Wind is accelerated over small scale features (smaller than about 10 km in horizontal scale) such as hills, ridges, and escarpments. Speed-up due to such terrain can increase wind speed by as much as a factor of 2. The largest increases are usually very localized, being restricted to the tops of such terrain features and can disappear within a range of about 50 to a few hundred metres away from the top of the terrain feature.

Dynamic interactions between the wind flow and larger terrain features such as constrictions in broad valleys, the outflow exit of mountain passes, exposed coastal headlands, and smooth lee slopes of ranges of hills, mountains, and plateaus can result in increases in the basic wind speed over areas extending several kilometres.

It is therefore recommended that Henan Power identifies all locations along the line where flashovers occurred and seek advice from meteorological experts about the effects of local variations on wind speed at these locations. Transmission line maintenance or operations personnel, or others who have relevant local knowledge will also provide valuable information.

### *Weather Loads used in North America*

Weather loadings used in North America are generally classified into three categories, namely: heavy, medium and light load. The combined wind and ice loading for each category is as follows:

- Heavy: 19 mm radial thickness of ice and 400 Pascal ($N/m^2$) of wind at an ambient temperature of -20°C
- Medium: 12.5 mm radial thickness of ice and 400 Pascal ($N/m^2$) of wind at an ambient temperature of -20°C
- Light: 6.5 mm radial thickness of ice and 400 Pascal ($N/m^2$) of wind at an ambient temperature of -20°C

The wind pressure of 400 $N/m^2$ corresponds to steady-state hourly wind velocity of approximately 25 m/s which is the normal maximum wind speed for most of the locations within North America.

In addition to the wind and ice loading, an overhead line must also be able to withstand the extreme ice of 25 mm at -20°C or the extreme wind of 720 Pascal at 35°C. For the northern part of the North American continent, ice is more of a concern than the south where wind could become a dominating factor. A map identifying the category of weather that an area falls under is provided in the standard. This map was prepared based mainly on historical weather records collected at weather stations by the Weather Bureau. The weather loading condition thus provided are intended to be the minimum requirement a utility must meet in the design of its overhead lines. Further refinement can be made by a utility using its local experiences or meteorological studies. The weather loading is used with safety factors, as explained in the next section, in the deterministic design approach to determine the strength requirement of the overhead line components.

The load on conductors shall be that of the ice-covered conductor using the specified radial thickness of ice and density of 900 kg/m3. In the calculation, the coating of ice shall be considered as a hollow cylinder around the conductor's outer circumference.

## *Safety Factors*

In deterministic designs of overhead lines, safety factors are used to cover uncertainties involved in weather loadings as well as uncertainties in material strengths. For steel structures, a typical safety factor of 1.3 is used. Manufactured materials such as steel provide more consistent strengths then natural materials such as wood poles. The following Table from the Canadian Standard C22.3 No. 1 shows safety factors for wood poles at different levels of reliability. For the most reliable lines (Grade 1), the safety factor for the wood pole is 4.0 i.e. the calculated average strength of the pole is designed to be 4 times that of the vertical load imposed by the weather loading for the area. The safety factor in this case covers the variation of strength of the wood pole and deterioration of wood with time. Information on Minimum Load Factors for Steel Structures and Guy Assemblies are also included in Tables 3-2, 3-3 and 3-4.

**Table 3-2**
**Minimum Load Factors for Wood Poles**

| Type of Load | Minimum Load Factor for Wood Poles | | | | | |
|---|---|---|---|---|---|---|
| | When Installed | | | At Time of Replacement[1] | | |
| | Grade 1 | Grade 2 | Grade 3 | Grade 1 | Grade 2 | Grade 3 |
| **Vertical** | 4.0[2] | 2.7[3] | 2.0 | 2.7[3] | 1.3 | 1.0 |
| **Transverse** (including angles) | 2.0 | 1.5[4] | 1.2 | 1.3 | 1.0 | 1.0 |
| **Longitudinal** With terminations or tension changes | 2.0 | 1.5[4] | 1.2 | 1.3 | 1.0 | 1.0 |
| Without terminations or tension changes | 1.3 | — | — | 1.0 | — | — |

[1]When the "at time of replacement" values are reached, the structure shall be replaced.
[2]May be reduced to 2.0 if effects of buckling are taken into account.
[3]May be reduced to 1.5 if effects of buckling are taken into account.
[4]May be reduced to 1.3 if effects of "p-delta" are taken into account.

**Table 3-3**
**Minimum Load Factors for Metal Structures and Towers**

| Type of Load | Minimum Load Factor for Metal Structures and Towers | |
|---|---|---|
| | Grade 1 | Grades 2 and 3 |
| **Vertical** | 1.30 | 1.15 |
| **Transverse** (including angles) | 1.25 | 1.10 |
| **Longitudinal** With terminations or tension changes | 1.65 | 1.25 |
| Without terminations or tension changes | 1.10 | – |

**Table 3-4**
**Minimum Load Factors for Guy Assemblies at Installation**

| Type of Load | Minimum Load Factor for Guy Assemblies at Installation | | |
|---|---|---|---|
| | Grade 1 | Grade 2 | Grade 3 |
| **Transverse** (including angles) | 1.6 | 1.25 | 1.0 |
| **Longitudinal** With terminations or tension changes | 1.6 | 1.25 | 1.0 |
| Without terminations or tension changes | 1.0 | – | – |

## *Reliability-Based Design*

In deterministic designs as described above, average values of material strength and weather loading are used along with a safety factor. Deterministic designs of overhead lines could provide a false sense of security even if a large factor of safety is used if there is a large variation in the strength of material and weather from the average values. In recent years, designs of overhead lines in North America are moving towards the reliability-based approach. For reliability- based designs, both the weather event and material strength are associated with a probability of attaining that value. Therefore, the probability of load exceeding the strength of the material can be calculated and the failure rate determined. However, reliability-based designs require extensive data on weather and material strength.

The reliability-based method is recommended for lines that are in areas where significant amounts of meteorological data are readily available. This method may also be used for lines designed to specific climatic loads, either derived from experience or through calibration with existing lines that had a long history of satisfactory performance.

In reliability-based designs, a transmission line is considered as a system composing of a series of components where the failure of any major component usually leads to the failure of the complete line. Therefore, the strength of components within the system is coordinated and adjusted to achieve a desired sequence of failure to optimize the overall economic and technical performance of the system.

The following provides a brief description of the methodology of reliability-based designs. It is meant to be an introduction rather than a comprehensive explanation for the subject. Understanding the methodology will enable a utility to collect proper data.

### Statistical Variation of Strength

The strength of a material or a component is a random variable which can be described by appropriate probability density functions, usually a Normal or Log-normal distribution. The Normal (Gaussian) distribution is appropriate for most ductile material, while the Log-normal is more typical of brittle material and those subjected to stringent quality control.

Although variable, strength of material is usually defined by a single value, extracted from its distribution function and designated as the characteristic strength, $R_c$. This value usually corresponds to a low exclusion limit, typically 2 to 10%. $R_c$ is either defined in component standards such as for insulator, hardware, lattice tower or conductors, or can be obtained from strength prediction equations, or through statistical testing of a large number of components, for example, foundations. The characteristic strength is sometimes called the guaranteed, minimum, or nominal strength.

If statistical data about strength is available, the 10% strength exclusion limit can be calculated from the mean and standard deviation of the strength distribution using Equations 3-5 and 3-6:

$$COV = \sigma_R / \bar{R}$$ **Eq. 3-5**

$$R_{10\%} = \bar{R} \times (1 - k \times COV)$$ **Eq. 3-6**

where:

| | | |
|---|---|---|
| $\overline{R}$ | = | mean strength, |
| $R_{10\%}$ | = | strength corresponding to a 10% exclusion limit, |
| COV | = | coefficient of variation |
| $\sigma_R$ | = | standard deviation of the strength, |
| $k$ | = | statistical factor (= 1.28, for Normal distributions) |

In the absence of statistical data, the characteristic strength $R_c$ can be assumed to have a 10% exclusion limit. If it is known that the exclusion limit of the characteristic strength, $R_c$, of the component is higher than 10% (for example 20%), this strength shall be reduced by an appropriate factor.

## Weather Load Level

The impact of extreme weathers on an overhead line could be detrimental to the power system. Fortunately, extreme weathers do not occur frequently. The frequency of occurrence of certain weather is defined by the return period. The return period is the average time elapsed between occurrences of an event. A wind speed with a 100 year return period will occur on average once every 100 years. It will not necessarily be reached or exceeded in every 100-year interval. On the other hand, it may occur more than once in the same interval.

The probability an event having a return period T to occur in a given year is equal to 1/T, thus the yearly probability of a "100 year wind" is 1%, and that of a 25 year ice load is 4%. If the yearly probability of occurrence $P_O$ of an event with a return period T is 1/T, the probability $P_U$ of this event not being exceeded in a year is given by Equation 3-7:

$$P_U = 1 - P_O = (1 - 1/T)$$ **Eq. 3-7**

and in n years:

$$P_{U_n} (P_U \text{ in n years}) = (1 - 1/T)^n$$ **Eq. 3-8**

Thus the probability, $P_{O_n}$, that a weather event with a return period T will be exceeded at least once within the length of the service life of the line n years, is given by Equation 3-9:

$$P_{O_n} = 1 - P_{U_n} = 1 - (1 - 1/T)^n \qquad \textbf{Eq. 3-9}$$

While the probability $P_{O_n}$ is a useful indicator of load occurrence, it does not correspond directly to the probability of failure of the transmission line, because failure is a combination of load events magnitude exceeding strength and thus cannot be derived on the basis of load magnitude alone. However, the increase in return period of design loads can be used to increase line reliability. Alternatively, reliability can also be increased by associating a given load with a lower exclusion limit of strength.

Lines designed to the reference reliability level of 50 year-return period weather event combined with a 10% exclusion limit of strength provide an acceptable reliability level to ensure continuity of service and safety. A higher reliability can be justified by the importance of the line in the network or system reliability considerations. For temporary lines and some wood pole lines, return periods of 25 years may be adequate.

## Load and Strength Equation

The general load-strength relationship for weather loads on an overhead line is given in Equation 3-10:

$$\textit{effect of loads } Q \le \varphi \times \textit{strength } R_c \qquad \textbf{Eq. 3-10}$$

where:

$Q$ = loads imposed by weather

$\varphi$ = strength factor, applied to characteristic strength to take various design aspects into account as described below

$R_c$ = the characteristic strength corresponding to either the damage limit or to the failure limit as defined by the application

**Strength Factor:** A strength factor, $\varphi$, is applied to the characteristic strength to take into account various design aspects. One of the key factors, $\varphi_s$, is related to the strength coordination between components. This factor, less than or equal to one, is applied to the characteristic strength of the components desired to be more reliable, while the component to fail first is assigned a $\varphi_s$ factor of 1.0. Other strength factors may need to be applied to the characteristic strength when the following conditions exist:

- The number of components subjected to the maximum load intensity is greater than one e.g. a series of insulators in a string or
- The strength of the component is obtained from tests that are not fully representative of actual line construction. In this case the factor is designated $\varphi_Q$ and is typically 0.9 to 0.95 depending on how closely the tests represent actual line construction.

## Reliability Calculation

The overhead line is considered reliable when its strength is greater than effect of applied loads. Since load and strength are random variables, there is, theoretically, always a probability that a given load event occurs with such a magnitude that it exceeds the strength of line components. Thus, however strong a line is designed and built, its risk of failure is never nil, and reliability based methods are the most appropriate tools to target a level of risk, economical to utilities and acceptable for service continuity.

Reliability based methods allow designers to focus on data collection to which design is the most sensitive in order to improve line design and achieve target reliability levels, compatible with service continuity and minimum safety requirements.

Load $Q$ and strength $R$ of transmission lines are random variables having specific distribution functions. Through past technical studies, it was recognized that ice and wind variables may be represented by an extreme type I function (Gumbel) while strengths of transmission line components generally follow the Normal or log-Normal functions.

When statistical parameters of load and strength are known, it is possible to calculate, or estimate, the yearly reliability or probability of survival, $P_S$, through analytical models or approximate methods. In Equation 3-11, $F_R$ and $F_Q$ are defined as the cumulative distribution functions of $R$ and $Q$ while $f_R$ and $f_Q$ are the probability density functions of the same variables.

$$P_S = P_{(R-Q>0)} = \int_0^{+\infty} f_Q(x) \times F_R(x)\,dx \qquad \textbf{Eq. 3-11}$$

Equation 3-11 gives the exact value of $P_S$ if curves $R$ and $Q$ are known.

## Possible Effects of Air Pollution and Airborne Contaminants

Pollution in the air has little effect on the strength of the air gap, unless large conductive particles are present in the air gap. Examples of large conductive particles ("electrically floating objects") that could affect the strength of an air gap include:

- Wire or other metallic particles carried by wind or birds,
- Balloons, particularly metalized balloons released near lines,
- Bird droppings,
- Large birds in the conductor-phase or phase-to-phase air gaps,
- Smoke and soot, although this tends to affect insulators first

## Data on Results of Wind Tunnel Tests on Structures, If Any

We are not aware of wind tunnel tests to determine dielectric strength of air gaps under power frequency conditions. Such tests are possible but are very complicated and expensive. Recently, there were studies performed on the effect of wind and turbulence on flashover of insulators and live working tools under steady-state AC energization and light contamination, and under DC energization, as discussed in the previous Section.

## Recommendations for Research and Tests on Full-Scale Structures

It is recommended to conduct laboratory tests on full-scale models of structures involved in the flashovers. Normally, electrical (flashover) tests are not preformed on structures installed in the field because such tests would be very expensive – large test equipment needs to be brought in, including power supplies, good grounding systems, etc.

Normally, electrical tests are performed in high voltage laboratories before structure design is completed. Structures are analyzed and "worst cases" are selected. Full-scale replicas of the selected structures are built, concentrating on the essential portions of each structure. Tests are performed and results are fed back into the design cycle.

## Mitigation Measures

Several mitigation approaches are possible to reduce the unacceptable outage rate, but the root cause(s) of the problem must first be determined.

Some general approaches include:

- Making appropriate changes to structure geometry details to change the “Gap Factor” (see discussions of the Gap Factor in the previous Section). This approach is usually relatively inexpensive and is suitable for retrofitting exiting structures. However, it normally results in small improvements and is considered a secondary measure.
- Increasing clearances. This may require extensive structure modification and is usually expensive as a retrofit measure for existing structures. Review of the mechanical and structural design of the structures should be conducted.
- Controlling insulator swing. This may require addition of insulators and would require mechanical loading analysis of structures, and possibly structure modifications. In some cases, restraining insulator swing can allow reduction of phase-to-structure distances, however, electrical performance of the line should be reviewed in such cases.

# 4
# GENERAL OBSERVATIONS AND RECOMMENDATIONS

Analysis of the information provided by Henan Power on outages on the 500-kV lines led to several important observations and recommendations for fundamental research. The observations and recommendations are summarized below.

## Observations

The large spread in sparkover AC voltage values presented in Section 2 indicates that the details of the energized and grounded electrodes are very important and can significantly affect the sparkover performance of the gap. For this reason, it is very difficult to estimate the AC sparkover voltage of a conductor-structure air gap without detailed analysis of the configuration and electrode shapes.

However, the very large difference between the expected electrical stress (318 $kV_{rms}$) imparted in the conductor-structure air gap, compared with the expected sparkover voltage (632 $kV_{rms}$) of any type of air gap 1.2 m in length, suggest that outages should not occur under usual conditions.

The inescapable conclusion, therefore, is that **either** the air gap is in fact considerably shorter than 1.2 m, **or** severe atmospheric conditions reduce the sparkover voltage of the gap very significantly.

Considerable literature search was conducted to identify useful data in other areas of research. Unfortunately, the information obtained through the literature search does not apply directly to the Henan Power outages. Still, some interesting observations were found and are listed in Section 2. They point to possible unexpectedly large reductions in the sparkover voltage of air gaps.

Hence, there is a significant body of evidence to suggest that strong wind and high humidity can have unusual effects on sparkover of air gaps. Much more research and testing, however, needs to be conducted to quantify the effects and understand the phenomenon in detail.

Several mitigation approaches are possible to reduce the unacceptable outage rate, and some approaches were listed in Section 2. However, the root cause(s) of the problem must first be determined.

## Recommendations for Further Research

The possibility that strong winds can lead to significant reduction of the gap sparkover voltage should be investigated in detail. It is recommended that special tests be set up first on small scale models, and then followed by larger more realistic models to investigate the effects of very strong winds on air gap sparkover. The test setup will have to include a strong wind generator (large air fans) and a high voltage supply, suitably insulated for the test voltage. For these reasons, the test setup is expected to be of large dimensions, and it may be prudent to start with small-scale tests first

Effects of severe atmospheric conditions on sparkover behavior of air gaps are not well understood and should be investigated. Existing test setup in the UHV test chamber for insulators, see Figure 2-5, at the EPRI-Lenox laboratory can be used for this purpose. The chamber has dimensions of 24 m diameter and 24 m high, has a wall bushing rated for 800-kV class and has standard rain spray systems that are capable of producing heavy rain conditions.

# 5
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# A
# ADDITIONAL PHOTOGRAPHS PROVIDED BY HENAN POWER

Note: All figure graphics/photographs provided courtesy of Henan Power.


**Figure A-1**
**Evidence of a Sparkover (Burn Mark) on a Steel Lattice Member**


**Figure A-2**
**Evidence of a Sparkover (Burn Mark) on a Steel Lattice Member**

**Figure A-3**
**Evidence of a Sparkover (Burn Mark) on a Steel Lattice Member**


**Figure A-4**
**Evidence of a Sparkover (Burn Mark) on a Steel Lattice Member**


**Figure A-5**
**Evidence of a Sparkover (Burn Mark) on a Steel Lattice Member**


**Figure A-6**
**Evidence of a Sparkover (Burn Mark) on a Steel Lattice Member**


**Figure A-7**
**Evidence of a Sparkover (Burn Mark) on a Steel Lattice Member**

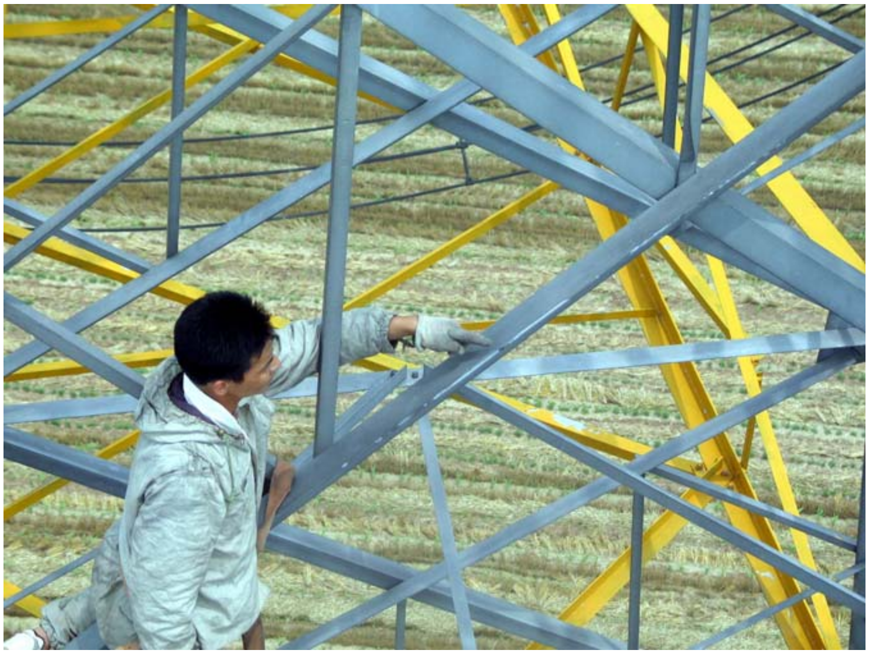

**Figure A-8**
**Evidence of a Sparkover (Burn Mark) on a Conductor**

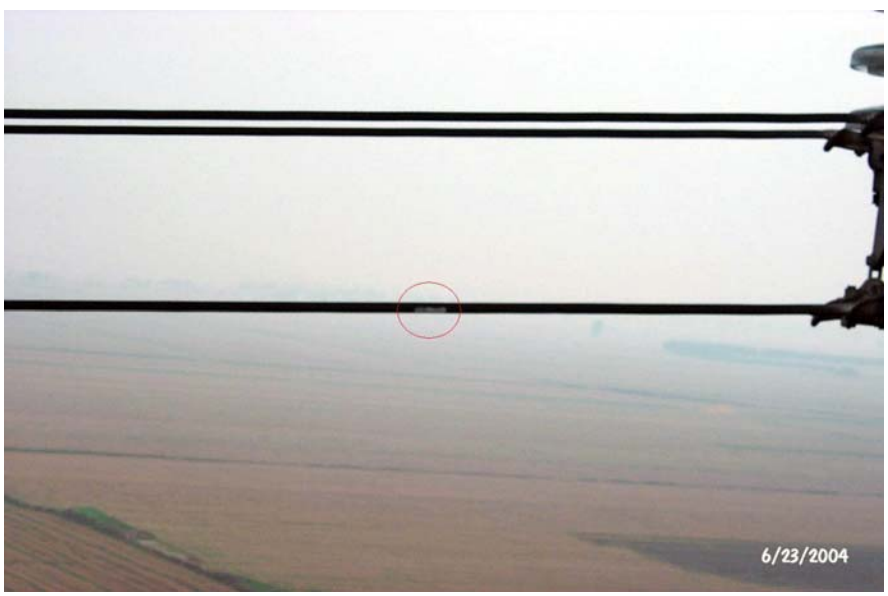


**Figure A-9**
**Evidence of a Sparkover (Burn Mark) on a Conductor**

**Figure A-10**
**Evidence of a Sparkover (Burn Mark) on Conductor Hardware**

**Figure A-11**
**Evidence of a Sparkover (Burn Mark) on Conductor Hardware**

**Figure A-12**
**Evidence of a Sparkover (Burn Mark) on Conductor Hardware**

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