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Energy Division

Assess the Impact of the Steep-Front, Short Duration Impulse on Electric Power System Insulation

Phase I Final Report

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POWER SYSTEMS TECHNOLOGY PROGRAM

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Energy Division

ASSESS THE IMPACT OF THE STEEP-FRONT, SHORT DURATION IMPULSE ON ELECTRIC POWER SYSTEM INSULATION
PHASE I
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ABSTRACT

Concern has been exhibited by the Department of Energy (DOE), utility companies, and manufacturers of electrical power apparatus with respect to the dielectric integrity of today's power systems and power system components when subjected to steep front, short duration (SFSD) impulse. Impulses of this type are characterized by voltage rise times of 10-250 ns and durations to several us. A review of the literature on SFSD impulse and its associated impact on the insulating systems used in power system apparatus was completed and an extensive bibliographic data base with some 400 entries on SFSD impulse including the characteristics, the sources, and the known or suspected impact on insulation systems was prepared. The bibliography itself is available as a separate report.

SFSD impulse was found to be the result of several sources including both lightning and nuclear electromagnetic pulse (EMP) and may contribute to the so called anomalous behavior or failure of electrical apparatus. The insulation systems used in power systems apparatus were ranked with respect to vulnerability to SFSD impulse. The power insulating systems believed to be at greatest risk are the porcelain/air structural insulation (line insulation) and the paper/oil/enamel systems (transformers). Events reported in the open literature as anomalous behavior or failure were cataloged and characterized. Since both theoretical and experimental information are lacking and much of the information available is speculative in nature, additional work is needed in the area of insulation and insulation system response under SFSD impulse. An outline of a program for research to determine insulation system response to SFSD impulse and to develope appropriate models was defined.

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Extensive use was made of information in electronic data bases accessed principally through Dialog Information Services, Inc., Palo Alto, California. Data bases used extensively were:

INSPEC - Information Division of the Institution of Electrical Engineers, England

NTIS	- National Technical Information Service
COMPENDEX	- Engineering Index, Inc.
DOE ENERGY	- Department of Energy
ELECTRIC POWER	- Electric Power Research Institute
GEOREF	- American Geological Institute

Additional data base resources were accessed with the assistance of the New England Research Application Center (NERAC), Storrs, Connecticut.

EXECUTIVE SUMMARY

This report summarizes the Phase I effort on the project "Assess the Impact of the Steep Front, Short Duration Impulse on Electric Power System Insulation", executed for the Oak Ridge National Laboratory under subcontract 11X-28611C.

This effort, the first phase of an anticipated two phase project, considered the dielectric behavior of insulants and insulation systems when exposed to impulses having wave fronts of 10-100 nanoseconds risetime and durations of a microsecond or less.

The overall objectives of Phase I were:

1. Determination and documentation of the state-of-the-art.

2. Identification of areas needing theoretical and/or experimental work.

3. Identification of appropriate models and experiments for evaluation in the second phase effort.

An extensive literature search, conducted, compiled and submitted to ORNL as a separate document, provided the basis for meeting the above objectives.

Expertise provided by the project team and by others in the electric power community was solicited to further aid in the determinations.

The major findings of this effort are:

1. The insulation systems utilized within electric power apparatus may be damaged or destroyed by steep front short duration impulses.

2. The probability and/or susceptibility of the insulation systems to such damage is not known and must be determined.

3. The ability of electric system's structural insulation, typified by air/porcelain, to withstand steep front short duration impulses is not known and must be determined.

4. From an electric power delivery point of view, the transformer is deemed to be the critical component at risk from the steep front short duration impulse. This is due to its very long replacement time and high cost.

5. The major insulation systems most at risk are those used in transformers and are the oil/cellulose paper system and the oil/enamel/paper system.

6. An understanding of the underlying physical phenomena involved in steep front impulse breakdown is not well defined and should be determined.

7. Modeling and experimental approaches for a Phase II effort are identified.

An investigative program is proposed which addresses the need and methods of execution for fundamental insulation system studies, modeling and low voltage experimentation. It is believed that this effort will provide a firm basis for the extrapolation of insulation system behavior to macromodels and distribution class apparatus, as the first priority. Confirmation of this expected behavior is required in order to further extrapolate to power class equipment, and to verify the performance of distribution class apparatus.

Not included in this program is the verification of the insulation system response of transmission class apparatus to the steep front short duration impulse. At this time it is believed that the cost of such verification outweighs the expected benefit.

The execution of this investigative program will yield some measurement of the vulnerability of power system components, especially transformers, exposed to steep front short duration pulses. The attainment of a better understanding of the basic phenomena involved can provide a firm foundation for the specification of protective procedures and devices if required. In addition, direction for the development of new improved insulating systems may result.

ABBREVIATIONS

AFWL	- Air Force Weapons Laboratory
ANS	- American National Standards Institute
ASTM	- American Society for Testing and Materials
AWRE	- Atomic Weapons Research Establishment
BIL	- Basic Insulation Level
CIGRE	- International Conference on Large High Voltage Electric Systems
DNA	- Defence Nuclear Agency
DOE	- Department of Energy
EI	- Electrical Insulation
EMP	- Electromagnetic Pulse
HEMP	- High Altitude Electromagnetic Pulse
IEC	- International Electrotechnical Commission
IEE	- Institution of Electrical Engineers
IEEE	- Institute of Electrical & Electronic Engineers
LEMP	- Lighting Electromagnetic Pulse
MHD-EMP	- Magnetohydrodynamic Electromagnetic Pulse
us	- Microsecond
NEMA	- National Electrical Manufacturers Association
NEMP	- Nuclear Electromagnetic Pulse
ns	- Nanosecond
ORNL	- Oak Ridge National Laboratory
PES	- Power Engineering Society
SFSD	- Steep-Front Short-Duration Pulse
SREMP	- Source Region Electromagnetic Pulse

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INTRODUCTION

The Office of Energy Storage and Distribution of the United States Department of Energy has formulated a program for the research and development of technologies and systems for the assessment, operation and control of electric power systems when exposed to the electromagnetic pulse. A section of that program is identified as Insulation Damage Study under which designation the current work was executed.

Examination of dielectric behavior under steep front (ns rise time), short duration pulses (up to 1 us) is just beginning. Interest in this area has been enhanced by the increased use of hydrocarbon insulation, some observed breakdown under certain conditions of pre-stress [1] and the postulated failure of transformers under fast surges [2]. While it is difficult to predict the response of a single insulating material under steep front, short duration pulses, breakdown would seem to be possible for pulses of adequate duration and intensity. Experimental data is needed to further quantify this behavior.

Clayton [2] and others have postulated that the delayed or anomalous failure of transformers may also be initiated by the steep front, short duration pulse. Consider a mixture of liquid and solid insulation, as found in transformers, and assume that a steep front pulse of adequate duration breaks down the liquid but only damages the solid. Such a damaged system might later fail under less than design conditions.

What are the sources of such steep front, short duration pulses? The multiple stroke lightning impulse is perhaps the most likely source. However, the back-flashover of lightning to tower or shield wire is also capable of producing such effects [2]. The currents induced by the nuclear electromagnetic pulse (NEMP) also have rise times of tens of nanoseconds and are capable of generating kiloamp currents of several microseconds duration [3,4,5].

The above effects have been discussed as potential problem areas for many years; however, the techniques and experimental apparatus necessary for examining these questions in detail were not readily available to the electric power industry. This work will attempt to answer some of these questions.

One method of attacking the experimental problem would be the testing of several insulation types starting from a known standard, such as the 1.2/50 us impulse used for lightning, and perform a series of tests using a steeper impulse and/or shorter duration.

Phase I of this effort includes an extensive literature search to determine what is known about the interaction of the Steep Front Short Duration (SFSD) impulse with electric power insulation systems. Included is the identification of perceived dielectric problem areas for power systems and apparatus. This is followed by the characterization of the problem of insulation response and the identification of models and proposed experiments to explain the perceived response.

Phase II is expected to: 1) undertake the experimental validation of the models proposed in Phase I; 2) develop

methods to statistically predict the insulation systems' response observed in the experiments; 3) correlate delayed/anomalous failures of apparatus in the field with the experimental findings; 4) provide direction for possible future insulation system development; and 5) suggest enhanced protection methods.

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I. A CHARACTERIZATION OF THE PROBLEM

1.0 INTRODUCTION

An increasing concern has been exhibited by the Department of Energy (DOE), utility companies, and manufacturers of electrical power apparatus with respect to the dielectric integrity of today's power systems and insulating components in the presence of Steep Front, Short Duration (SFSD) voltage impulses. Impulses of this type are characterized by their rise times of 10-250 nanoseconds and durations extending up to several microseconds. They can occur as single impulses or be repetitive in nature, and may contribute to the anomalous dielectric failures in electrical apparatus, typically distribution and power transformers, transmission cables, rotating machines and electronic controls.

Recent efforts by DOE and others have emphasized the effects brought on by steep fronted electromagnetic waves induced by thermonuclear explosions (EMP) on electrical systems and their associated insulating structures. Other sources of SFSD impulses however, have been identified as having similar, but not as widespread, damaging effects on apparatus of a power system. These include multi-stroke lightning impulses, insulation backflashes associated with lightning, circuit breaker restrikes, switching surges and cable dielectric breakdown.

A comprehensive review of the literature on steep fronted impulses has resulted in the recent completion of a

bibliography report [1] in accordance with the requirements of Task I of this project. Two major areas of interest surfaced as a result of the report. The first centered on the characteristics of power system apparatus subjected to various types of SFSD impulses while the second focused on the measured dielectric response of components comprising these systems, i.e. gases, liquids, and solid materials. Typical insulations, utilized either singly or as composites in power system apparatus, include air, nitrogen, SF_6, porcelain, oil, cellulose, wood and resins in many combinations. There were remarkably few references uncovered in the search pertaining to the interactions between the system structural insulation, primarily porcelain, in any of many forms and configurations, and SFSD impulses.

It was apparent from the existing literature that very little is known regarding the mechanisms controlling the breakdown response of these relatively impure materials, particularly for insulating systems involving composites. Unlike studies conducted on "pure" materials, the development of theoretical models based on a mechanistic understanding would under these circumstances appear to be an impractical approach.

2.0 THE ORIGIN AND CHARACTERISTICS OF SFSD IMPULSES

Prior to the literature search performed by this study, the following had been identified [2] as primary sources of steep front impulses on power systems:

- Atmospheric discharges - single and multi-stroke lightning.
- Electromagnetic Pulses (HEMP, SREMP, MHD-EMP, or collectively NEMP).
- System generated transients - circuit breaker restrikes and multiple reignitions, short circuit faults and cable dielectric breakdown.

The typical characteristics of impulses generated from the above sources are compared in Table I, condensing information covered in more detail in Section II pages 21-23.

Table I

Characteristics of SFSD Impulse Sources

Typical Values

	Lightning	EMP Plane Waveform	System Generated
Field Strength			
Electric:E	<40 kV/m	<50 kV/m	<10 kV/m
Magnetic:H	<300 A/m	<1000 A/m	<300 A/m
Impulse Shape			
Risetime	20-500 ns	<10 ns	<10 ns
Time to half value	5-20 us	10-200 ns	1-5 us
Type of Impulses	single, repetitive	single, repetitive	single, chopped oscillatory
Peak Current	<200 kA	10 kA	--
Peak Voltage	--	<2000 kV	2-3X System Voltage
Pulse Durations	10-1000 us	1 us	1-10 us

3.0 POWER SYSTEM VULNERABILITY

Steep fronted impulses have for years presented special problems for electrical equipment designers and utility engineers in their efforts to provide overvoltage protection to apparatus and the power system as a whole. Numerous accounts are given, particularly in unpublished reports, of anomalous failures in the field. The damage reported in many cases is a dielectric failure in a winding (e.g. in large transformers and generators) associated with either a violent lightning storm or the operation of a circuit interrupting device such as a vacuum or gas insulated switch. Often, surge arresters providing overvoltage protection to the failed windings show no evidence of failure. It is a well established fact that large power transformers are often, by design, over insulated as much as 15% in order to avoid field repair/ replacement costs and to offset the lack of understanding of surge voltage distributions and reflections from steep fronted impulses. Information gleaned from a number of unpublished reports indicating field failures associated with steep fronted waves, provided a means to assess and thereby rank power apparatus as to susceptibility to damage (Table II).

Table II

System/Apparatus Vulnerability

	Damage	Repair/Replacement
	in order of decreasing susceptibility	in order of increasing difficulty/ cost
Electronic Controls	↓	↓
Cables		
Distribution Transformers		
Line Insulation, Porcelain Support Structure		
Power Transformers		
Generators		

Apparatus identified as being most at risk are in general not protected, e.g. by surge arresters. Those classified as being most susceptible to damage are seen as the least difficult in general to repair or replace. Despite the fact that power transformers are ranked (Table II) less susceptible to damage (based primarily on the 1 us rise time surge protection provided), their complexity, high repair/replacement cost and critical role in the power system makes any failure a catastrophic event to a utility company. The numerous anomalous failures of power transformers in the field are not only a cause of concern but provide the motivation for efforts to understand the effect of the more steep fronted impulses on these devices.

4.0 PRESENT ASSESSMENT OF THE IMPACT OF SFSD IMPULSES ON POWER APPARATUS AND INSULATION

Although a current concern is the vulnerability and integrity of power system apparatus subjected to SFSD waves induced by HEMP sources, there is increasing attention being given to the damaging effect on apparatus from transients generated from within the power system itself [4-12]. A number of published studies have sought to elucidate the response of apparatus to system generated transients by direct measurement techniques while others have attempted to characterize their response by modeling the insulating components near the switching device causing the disturbance. A majority of more recent accounts have centered on determining the surge response of large power plant generating machines through voltage distribution measurements within the insulating windings. The reports indicate it is not uncommon to find an enhancement of the surge voltage amplitudes well within the windings. Although similar measurements on large transformers have been made, these have been reported in only a few cases [13-14]. Information on the voltage-time characteristics and withstand capability of transformers using fast front surges in the submicrosecond region are almost non-existent.

A substantial body of information is available in the open literature characterizing power system insulation under lightning impulse conditions. Power apparatus has long been tested with conventional impulse generators used to produce the standard 1.2/50 us impulse wave as well as in some cases waves having front times in the vicinity of 200 nanoseconds. Conventional generators, on the other hand, are often unable to produce high rise time impulses when

coupled to test circuits having substantial loop inductances. Therefore, more recently, stripline generators and pulse-forming lines have emerged as sources for generating nanosecond pulses in the laboratory in order to characterize the response of dielectric materials. Caution must be taken in testing with fast fronted waves since wave propagation effects (e.g. the surge propagation characteristics of a transformer bushing) can substantially alter results. Efforts have therefore been made to characterize not only the whole apparatus but to base conclusions on test results obtained from representative dielectric structures identified as critical as well.

5.0 MODELING APPROACH

A modeling approach can provide a means toward the understanding the dielectric breakdown response of insulating materials/systems subjected to impulse conditions. The majority of published papers reviewed on the subject center on experimental studies with oil and cellulose insulation and its' response to AC and fast rise time impulses. The investigations focus on the partial discharge inception and breakdown voltage-time characteristics of models comprising both oil and cellulose in various structural configurations. The models, for the most part, represent critical insulating areas within oil-filled transformers such as turn-turn and section-section insulating subassemblies, and oil-duct sections constructed with pressboard barriers and spacers. The results reported extend over a time range from several microseconds, corresponding to lightning impulses, to as long as 10 hours for 60 Hz conditions. Very little information is available in the public domain describing the breakdown voltage/time characteristics of oil-cellulose composites and interfaces subjected to SFSD impulses in the nanosecond range. This is perhaps due to the difficulties previously discussed with regards to generating and recording fast rise time voltage events in the laboratory, or, as may be the case, the experimental problems associated with breakdown testing solids, such as paper and pressboard. Unlike gases and liquids, the non-self healing nature of these solid materials creates a need to perform a large number of tests in order to insure a reasonable degree of confidence in the results.

The most significant findings reported by investigators attempting to model and characterize the breakdown behavior

of transformer (oil-cellulose) insulation may be summarized as follows.

- The breakdown voltage depends on geometry (area or volume) and experimental configuration [15-21].

- The electric strength of oil gaps with layered paper overwrapping the electrodes, particularly when the paper is well impregnated is enhanced [18, 20, 21].

- The breakdown voltage for oil gaps utilizing pressboard spacers is reduced [20,21].

- The breakdown voltage for oil gaps utilizing pressboard spacers is highly sensitive to contaminants in the oil, such as water and cellulose particles [16].

- The reduction in breakdown sensitivity of oil immersed cellulose specimens tested under impulse testing as opposed to testing under power frequency conditions [20].

An adequate mechanistic description of the breakdown behavior of cellulose oil immersed insulating structures tested under impulse conditions has not emerged. Any attempt to develop a theoretical model to describe the breakdown processes may well be a formidable task. The oil/cellulose materials utilized in the construction of power apparatus are for the most part, impure, complex in nature and poorly understood even in the case of their response to AC voltage breakdown conditions. The breakdown mechanisms involved during the application of conventional lightning surges (typically 1 us) will in all likelihood

be governed by a number of factors. During the application of SFSD impulses, e.g. 10 ns to 200 ns rise time, the fundamental mechanisms and governing factors involved may be entirely different. The elucidations of these mechanisms requires sophisticated diagnostic methods for observing pre-breakdown events such as high speed Schlieren photography, Kerr effect measurements to determine precise electric field profiles, image intensifier techniques to record pre-breakdown light emissions, and acoustic emission detection of partial discharges. An important consideration is whether, within the time frame for Phase II work, sufficient information could be obtained utilizing these techniques to establish the breakdown processes in force and thereby form the basis for a theoretical model. An alternate approach may be to develop a theoretical model representing the response of a transformer to a fast fronted impulse through the application of electromagnetic and transmission line theory, use of winding parameters and computer assisted analysis. The verification of the model could be made by comparing predicted locations of highest dielectric stress with results of internal voltage distribution measurements.

6.0 REFERENCES

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II. LITERATURE SEARCH AND BIBLIOGRAPHY

1.0 INTRODUCTION AND SUMMARY

In the initial task of this project, an extensive literature search was performed to determine the extent of prior work in the general area of steep front short duration impulses and their interaction with electric power systems and apparatus insulations. For the purposes of this project, the steep front short duration (SFSD) impulse is defined as having a time to crest of 500 nanoseconds or less, and durations, identified as time to half crest on the tail, of 2 microseconds or less. The phenomena involving the SFSD impulse and insulation systems was compared with that of the standard lightning impulse wave shape, 1.2x50 microseconds. A significant body of literature based on the standard lightning impulse wave has been accumulated over many years. Virtually all of the germane SFSD impulse literature has been generated in the last 25 years with a very small amount being published in the early 1940's.

The availability of instrumentation capable of detecting and measuring the nanosecond and subnanosecond risetimes of these SFSD impulses has led to further investigation into the characterization of lightning impulses and other high-speed, undesirable transients on power systems. The anomalous failure of certain electric power apparatus has been attributed to these higher speed transients.

This literature search included: Experimental data and reports of experiments relevant to this project;

theoretical or statistical models of insulation response to SFSD impulses; anomalous insulation failures attributable to SFSD impulses; and theoretical and experimental investigations of insulation mixtures.

All the literature reviewed consisted of documents in the public domain, which includes published reports not having widespread circulation, technical notes, proprietary records and reports, deliberations of industry technical committees and personal notes. Published industry standards as well as several in the proposal stage were also consulted.

The time period covered was from 1960 to July, 1985. Some earlier references dated from the 1930-1960 period were also consulted.

The sources of steep-front, short-duration impulses, representative wave shapes, insulation and insulation systems, literature sources, bibliography format and directions for use of the bibliography are covered in detail.

1.1 Conclusions

Based upon this literature search, it is the opinion of the researchers on this project that the transformer is the critical piece of electrical apparatus on transmission and distribution systems having exposure to and likelihood of damage from the steep front short duration impulse. This is due to the important role played by the transformer in electric power systems coupled with long replacement times and high cost.

2.0 SOURCES OF STEEP FRONT SHORT DURATION IMPULSES

As a result of the literature search performed in this task, the following sources of steep short duration impulses have been identified:

- The most frequently cited source of impulses appearing on the electric power system is lightning. Recent advances in the state-of-the-art in instrumentation and its more widespread application to the measurement of lightning phenomena have made it possible to detect and measure higher frequency components of the lightning waves, yielding rise times in the order of 40 nanoseconds and crest currents of 200,000 amps.

- Overvoltages on power systems caused by lightning and/or switching surges have caused flashover of air/porcelain insulation resulting in fast fronted transients appearing on the system.

- Switching operations on unloaded circuits have caused bushing failures on GIS systems. Suspect is the SFSD impulse.

- Restrikes occurring during the normal operation of air break switches are a known source of overvoltages which can cause insulation damage and resulting failure.

- Reignitions associated with the operation of vacuum interrupters/circuit breakers and the like may have repetitive quasi-triangular waveforms with typically 30 microsecond rise times and 10 nanosecond fall times.

- Current forcing phenomena in 3-phase vacuum circuit breakers is produced by an abnormally early current zero, a current chop, in one phase of the circuit breaker that causes the other two phases to reach an early zero current.

- Current chopping phenomena, (abrupt cessation of current flow), occur in all switching devices to a degree. This is commonly associated with vacuum interrupters because of the short deionization time of the plasma contained therein.

- High altitude electromagnetic pulses (HEMP) associated with nuclear explosions above the earth's atmosphere.

- Traveling waves and reflected waves in cable systems.

- Failure of cable insulation resulting in a cable fault can produce SFSD impulses.

- Impulse testing, particularly chopped wave impulse testing in the laboratory and/or on the manufacturer's assembly/test floor.

3.0 WAVE SHAPES

The wave shapes associated with the above transients can be identified as falling into one of the following three categories:

- o 1.2 x 50 microseconds
- o 100 x 500 nanoseconds
- o 10 x 300 $\pm$ 200 nanoseconds

The above wave shape designations are to be interpreted as the virtual time to crest and the time to half crest on the tail.

The first of these waves is that commonly used in industry-wide impulse testing to determine the Basic Insulation Level (BIL) of the apparatus.

The second wave is representative of faster system transients and hypothesized slower NEMP waves resulting from NEMP coupling to conductors.

The third wave, characteristic of a NEMP free field waveform, is also representative of the fastest transients on the systems. It is associated with insulation failure attributable to lightning arrester return strokes and switching transients particularly in GIS systems and back flashovers.

Current amplitudes and voltage amplitudes of these waves are not herein identified. These amplitudes have a wide range dependent upon the specific type, class and application of the apparatus and systems.

4.0 INSULATION AND INSULATION SYSTEMS

Power system and apparatus insulation systems in use on the nation's electric power network include: air, nitrogen, sulfur hexaflouride, porcelain, oil, cellulose, wood and resins in many combinations. Specific applications of insulants are listed below.

References searched and cited in the bibliography included the following materials and systems in conjunction with the steep front short duration impulses.

4.1 Transformers

Oil/Oil-Paper/Pressboard/Porcelain/Air-Nitrogen
Silicone Oil/Paper/Porcelain
Freon(s)/Paper/Porcelain
Sulfur Hexaflouride/Polyimide/Porcelain-Resin(s)
Dry Type
- Organic Compounds
- Inorganic Materials

Polychlorinated Biphenols/Paper/Porcelain
Miscellaneous material used in conjunction with the above materials: Epoxy Reinforced Fiberglass; Wood; Masonite; Melamine

4.2 Bushings

Condenser
- Oil/Paper/Porcelain
- Oil/Paper/Resin/Porcelain

Gas
- Air/Nitrogen/Porcelain
- Sulfur Hexaflouride/Porcelain

Solid

- Polymer Concretes
- Epoxides

Liquid

- Oil/Porcelain
- Capacitor Dielectrics/Porcelain
- Silicone Oils/Porcelain

4.3 Cable Potheads

Cured and Non-Cured Elastomeric Tapes in Conjunction with Cable Insulation and Bushings (above)

4.4 Cables

Oil/Paper/Jacketed

Oil/Paper/Polyethylene (uniaxially oriented)

Forced Oil

Polyethylene

- Crosslinked Polyethylene
- High Density Polyethylene

Ethylene Propylene Rubber

High Pressure Gas/Insulating Spacers

Superconducting Cryogenic/Vacuum/Insulating Spacers

4.5 Controls and Associated Protective Devices

Low Voltage Wiring/Supports

- Thermoplastics
- Phenolics
- Epoxy/Glass Laminates

Transient Protection Elements

- Metal Oxide Varistors, Gapped and Non-Gapped
- Gapped Silicon Carbide Arresters
- Zener Diodes
- Capacitors

Series Resistors

Gaps

4.6 Rotating Machines and Bus

Epoxy/Fiberglass

Mica Laminates

Polyesters

Organics - Varnishes, Resins, Tapes, etc.

Air

Porcelain

4.7 Capacitors

Cellulose Paper/Castor Oil/Porcelain

Cellulose Paper/Polychlorinated Biphenol (PCB)/ Porcelain

Cellulose Paper/Non-PCB Fluids/Porcelain

Polypropylene/PCB/Cellulose Paper/Porcelain

Polypropylene/Non-PCB Fluids/Paper/Porcelain

Polypropylene/Non-PCB Fluids/Polyethylene/Porcelain

4.8 Surge Arresters, Lightning Arresters, Overvoltage Protective Devices

Porcelain or Glass Housings

Air, Nitrogen, Sulfur Hexaflouride

Misc: Ceramics, Epoxy Reinforced Fiberglass

Protector Tubes

Horn Fiber

4.9 Switchgear

Circuit Breakers (See also Bushings)

Insulating Oil

Sulfur Hexaflouride

Air

Vacuum

Misc: Porcelain, Epoxy Reinforced Fiberglass, Ceramics, Polymer Concrete, Teflon, Nylon, Delrin, etc.

Reclosers (see Circuit Breakers)

Switches (see Circuit Breakers)

Fuses

Porcelain/Air

Phenolics

4.10 Shunt Reactors (See Transformers)

4.11 Series Reactors (See Transformers)

Resins

4.12 System Insulation (Combined Mechanical and Electrical)

Porcelain Suspension Insulators

Porcelain Post and Cap and Pin, Insulators

Porcelain Housings

Porcelain

Wet Process

Dry Process

Glass Suspension Insulators

Glass Pin Insulators

Polymer Concrete Post Insulators

Polymer Concrete Housings

Wood-Cross Arms, Poles, Strain Insulators

Epoxy Reinforced Fiberglass

5.0 LITERATURE SOURCES

The following sources were used in this literature search and bibliography preparation:

Open literature, world wide origin and distribution was accessed through the use of electronic data bases augmented by search services provided by the National Technical Information Services (NTIS) and the New England Research Applications Center. Extensive use was made of the Kurt F. Wendt Engineering Library, University of Wisconsin-Madison.

Primary electronic data bases used were:

INSPEC	Institution of Electrical Engineers Citations and Abstracts Publications
COMPENDEX	Engineering Index
NTIS	National Technical Information Service
DOE ENERGY	Department of Energy
ELECTRIC POWER	Electric Power Research Institute (EPRI)

The most extensive of these data bases is INSPEC, covering 3005 journal titles, from 1969 to July, 1985, the cut-off date for this search.

Additional sources of information used were:

Industry Standards - International Electrotechnical Commission (IEC), American National Standards Institute (ANSI), Institute of Electrical and Electronic Engineers (IEEE), National Electrical Manufacturers Association (NEMA) and American Society for Testing and Materials (ASTM); published standards as well as certain committee communications.

International Conference on Large High Voltage Electric Systems (CIGRE) - internal documents.

Atomic Weapons Research Establishment (AWRE) - Aldermaston (United Kingdom) reports.

Air Force Weapons Laboratory (AFWL) - Dielectric and Switching notes.

U.S. Reports Not for General Distribution - not classified.

Sandia Laboratories Reports - not classified.

Lawrence Livermore Laboratories Reports - not classified.

Oak Ridge National Laboratories Reports.

Department of Defense - unclassified reports.

Proprietary Reports - multiple sources.

Personal Communications.

A group of Classified Reports were consulted and determined to be not germane to the insulation systems considered in this project.

6.0 BIBLIOGRAPHY FORMAT

The wide range of time frame in which the documents were published, the diverse nature of the subject matter and the difficulties encountered in obtaining hard copies of the documents from the many sources dictated an open, random format for the bibliography listings.

Accordingly, the references have been listed more or less in the order in which the documents were received and reviewed, each germane document being given a unique identification number.

A substantial number of references were identified as prospective candidates for inclusion in the bibliography. All of these references were reviewed by one or more of the project team members. Only those deemed to be germane to the project goals were included in the bibliography. Abstracts of each of these documents, prepared by the original author(s), by other reviewers or by this project's team members are included.

Following reviews and selection of the appropriate documents, a group of keywords was assembled which, in their various iterations and in conjunction with an alphabetized-by-author listing of references, permits ready access to the information in the bibliography.

The references are therefore effectively cross indexed in a multipage matrix type index by:

Author (prime authors in the case of multiple authors)

Unique Document Number (ranging from 1 through 364)

Keywords and Corresponding Number (1 through 41)

The directions for the use of the bibliography, duplicated from that document, follow, as does a listing of the keywords, an example page of the matrix index and an example page of the citations.

7.0 DIRECTIONS FOR USE OF BIBLIOGRAPHY

All references are in the same format consisting of:

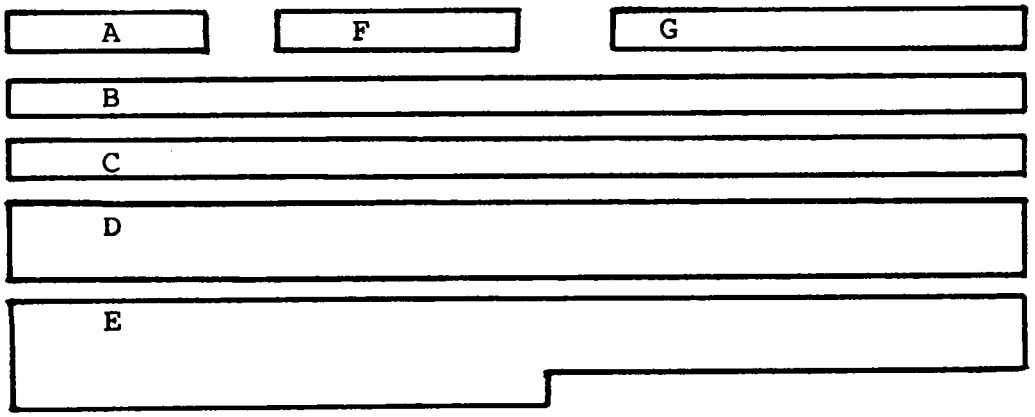
A. A unique reference identification number (the range of numbers is 1. to 364.)

B. Title

C. Author or authors

D. Citation - where the document can be found and language used if other than English

E. Abstract



F&G. Identification of references in other data bases. May or may not be present.

A matrix type index has been generated consisting of KEYWORDS and the AUTHOR of the references. The references

are arranged in rows in alphabetical order of the first (prime) author. The KEYWORDS are in turn listed in alphabetical order with a corresponding number, 1 through 41, these numbers identifying columns in the matrix. Entry can be made either by KEYWORD or AUTHOR.

If a KEYWORD appears in a reference, the Unique Reference Identification Number will be printed in the appropriate KEYWORD column opposite the name of the prime author.

The references in the Bibliography are listed in ascending order of the Unique Identification Number.

A listing of the KEYWORDS is given in Figure 1.

A sample page from the matrix type index is displayed in Figure 2.

A sample page from the Bibliography is shown in Figure 3.

C-1

KEYWORD INDEX

1. ANOMALOUS FAILURE(S)
2. ARRESTER(S)
3. BACKFLASH, BACKFLASHOVER(S)
4. BREAKDOWN(S)
5. CABLE(S)
6. DEGRADATION
7. DISCHARGE(S)
8. DURATION
9. ELECTROMAGNETIC
10. EMP, NEMP, SREMP, HEMP, LEMP, MHD-EMP
11. FAILURE(S)
12. FAST
13. FRONT
14. GAS INSULATION
15. GENERATOR(S)
16. IMPULSE(S)
17. INSTRUMENTS AND INSTRUMENTATION
18. LIFE
19. LIFETIME(S)
20. LIGHTNING
21. LIQUID INSULATION
22. MODEL(S), MODELING
23. MOTOR(S)
24. OIL INSULATION
25. OVERVOLTAGE(S)
26. PAPER INSULATION
27. PARTIAL DISCHARGE(S)
28. POLYETHYLENE
29. POLYPROPYLENE
30. PULSE(S)
31. REPETITIVE
32. RESONANT, RESONANCE
33. RESTRIKE(S)
34. ROTATING MACHINE(S)
35. SHIELD, SHIELDING
36. SHORT
37. SOLID INSULATION
38. STEEP FRONT IMPULSE(S)
39. TEST(S)
40. TRANSFORMER(S)
41. TRANSIENT(S)

FIGURE 1

E-8

(See page C-1 for KEYWORD INDEX)

	Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SMITH, I.D.	278				X				X	X	X				X	X
SPENCER, C.E. et al	207															X
STEIN, W. et al	185															
STEMBER, L.H. et al	134					X						X				
STORR, T. H. et al	308				X			X		X						
STORR, T. H. et al	328				X					X						
SWISS, J.	274									X						
TALUKDAR, S.N.	225															
TANASESCU, FL. et al	64							X		X	X					X
THIONE, L. et al	4		X	X	X	X		X		X						X
TOTH, S.	77															X
TOTH, S.	140															
TRIPATHY, S.C. et al	223									X						X
UMAN, M.A. et al	187									X	X					
UMNOV, V.Y. et al	257				X					X						
UNGAR, S.G.	107				X	X										
VAN BRUNT, R.J et al	103							X					X		X	
VAN BRUNT, R.J et al	269							X		X						
VANCE, E.	249					X				X	X					
VASIL'EV, E.N. et al	1									X						
VENKATASESHAIA et al	254	X			X				X	X	X					
VOGTLIN, G. E.	316				X										X	
VOLZKA, D.R.	32									X						X
VOROB'EV, A.V. et al	123										X					
WAGNER, C.F. et al	200															
WARD, B. E.	58							X		X						X
WARREN, JR., F et al	152				X					X					X	
WATSON, H.	105					X		X								
WATSON, W. et al	276		X													X
WEIDMAN, C.D. et al	192									X			X			
WEIDMAN, C.D. et al	197							X						X		
WEIDMAN, C.D. et al	198									X			X			
WHALLEY, G.W. et al	66								X	X						
WHITE, R.A.	155												X			X
WICHMANN, A.	85				X			X		X						
WIK, M.W.	24									X	X					X
WRIGHT, M. T. et al	289													X		
WRIGHT, M.T. et al	169									X		X	X	X		X
YAKOV, S.	258								X							
YAMASHITA, HIS et al	145				X			X		X					X	X
YOKOKURA, K. et al	122					X								X		
YOKOYAMA, S. et al	220															
YONAS, G.	50				X			X		X						X
YOSHIMURA, N. et al	248															
YOUNG, F.S. et al	193		X						X							

FIGURE 2

NEMP BELOW ABOUT 3 X 10^5 HZ. IMPLICATIONS OF THESE RESULTS FOR AIRCRAFT IN FLIGHT ARE DISCUSSED.

188.

ELECTROMAGNETIC PULSE AND THE ELECTRIC POWER NETWORK

KLEIN, K.W.; BARNES, P.R.; ZAININGER, H.

IEEE TRANSACTIONS ON POWER APPARATUS AND SYSTEMS, VOL. PAS-104, NO. 6, JUNE 1985, PP. 1571-1577

THIS PAPER DEFINES THE NUCLEAR ELECTROMAGNETIC PULSE (EMP) - ELECTRIC POWER SYSTEM INTERACTION PROBLEM. A DESCRIPTION OF HIGH ALTITUDE EMP (HEMP) CHARACTERISTICS, SOURCE REGION EMP (SREMP) CHARACTERISTICS, AND MAGNETOHYDRODYNAMICS EMP (MHD-EMP) CHARACTERISTICS ARE PRESENTED. THE RESULTS OF INITIAL CALCULATIONS OF EMP INDUCED SURGES ON ELECTRIC POWER TRANSMISSION AND DISTRIBUTION LINES ARE PRESENTED AND COMPARED WITH LIGHTNING INDUCED SURGES. POTENTIAL EMP IMPACTS ON ELECTRIC POWER SYSTEMS ARE DISCUSSED, AND AN OVERVIEW OF THE DEPARTMENT OF ENERGY (DOE) EMP RESEARCH PROGRAM IS PRESENTED.

189.

D.C. INSULATION ANALYSIS: A NEW AND BETTER METHOD

REYNOLDS, P.H.; LESZCZYNSKI, S.A.

IEEE TRANSACTIONS ON POWER APPARATUS AND SYSTEMS, VOL. PAS-104, NO. 7, JULY 1985, PP. 1746-1749

A RECENTLY DEVELOPED METHOD PROVIDES BETTER ANALYSIS OF INSULATION WHEN TESTING WITH DIRECT CURRENT. THE

III. PROPOSED MODELS AND EXPERIMENTS

1.0 OBJECTIVE

The objective of this task in Phase I is to propose models and/or experiments to be utilized in investigations in the Phase II effort of this project.

Evaluations are to include the steep front short duration (SFSD) pulses as well as the industry standard 1.2x50 us impulse. The standard impulse effort will serve as a bridge between the SFSD work and the existing large body of test data.

The models are to be theoretical (however, not necessarily mechanistic), empirical and/or experimental, and are to represent the electric power system insulation deemed to be most susceptible to damage from the SFSD pulse.

The experimental programs will provide:

1. Required input for the understanding of the physics of insulation system response

2. Guidance in the development of the theoretical, empirical and experimental models

3. Confirmation of the expected performance of the macro experimental models

4. A basis for extrapolation of performance expected from electric power apparatus and systems.

2.0 BACKGROUND

This project effort has identified the transformer as being the electric power apparatus component having the greatest impact on power delivery in the event of SFSD pulse damage. Both power class and distribution class transformers are included. The investigations to be performed in this task will concentrate on, but will not be devoted exclusively to, insulation systems used therein.

Noticeably lacking in the literature search were references to interactions between steep front impulses and the electromechanical performance of the transmission and distribution system insulation. The vast majority of this insulation consists of unit porcelain insulators in many combinations and configurations. Overvoltage failures of typical porcelain insulators are known to occur. The characteristics of the overvoltages and their causes may not be well defined. Sound engineering judgment dictates that the susceptibility of the porcelain insulation to damage from the SFSD pulse be assessed. If damage does occur, its severity and consequences must be determined.

The effort in this task therefore identifies the specific insulation systems to be investigated, considers how best to determine the physical phenomena and performance limits associated with SFSD pulse exposure, and proposes models and experiments to achieve these goals.

3.0 INSULATION SYSTEM SELECTION

3.1 Power Transformers

The two major types of transformers in use today are of the core form and shell form design. They both use insulation systems of cellulose paper impregnated and immersed in oil for conductor and turn insulation, with cellulose pressboard used for intercoil insulation and oil ducts. Other insulating materials, porcelain, epoxies, polyesters, tempered hardboard and wood, may also be used.

The behavior of these two types of transformers upon exposure to impulses differs. Steep fronted impulses may excite naturally resonant circuits in the shell form transformer, producing overvoltages near or at the middle of the winding. Core form transformers, on the other hand, tend to be overstressed in the first few turns of the high voltage winding under similar exposure.

Oil filled/insulated transformers most frequently employ condenser bushings that use either paper oil or resin bonded cellulose paper cores. The bushing size is determined by voltage rating, BIL and current capacity. They may be of substantial length and capacitance which may result in a sloping off of incoming SFSD impulse surges, thereby possibly reducing the severity of the voltage stress in the transformer winding.

Conventional overvoltage protective measures include the installation of lightning arresters and/or spark gaps, generally on the top of the transformer adjacent to the bushings. The characteristics of the overvoltage

protective device must also be determined when exposed to the SFSD pulse. An ultimate concern of this project is the behavior of the combination of the bushing, the transformer and the protective device, when exposed to such pulses.

3.2 Distribution Transformers

Distribution transformers use oil as the major insulant with high voltage conductor insulation of enamel. Barriers of calendered kraft cellulose provide coil to coil insulation. Coil to core insulation is typically provided by resin impregnated kraft or fiberglass/epoxy cylinders. Primary-secondary winding coil insulation is achieved in a similar manner. If the secondary winding is of sheet construction, turn insulation is achieved through the use of kraft sheet. If the secondary is wire wound, the enamel may provide both the conductor and turn insulation. The entire assembly is impregnated and immersed in oil.

Overvoltage protective devices are normally applied to the primary and are mounted as close as possible to the transformer bushing.

The most recent applications of the MOV type lightning arrester provide for the installation of MOV type elements inside the distribution transformer tank as close as possible to the winding terminals. Installation of lightning arresters on the secondary side of a distribution transformer is not a common practice. There is, however, increasing recognition that protection on the secondary may be desirable.

3.3 Instrument Transformers

Conventional potential transformers are constructed from the same insulating materials as distribution class transformers. The higher voltage potential transformers may consist of cascaded distribution type core/coil assemblies. Their problems and performance are expected to be somewhat more complex than their distribution or power class counterparts when exposed to EMP. These devices are perhaps less widely applied than the capacitively coupled potential transformer (CCPT) or device (CCPD) but are suspected of being more susceptible to damage from the SFSD pulse.

3.4 Regulating/Tap-changing Transformers

The construction of these units is very similar to their respective counterparts in power or distribution transformers of similar MVA and voltage class. The major difference is the large number of winding taps required for voltage control and the installation of a tap-changing switch. Additional insulation is involved in the form of cable trays and tap supports. Due to the large number of tap positions creating winding surge impedance discontinuities, the possibility of voltage build up and resulting failure exists.

3.5 Power Cables

Power cables are constructed with paper/oil or solid dielectric insulation systems. Primary areas of dielectric weakness are at cable splices and potheads which are normally part of field installation. Long term cable insulation degradation is generally due to moisture

ingress. Due to the change in surge impedance between an overhead system and the cable, the cable/pothead assembly may be particularly susceptible to SFSD surges.

3.6 Controls

Controls, control circuitry, relays and the like interact with sensing devices, communication links and the controlled device. It is generally recognized that EMP can disrupt the control system and may contribute to the difficulties in maintaining electric service continuity. Considerable emphasis is being placed on this subject by standards groups and by the utilities themselves.

Operating procedures are being developed to minimize the service outages attributable to EMP. Control circuit shielding practices are being updated and, where economically possible, implemented.

Solid state controls and relays may be particularly susceptible to EMP and SFSD pulse damage, more so than their electromechanical counterparts. These devices are, when connected to power apparatus, relatively low cost and easily replaced, provided of course that replacements are available. Other hardening measures are also being employed, such as the use of fiber optics (immune to EMP interference) and plumbed microwave circuits. This subject matter will not be further addressed in this task.

3.7 System Structural Insulation

Virtually all transmission and distribution systems use porcelain for structural insulating purposes. UHV and EHV transmission lines characteristically use porcelain

suspension insulators. Lower voltage systems may use a combination of suspension insulators and post type insulators. The distribution class systems may use a mixture of suspension, post, cap and pin and pin type insulators. Toughened glass suspension type insulators are used to some extent; however, porcelain units are by far the most popular.

3.8 Selected Insulation Systems

Resources sufficient to thoroughly investigate all of these systems are not expected to be available. It will be necessary therefore to restrict the number of systems to those having the greatest potential yield of information.

Hence, the insulation systems selected are:

1. The oil/paper system used in the power class transformer. Some of the information developed is expected to be applicable to condenser bushings, cables and certain portions of distribution transformers.

2. The oil/enamel/paper system used in the distribution class transformer. Some of the information developed is expected to be applicable to instrument transformers and, to a lesser degree, power transformers.

3. The air/porcelain system exemplified by its utilization in system structural applications. Some of the information developed is expected to be applicable to condenser and noncondenser type bushings and lightning arrester housings.

4.0 APPROACH TO MODELS AND EXPERIMENTS

4.1 Summary

Theoretical modeling of power apparatus on a fundamental level is not thought to be a worthwhile approach during Phase II of this project. Despite the complex dielectric arrangements associated with transformers, experiments with the application of fast pulses on these physical models are likely to be the most fruitful approach. A description of the transformer configuration as a whole will be necessary to account for transmission line effects and supplementary diagnostic tests on smaller models are recommended to obtain some mechanistic understanding of steep fronted pulse phenomena.

Experimental data, both where available and developed during Phase II, will be used to construct empirical and statistical models where possible.

4.2 General Considerations

A decision must be made concerning both standardized steep fronted waveforms and representative geometries. The waveform question must be governed by anticipated EMP and other transients appearing on power systems. It is clear, however, that at least one of the waveforms selected should exhibit a front time which is significantly shorter than that for which most of the existing data is available. A risetime of about 10 ns is a realistic and appropriate value on which to standardize. The choice of tail (or plateau) duration is a more difficult question since its effect may be dependent, in some measure, on the insulation

structure under consideration. It may therefore be desirable to invoke a plurality of tail times in the range 50-1000 ns. If a delay line generator was being used, this could be readily accomplished by changing cables.

Decisions on the choice of waveform cannot be completely divorced from the question of what can realistically be replicated in the laboratory. In this regard scale is also an important consideration. Voltages of the order of 500 kV rising in 10-20 ns can realistically and economically be generated. However, testing models representative of full scale EHV equipment would require substantial facility development such as that currently being undertaken at Ontario Hydro for gas insulated systems. The nature of the V-t characteristic is such that very large overvoltages may be required to insure that breakdown occurs on the wavefront. This implies that dielectric structures of modest dimensions may require substantial peak voltages.

Selection of geometrical configurations for test is perhaps the most critical issue since a priori judgments must be made concerning the situations most likely to produce breakdowns under fast rising surges. It is expected that these will include:

- Divergent field situations
- Creep surfaces
- Dielectric barriers and interfacial structures

The problems of instrumentation when testing with very fast fronts cannot be overstressed. There has been recent development work on dividers for use at 500 MHz undertaken by the National Bureau of Standards and Ontario Hydro.

Some forward looking utilities (notably Bonneville Power and American Electric Power) have also been gaining some field experience in this area. However, it is suspected that much of the published work to date may be instrumentation limited.

At Rensselaer Polytechnic Institute, voltage risetimes of 10 ns are being reported but it is likely that the actual risetimes are shorter. Furthermore, when recording such transients, interference and synchronization problems are much more severe than when working with lightning impulses, necessitating rigorous attention to screening and isolation techniques. There are very few transient recorders or oscilloscopes available with sufficient bandwidth to adequately capture single shot transients. (Currently the Tektronix 7912 AD digitizer and the 7834 storage oscilloscope are really the only viable instruments commercially available.)

Self healing media (gases and liquids) present little problem for testing. In contrast there can be little protection, however, from degradation caused by the through current from a low impedance pulse generator. There are inherently severe limitations placed on the number of breakdowns that can be accommodated when solids are present. The nature of test enclosures exhibiting the correct impedance in some fast pulse systems makes it very difficult to change samples unless special arrangements are made to automate the process. This problem is particularly acute in the case of oil/paper systems which will require proper impregnation prior to test.

The large variety of insulation systems used in power system equipment implies that choices must be made concerning the selection of media/structure(s) for initial

study. Since the power transformer is obviously vulnerable, the selection of the oil/paper system for investigation is a sensible and logical choice. However, although the major factors in the breakdown of transformer insulation under power frequency and lightning surge conditions have been identified [1], the basic mechanisms of failure are by no means understood. This results from the fact that the oil/paper dielectric structure is a very complex physical and chemical entity whose properties are both very variable and poorly characterized. Experiments carried out, for example, on paper lapped conductors forming a duct in oil [2], are often difficult to reproduce and the results are characterized by considerable variation. In this sense, it appears that the logical choice of dielectric system is also one of the most difficult to research. However, the decision to study the oil/paper system would inevitably cause some shift of emphasis from theoretical models and simulation to experimental characterization. It is the firmly held view that knowledge of the mechanism of breakdown at a fundamental level precludes the mathematical description of the process to the extent required to build a meaningful computer based model. This does not, however, prevent some initiatives in the modeling area as are indicated in Experimental Approach below. Despite the difficulties outlined above, a well designed experimental program is recommended.

4.3 Experimental Approach

4.3.1 Aspects of Oil/Paper Dielectrics

Recommendations on an appropriate experimental approach for characterizing the impact of steep short duration surges on

oil/paper insulation, certain information is available from previous studies with lightning surges [3,4]. No comprehensive study of oil/cellulose has been found under nanosecond pulse conditions, but some judgments can be made based on the anticipated physics. Aspects which are considered of importance may be summarized as follows:

a. V-t Data

From the point of view of insulation coordination, the most important aspect is to determine the volt-time curves for the chosen configurations in comparison with similar characteristics under 1.2/50 us conditions. Experience in gas systems has shown that "tail" breakdown is often predominant for surges rising in times of less than 50 ns unless substantial overvoltages are applied. It is important to assess not only the traditional V_{50} values but also the time to breakdown. The primary question to answer is whether or not the steeply rising electric strength exhibited by most insulation systems as breakdown time decreases is well behaved in the submicrosecond region. There have been indications that this may not be the case for some materials. From the experimental point of view this aspect imposes the most difficult instrumentation problems since it is necessary to reliably resolve less than 1 ns intervals.

b. Effect of Impregnation

For oil/cellulose systems, the degree of impregnation is known to be an important parameter in power frequency applications. Its effect under 1 us surge conditions has also been documented [5]. If

inadequate impregnation provides gaseous cavities large enough to create field distortion or introduce a gas phase of sufficient mean free path, then it may be presumed that similar results can be expected under nanosecond pulse conditions.

c. Size Effects

It is well known that liquids (as well as other dielectric systems) exhibit electric strengths which change with electrode area, interelectrode gap and stressed volume. Whether volume or area is the controlling factor is still not fully resolved as all the size aspects are clearly interlinked. There have been theoretical arguments put forward in favor of area [6] although several of the published experimental studies on realistic oil volumes have found some evidence to support volume [7-9]. There are compelling arguments for viewing size effects in terms of a weak link process in which the insulation is considered as having a plurality of parallel units with statistically distributed strengths. Using the first asymptotic distribution of extreme values, such a size effect may be predicted to be logarithmic in nature [10] which is in approximate agreement with experimental findings [7].

There have been some recent views expressed [11], which have been backed up with experimental evidence [12], that the observed size effect is a measure of the local stored energy available for the breakdown process. In this way, the capacitance of the test structure can contribute to the local stored energy (hence providing a size effect), but energy, for

example from the dielectric test source, cannot be provided fast enough to affect the breakdown process. From the point of view of Phase II effort, this aspect could be of importance since it would imply that characterizing a particular insulation system under fast pulse conditions may not itself be enough. It may also be necessary to consider the charge storage ability of the surrounding dielectric structure within a transformer or other adjacent components.

Whether size effects are weak-link in behavior (particles, bubbles, asperites, etc.) or energy dependent, there may be significant differences as pulses get faster. Stressed area (or volume) is thus an important parameter especially as power system equipments utilize large volumes of stressed materials.

d. Field Divergency

High speed Schlieren studies in oils [13-17] and oil/paper systems [5] have indicated significant differences in behavior depending on the nature of the field distribution. For example, positive streamer velocities in oils are nearly an order of magnitude faster than those emanating from negative electrodes. Again, in oil/paper systems the nature of the field divergency and discontinuities caused by interfacial effects change both the location and nature of the breakdown event. In this context the triple point junctions formed at the spacer in a transformer oil duct have been shown to be a source of shock wave emissions prior to impulse failure [5], and thus

clearly are initiating points for the breakdown process which follows in times significantly less than 1 us under these circumstances.

e. Interfacial Charging

The use of paper covered conductors inherently creates a composite dielectric arrangement. There is some evidence that charges on the surface of the paper supply energy to the breakdown site [5]. This is clearly a very complex situation but, as voltage durations become commensurate with streamer crossing times and charging time constants, one might expect the characteristics of breakdown to be affected.

f. Statistical Time Lags

As with most dielectric systems, the enhancement of electric strength characteristics in the short time regime can be expected to be due, in part, to the statistics of the initiating process. It is clear from studies in the gas phase that statistical time lags in fact dominate the V-t characteristics, except perhaps at high overvoltages. It is thus likely that many of the effects discussed above may be masked and thus not apparently contribute except in the lower tail of the statistical time lag distribution. However, it is the lower tail of this distribution which is of importance from the practical point of view. It is necessary to not only look at the likely impact but also the worst case scenario which could occur if the pulse were applied at an inopportune instant of time.

This situation should be recognized in an experimental program and appropriate account taken of it. There are two basic techniques which have been identified for this purpose. The first, pioneered by the City University, London [18] for surges with very fast fronts in n-hexane, involves examining the statistics of breakdown in order to isolate the statistical and formative processes. More recently, this technique has been used to good effect to isolate corona stabilization from statistical effects [19]. Alternatively, attempts may be made to minimize the impact of the statistical delay by flooding the test structure with initiating electrons. In gases this is routinely done [20-22] by UV- or gamma-irradiation. UV irradiation of transformer oil is not likely to be very effective, however, due to the strong absorption of short wavelengths caused by the polycyclic aromatics present.

4.3.2 Mechanistic Studies

Although volt-time curves would be an important objective of the planned experimental program, the informed design of insulating structures or formulation of protection schemes will also require some understanding of the mechanism of failure on this time scale. A good example of this can be found in the work of Schwabe, et al. [23]. There it was demonstrated that streamer development in oils is dependent on the rate-of-rise of the applied surge and that the clipping of the voltage by an arrester may not assure that an initiated streamer will not propagate and cause breakdown. Furthermore, the information from a program which is only concerned with breakdown in composite systems, such as oil/cellulose [3], is very limited and it

is doubtful whether much mechanistic data would be revealed. In this context careful design of the experiments is needed as well as innovative techniques to obtain the necessary information. For example, setting up space charge or surface charge prior to the application of a surge or the use of sweep fields can provide a great deal of valuable insight into the breakdown process. However, experience has taught us that interpretation of dielectric phenomena solely from terminal measurements is very difficult and other means will have to be used to obtain additional information. Examples of methods which have been used to good effect in the past when examining oil/paper systems include:

- Shuttered image intensifier techniques
- Fast photomultiplier studies
- Schlieren optics
- Ultrasonic emission monitoring

4.4 Approach to Theoretical Modeling

4.4.1 Background

The development of a meaningful computer based simulation of breakdown must recognize both the opportunities and, more often, the severe limitations appropriate to the particular situation involved. In practice nearly all practical systems involve the complication of interfaces. For this reason, a meaningful theoretical model must account, in detail, for the complex processes which

precipitate breakdown in composite systems such as the oil/cellulose structure typical of power transformer construction.

Conventional lightning surges rising in 1 us typically result in a capacitive, rather than resistive, distribution of stress and are associated with the elimination, or freezing, of certain mechanisms known to be important to breakdown under sustained stresses. Particle effects in liquids and gases and electrohydrodynamic motion in liquids are clear examples of such agencies. However, for surges rising in a few nanoseconds, other factors also become critical. Of primary importance in this respect is the fact that the pulse front time becomes commensurate with the transit time of fundamental particles involved in the breakdown process. From the point of view of modeling this can be helpful since one may readily identify situations where ion (or in specialized circumstances, electron) migration in the electric field will create differences which are sensitive to wave front or tail times. Furthermore, as the wavefront becomes progressively shorter still further mechanisms may be eliminated (e.g., cavitation in liquids) which should simplify a simulation effort.

However, it is evident from the survey of the existing literature (Task 1) that the state of knowledge of the appropriate mechanisms in composite systems is not sufficiently advanced to make an all embracing simulation worthwhile. Indeed, the modeling of single media processes (e.g., corona stabilization in electronegative gases or channel propagation in liquids) is not at the stage yet where it can be used for design purposes due to the need to make assumptions about the predominant underlying

mechanisms. Furthermore, previous work in this area has usually been concerned with "pure" materials. The constructional materials used in the power systems industry are impure, complex and poorly characterized, thus compounding the problems of a modeling effort. In particular the state of knowledge in the liquid area is such that there really is no concensus at all on the nature of the events leading to breakdown. This means that any modeling effort will inherently involve considerable speculation. Despite significant research effort with high speed Schlieren systems by Exxon, General Electric and several university groups in the last ten years, there is still no agreement on fundamental issues such as whether streamers propagate by field ionization at their tips, the involvement of the gas phase, initiation processes at electrodes and other surfaces, etc. Most of the existing modeling carried out to describe the electrical properties of liquids is aimed at ion migration, electrohydrodynamics and conduction aspects.

Notwithstanding this situation, it is felt that there are some aspects for which some modeling effort would be fruitful and these are summarized in 4.4.2-4.4.5 below. They have been selected as being appropriate not only because of their perceived importance to the goals of the program, but also because most of the activity outlined can be accomplished by building on existing software or experience.

4.4.2 Representation of Apparatus

It may not be assumed that breakdown under fast pulse conditions is only a function of the material, geometry and dielectric structure. Unfortunately, at the frequencies

corresponding to the front times envisaged, even short conductor lengths will behave like transmission lines. This can substantially modify the stress seen by the dielectric and must be adequately modeled when assessing the impact of steep fronted surges on real equipment. Some engineering judgment will be needed in assessing the predominant propagation modes in a complex structure like a transformer and in many cases the relevant inductances and capacitances may also be uncertain and calculations will have to be performed based on unit dimensions. However, analysis of this situation can be conveniently made using versatile software already available, such as the EMTP package developed at Bonneville Power, and the McGraw-Edison Transient Analysis Program (METAP).

It is envisaged that an experimental program to determine the behavior of transformer materials would need to be supported by modeling the structure to ascertain the variations of local voltage with time. Since the line end terminal has been traditionally thought at risk, it will also be necessary to take the surge propagation characteristics of the bushing into consideration. If the supply of energy to the breakdown site is indeed found to be important then clearly such an exercise becomes of considerable importance (discussed in the Experimental Approach, Size Effects section).

Only when both the dielectric capability and the stress time relationship in the presence of steep surges are known can the integrity of a transformer be assessed.

4.4.3 Empirical Modeling

Some of the work at AWRL, Aldermaston, UK involving the effects of steep surges [24] has been successful in

providing empirical descriptions of the response of dielectric materials. Although empirical models are inherently geometry and material specific, they do provide a quantifiable basis for undertaking design. It is anticipated that a small effort to research empirical models (such as described in the Appendix, pg. 71+) would be a worthwhile addition to an experimental program. By this means it should be possible to provide coefficients for a mathematical description of breakdown in terms of the salient parameters. Moreover, if additional diagnostic measurements are made as suggested in the Mechanistic Studies section above, it should also permit some measure of mechanistic description of the process to be obtained, since variations in streamer velocity, light and acoustic emission, time lags, etc. would be available in relevant circumstances.

As a result of high speed Schlieren studies [13-17] by several groups in the last ten years, a considerable, although fragmented, data base is now available on the propagation of streamers in liquids (including transformer oil). Although much of this has been obtained for surges having front times of about 1 us, it may nevertheless provide some basis for extensions into the shorter time domains.

4.4.4 Finite Element Modeling

Finite element techniques are now widely available for mapping fields, at least in two dimensions. Unlike finite difference methods, the changing of boundary conditions and material properties becomes an easy matter especially with the use of the sophisticated automatic pre-processing software now available for automatic grid generation.

Although mechanisms are not well understood, it is nevertheless true that most of the factors involved are highly dependent on electric fields. It might thus be fruitful to use an existing finite element routine to examine the implication of a number of different scenarios. In this way it may be feasible to determine whether an acceptable field dependent model could be advanced to fit the existing data. Because of the importance of interfaces and barriers in the practical situations, they could perhaps be modeled by treating the solid as modifying the boundary conditions for liquid-gas simulation. In this way field enhancements created by the interface and any associated triple point junctions could be represented together with a time varying trapped charge on the solid.

4.4.5 Statistical Models

It should be anticipated that some data on the statistical aspects of fast pulse breakdown will be obtained from an experimental program utilizing carefully chosen dielectric structures. If the statistical aspects are appropriately treated this, in itself, may provide some insight into the characteristics of breakdown under fast pulse conditions, especially when comparisons are made with conventional 1.2/50 us data. However, even when this is combined with information from a simulation of the voltage-time characteristics of the surrounding structure (and bushing if appropriate) as suggested in the preceding Representation of Apparatus section, the behavior of a transformer as a complete entity may not be reliably predicted unless only one site was shown to be critical. However, if the breakdown probability density functions for several representative transformer configurations were available

from an experimental program, then, by suitable Fourier transformation, a mathematical convolution could be performed to provide predictions for the transformer as a whole. In other words, a hybrid probability distribution function would be available to describe the failure of a transformer as viewed from its terminals.

The distribution of the associated breakdown time lags is also an important property especially in the context of short pulses. Similar stochastic techniques could be used to distill a working model for a transformer from comprehensive laboratory data on representative structures. However, the success of this kind of approach is linked to the tackling of the scaling question discussed previously in the General Considerations section.

4.5 Experimental Effort

In all the experimentation, high quality reliable data is mandatory. This data combined with information from other parts of this proposed program will be used to determine the probability of damage occurring from SFSD pulse exposure. Replication of the experiments is required to provide the desired confidence level.

A first step in the experimental effort should be to apply conductively coupled, low voltage (1 kV) fast front impulses to the terminals of the components representative of the transformer and bushing insulation systems. Voltage distribution can be easily and conveniently determined under these conditions, permitting characterization of transformer and bushing responses. The characterization of the gapped silicon-carbide lightning arresters and/or MOV

type arresters would require higher voltage, higher energy sources. A source capability on the order of 250 kV, conductively coupled, may be required to adequately characterize lower voltage distribution class devices. Similarly rated porcelain insulators could also be characterized using source equipment of this same voltage source capability. In order to adequately characterize devices with 72.5 kV rating, a source having a capability of approximately 750 kV, conductively coupled, would be required.

The intent of this effort is to obtain experimental data which will permit modeling and forecasting of the response of these insulation systems. Further investigations will be conducted in macroscopic experimental investigations at higher voltages. As presently conceived, there would be some overlap, but no duplication. The low voltage effort is intended to provide information pertaining to the locations of the most severe dielectric stresses within the components and does not necessarily involve the failure of the dielectric system or component. In the case of the porcelain components, where evaluations will be made at higher than rated stresses, permanent damage to the component may be expected.

For adequate characterization, the selected components will require evaluations at more than one stress level. It will be necessary to determine the overall voltage performance characteristic in which the subject device is expected to both withstand the dielectric stress and, at higher stresses, fail. The onset of partial discharges is one known precursor to degradation, and an indicator of damage to the insulation, particularly in the case of the oil/paper system.

It is recommended that, at least in part, some commercial products of the 15 to 38 kV class be used for the these investigations. Where appropriate, these devices will be terminated on both the source and load sides in impedances characteristic of their normal application.

The use of three wave shapes is recommended: 1.2x50 us, 100x500 ns and a nominal 10x200 ns. The duration of the faster two waves will be somewhat dependent upon the physical phenomena encountered. As a lower limit a wave, 10x100 ns, corresponding to the fastest wave proposed in the latest draft of the Surge Withstand Capability Test ANSI/IEEE C37.90.1-198X, is recommended.

A next step in the experimental characterization of transformer insulation would be to perform low voltage, voltage distribution measurements on one or more power transformers scheduled for rebuilding. The measurements desired would require that the turn insulation be penetrated at many locations. Use of transformers scheduled for rebuilding would eliminate any damage repair charges or specimen purchase charges which would otherwise be encountered. These experiments will require repeated easy access to the core/coil assembly of the power transformer to permit reinsertion of this assembly into the transformer tank, reimpregnation, etc. The scope of the effort dictates that a core-form transformer 145 kV to 345 kV primary 15.5 to 38 kV secondary and 10-40 MVA be used.

The physical size and ancillary handling apparatus, oil storage tanks, heavy lift cranes, pumps, etc. further dictate that a transformer repair facility be used for this work.

If in subsequent macromodeling efforts, transformer primary coil sections are deemed to be the most appropriate test specimens, additional coils of this same design can be wound and processed at minimal expense as part of the production run for the rebuilding of the transformer. The only problem foreseen is the timing involved in obtaining access to an appropriate transformer.

Information obtained from the low voltage measurements on the power transformer will directly assist in the development and/or verification of a theoretical model for the insulation system. Adequate, detailed information of the type required, particularly with respect to impulse voltage distributions within a single turn, is believed to be not available. This latter statement is also believed to be true for distribution transformers of both shell and core form designs, the primary winding construction for both being similar.

The macroscopic experimental investigations imply that higher voltages and higher voltage stresses will be necessary to generate degradation and failure conditions on distribution class commercial devices and on realistic models of higher voltage power transformers. These experiments will be used to confirm the failure locations in the models as prognosticated from the low voltage efforts, and to allow extrapolation of these failure conditions and locations to representative commercial apparatus.

Carrying this philosophy an additional, logical step would require that physically large, energized UHV apparatus be subjected to SFSD impulses of sufficient magnitudes to damage and/or destroy the insulation. It is believed that evaluations of insulation systems under these conditions at

this time are not warranted because of the high cost involved for the limited information obtained. It is considered that the most logical approach would be to execute definitive experiments on far more economical specimens, assisting in obtaining a better understanding of the physical phenomena involved. This data would then be used to forecast the probability of degradation/damage as a precursor to failure. Consideration could then be given to planning for direct SFSD evaluation of the larger, high voltage equipments and their insulation systems.

The macroscopic investigations should also cover the effects of SFSD pulse applications to lightning arrester protected bushing/transformers. In order to avoid a large low voltage modeling effort on both bushing and the arresters, these experiments are best performed using commercial apparatus. Also, in view of current controversy as to the performance of the silicon carbide arresters and the metal oxide varistors in response to even moderately fast current waves (e.g., 4x10 us) both types of arresters must be evaluated in conjunction with appropriately rated bushings/transformers.

The complete evaluation of commercial apparatus or apparatus components having ratings in excess of 72.5 kV and less-than-or-equal-to 345 kV would require several generator sources having maximum output voltage capability in the 1.6 to 2.0 MV range. Conventional 1.2x50 us generators of this capability are readily accessed, being operational at any of a dozen or more laboratories in North America. This basic generator provides for one of the required waves as it stands. Modifications to this generator can be expected to achieve the 100x500 ns requirement, but not the 10x300 ns need. An SFSD pulse

generator, a 2.2 MV EMP unit capable of meeting the short risetime requirement is understood to be available for electric power insulation systems evaluations. Use of this capability would be predicated upon the desire and need for direct test data on these commercial components. It is reiterated that at this time the total cost of such an experiment outweighs the value of the data thus obtained.

The macroscopic investigation should also include experiments on commercial structural insulation of distribution class ratings. The performance of porcelain insulators of at least four types of a single voltage rating should be determined. In the event that unexpected damage is encountered, consideration of protective measures should be proposed.

Insulation system degradation from repeated application of SFSD pulses could be a very lengthy, expensive proposition. In order to keep the costs of the program within reasonable bounds, the following approach is recommended.

Simplified models of a specific insulation system are to be used. As an example, for the oil/paper system, a simple cell containing closely spaced non-symmetrical electrodes is recommended. One or more small pieces of paper are placed between the electrodes, the cell then vacuum impregnated with transformer oil. Repetitive pulses having a predetermined magnitude, and of the wave shape desired, are applied at the rate of 60/second, or in excess of 5×10^6 pulses per 24 hours. Degradation of the insulation system can be determined by changes in the displacement current. This technique, used as a course screening procedure, will determine an initial susceptibility of an

insulation system to SFSD pulse damage. Additional combinations of pulse magnitude, wave shape, energy level, pulse rate, etc. can then be used to further define the insulation system characteristics. Suitably sized cells and specimens can be used to provide sufficient degraded paper samples to provide for a qualitative and quantitative evaluation. Statistical data leading to probability of failure estimates can also be obtained using these techniques.

5.0 CORRELATION BETWEEN FAILURE MECHANISMS AND EXPERIMENT

The failure mechanisms to be postulated in this proposed effort will be utilized in the examination of all accessible failure sites. It would be highly desirable for there to be few if any discrepancies between the evidence from the laboratory failures and the postulated mechanisms.

6.0 CORRELATION BETWEEN FIELD FAILURES AND EXPERIMENT

It is highly desirable that laboratory failure sites be compared and/or correlated with so called anomalous failure sites from apparatus field failures. It is foreseen that an unusually high level of cooperation from utility customers, several manufacturers and the investigators will be required to cover this aspect of the project to a reasonable degree. Certainly any substantive information on failures volunteered by interested cooperating utilities can be taken into consideration. The duplication of SFSD pulse caused failures in this apparatus is considered to be beyond the scope of this proposed experimentation program.

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8.0 APPENDIX

MODELLING OF THE BREAKDOWN OF OIL INSULATION
BY THE PROPAGATION OF STREAMERS

Ian Smith, November 1985

ABSTRACT

Measurements of the velocities of streamers from needle points in oil are used to explain the observed breakdown properties of uniform field gaps by relating the fields at the streamer tips in the two different field configurations. It is necessary to assume a threshold field for streamer initiation from a flat electrode. Measurements of needle streamer velocities at lower voltages would improve this empirical model, which is believed to be useful for predicting the breakdown in other geometries, as well as the history of its growth.

Acknowledgments

The model described in this note is essentially the same as one that was put forward by the author and J.C. Martin at AWRE in 1965. Here it has been developed by a more detailed analysis of the electric fields and by incorporating a threshold field.

8.1 Introduction

This note summarizes work performed by Pulse Sciences Inc. under sub-contract to McGraw-Edison Power Systems on their

program to "Assess the Impact of Steep Front, Short Duration Impulses on Electric Power System Insulation" for the U.S. Department of Energy.

Empirical formulas exist that describe the breakdown strength of oil in uniform fields and in needle-plane gaps as a function of pulse duration in the sub-microsecond range. In both cases the time-dependent nature of the breakdown appears to be associated with the propagation of a conducting streamer across the gap. A quantitative description of the breakdown of both uniform field and point-plane geometries in terms of a common dependence of streamer velocity on electric field quantities would allow the prediction of breakdown levels in other geometries. These include the following.

1. Fields that are moderately enhanced at one electrode, or at both.

2. Configurations with large field enhancements that are different from needle-plane gaps, e.g. where the electrodes are small spheres, small rods, or wires.

3. More complex geometries such as three electrode systems, including those where the potential distribution changes during the time of voltage application. (The three electrode triggered oil switch is an example of this.)

4. Oil-solid insulation systems, in which pulses produce streamers in the oil that may reach and damage the solid, which is not self-healing and may therefore fail on subsequent pulses or ac.

The work reported in this note attempts to make such a correlation between uniform field and needle-plane breakdown. The analysis and assumptions are described. The assumptions that must be made to fit such a model to empirical breakdown formulas are discussed. The predictions of the empirical model are discussed.

8.2 Empirical Results for Uniform Field and Point Plane Oil Breakdown

The results in general use in the pulse power community mostly derive from work done by J.C. Martin and his group at AWRE Aldermaston in the 1960's. For uniform fields, the time dependence of breakdown was described by a formula put forward by Smith [1].

$$F t_{eff}^{1/3} = \text{a constant} \qquad (1)$$

F is the peak electric field (expressed in kV/cm) and t_{eff} is the time for which the field exceeds 63% of peak. The use of t_{eff} is an attempt to reduce arbitrarily shaped voltage waveforms to an equivalent time at peak voltage. A more rigorous expression of the result would be

$$\int_0^{t_B} F^3(t)\,dt = \text{a constant}$$

where t_B is the time to breakdown from the start of the pulse. This can be expressed as

$$\int_0^{t_B} F(t)^3\,dt = \hat{F}^3 t_{eff}$$

where t_{eff} is the equivalent duration of a pulse of constant amplitude equal to the peak field $\hat{F}$. Hence

$$\hat{F}^3 t_{eff} = \text{a constant}$$

and

$$\hat{F}\ t_{eff}^{1/3} = \text{a constant}$$

The range of times for which formula was proposed was from about 10 ns to 0.5 us. The value of $Ft^{1/3}$ decreased with increasing electrode area; Reference 1 suggested that this could be represented by

$$Ft^{1/3}\ A^{0.078} = 0.48 \qquad (2)$$

Subsequent large area test data obtained in the Aurora program [2] lead the author of Reference 1 and the present paper to prefer

$$Ft^{1/3}\ A^{0.075} = 0.48 \qquad (3)$$

The time for a streamer to propagate a distance d in oil from a sharp needle to an opposing plane electrode was expressed by Herbert [3] by an equation describing the mean velocity ($\bar{u}$), cm/us as a function of voltage.

$$\bar{u} = d/t_{eff} = 90\ V^{1.75} \text{ (positive point)} \qquad (4)$$

or

$$= 31\ V^{1.28} \text{ (negative point)} \qquad (5)$$

Again, t_{eff} is used to simplify measurements of different waveforms. These expressions are said to be valid up to voltages of about 1 MV. Expressions that include a dependence on d, and which generally give lower velocities, have been fitted to data above 1 MV, but the sub-megavolt formulas are the ones that apply in the present analysis.

8.3 Correlation of Uniform Field and Point-Plane Results

The point-plane formula contains no information about velocity as a function of the position of the streamer as it crosses the gap, but the fact that the mean velocity does not change as the gap is varied with constant voltage suggests that the velocity depends only on voltage and is approximately independent of the streamer position. This suggests a further interpretation. It is clearly a reasonable assumption that the streamer velocity depends only on the electric field in its region. The electric field near the streamer tip will be determined largely by the voltage and is largely independent of the length of the streamer or its distance to the ground plane if the radius (r) of the streamer tip is very small compared with these dimensions, so that the field is approximately

$$k*V/r \qquad (6)$$

where k depends only weakly on the configuration.

In the uniform field case, the streamer is believed on the basis of evidence from open shutter photographs and some time resolved photographs to initiate at one electrode (usually the positive) and propagate to the other. In this case, the field on the streamer tip is strongly influenced

by the planar electrode of origin, which will reduce the field from the value obtaining when the streamer is launched from (and becomes in effect an extension of) a needle. The field at the streamer tip will increase as it moves away from the plane. If the field can be computed as a function of this distance, and compared with the approximately constant field that exists with the needle geometry, the velocity at each streamer position, and hence the total closure time, can be calculated.

One difficulty that is immediately apparent is that if the streamer is assumed to initiate at the planar electrode at the onset of the pulse, the time dependence predicted for the uniform field breakdown will inevitably be that expressed in the streamer velocity formula; the result will have the form

$$Ft^{1/1.75} = Ft^{0.57} = \text{a constant} \qquad (7)$$

(Estimates of the uniform field breakdown strength were in fact made by the AWRE group using preliminary needle-streamer velocity result of the form

$$\bar{u} \propto V^{1.5}$$

and this led to an expectation that the uniform field result would be of the form

$$F^{3/2}t_{eff} = \text{a constant}$$

This expectation led to the adoption of t_{eff} as the time above the 63% level. In the expression

$$\int_{o}^{t_B} F(t)^{3/2}\, dt$$

the integration can be approximated by using a t_{eff} that is the full width at half maximum of $F(t)^{3/2}$, and this can also be obtained by measuring the width of F(t) at the 63% level, since $0.63^{3/2} = 0.50$).

The observation that the time dependence of uniform field breakdown is actually weaker than that implied by equation 7 can be reconciled with the streamer result in more than one way. First, it may be supposed that most of the streamer growth occurs while the streamer tip experiences fields lower than those obtained in the needle-streamer experiments, and that the needle-streamer relation does not hold for the lower fields, where the voltage dependence becomes stronger. The disadvantage of this postulate is that no further analysis can be carried out without streamer data at lower fields. Also, data for lower voltages published in the open literature [4] suggests that the voltage dependence is weaker, and moreover gives a considerably lower velocity than the AWRE data, at least in the region of 100 kV where the two sets of data approach each other.

A second possibility is that a threshold field exists for streamer propagation from a flat electrode. As a result, on a rising voltage waveform there is a period before the streamer starts out; the time dependence will then be generally weaker, and not representable as an inverse power. The time dependence expressed by equation 1 can be interpreted as an average over the range 10 ns to 0.5 us, with the stronger dependence more like that of the needle-streamer relation applying for short times, and a

weaker dependence applying for larger times where the breakdown field approaches the threshold. This view is consistent with observations made in the Aurora program that in the range $t_{eff} \simeq 0.4$ us the time dependence was better characterized as $Ft^{1/4}$ or $Ft^{1/5}$ = a constant [2].

The threshold field interpretation has therefore been adopted here. It should be noted, however, that it is quite possible that this is not a true threshold but a formative time for the streamer (or an early propagation phase) that is still weakly voltage dependent.

8.4 Comparison of Streamer Fields in Uniform Field and Needle Geometries

8.4.1 Needle Streamer Configuration

It is assumed that the streamer is a single straight conducting filament with a tip that has a small radius, r_o. The exact value of the radius turns out not to be very important, because it enters similarly into field calculations in both needle and uniform field geometries. We may take $r_o = 10^{-3}$ cm, which is similar to the radius of 15 um suggested by Reference 4.

Review of the literature shows that the method most typically used to estimate the field at the tip is to approximate the shape of the streamer as a hyperboloid of revolution opposed to a planar electrode. On this basis Reference 5 gives the field at the tip of the streamer as

$$2\ V/r_o\ \ln(1 + 4d/r_o) \qquad (8)$$

where V is the applied voltage and d the distance of the streamer from the plane. Reference 6 gives essentially the same result

$$2\ V/r_o\ \ln 4d/r_o \qquad (9)$$

For a gap d of about 1 cm, these results give

$$E \simeq 0.25\ V/r_o \qquad (10)$$

and for different gaps the coefficient changes very little.

Reference 7 gives the results of numerical calculations of the field near the tip of a cylinder with a hemispherical cap opposed to a plane electrode, where the ratio of the gap d to the radius r_o is 160. The calculated peak field is 0.61 V/r_o. This can be compared with the value obtained from equations 8 and 9, which is 0.31 V/r_o. The field is almost twice as large for the capped cylinder, probably because this does not flare out behind the point as does a hyperboloid of revolution.

Reference 4 gives the result of another calculation using a charge simulation method to calculate the field on a streamer with radius 15 um at distances of up to 2.5 cm from a ground plane. At 2.5 cm, the field is equivalent to 0.85 V/r_o, whereas equations 8 and 9 would give 0.22 V/r_o. The factor by which the calculated field exceeds the hyperboloid result is thus even larger than in the calculation for the capped cylinder. However, this result is difficult to accept, because it appears to be too close to the result V/r_o that would obtain for an isolated sphere. The reduction of field that would result

from the shielding of the hemispherical streamer tip by the streamer length must surely exceed 15%.

Thus in this analysis the hyperboloid field approximation expressed by equation 10 will be adopted. While it is recognized from the capped cylinder result that higher fields could be present, it is also possible that the tip field could be reduced by shielding from other branches of a multiply branched streamer, or by the effect of resistive voltage drop along the streamer.

8.4.2 Uniform Field Configuration

Here it is assumed that the streamer is a single straight conductor growing out from and perpendicular to one electrode, with a height h and the same radius r_o as in the needle streamer case. An expression for the electric field in this configuration can be obtained [8] by assuming that the streamer is a prolate hemispheroid. This treatment corresponds well with the hyperboloid treatment used in the needle configuration, since both shapes flare out somewhat behind the tip.

Equation 6 of Reference 8 can be shown to reduce to

$$E_o = E\ (\alpha-1)(1-1/\alpha)^{1/2}/[\text{arc tanh}(1-1/\alpha)^{1/2}-(1-1/\alpha^{1/2}] \quad (11)$$

where $\alpha = h/r_o$, E is the maximum field at the tip of the streamer, and E_o is the applied uniform field. Equation 11 is plotted in Figure A-1 as a function of the ratio of the length of the streamer to its radius. The solid line in Figure A-1 represents the valid range of equation 11, which does not apply for $\alpha \leq 1$. The value of the field enhancement E/E_o approaches 3 as $\alpha \rightarrow 1$, and

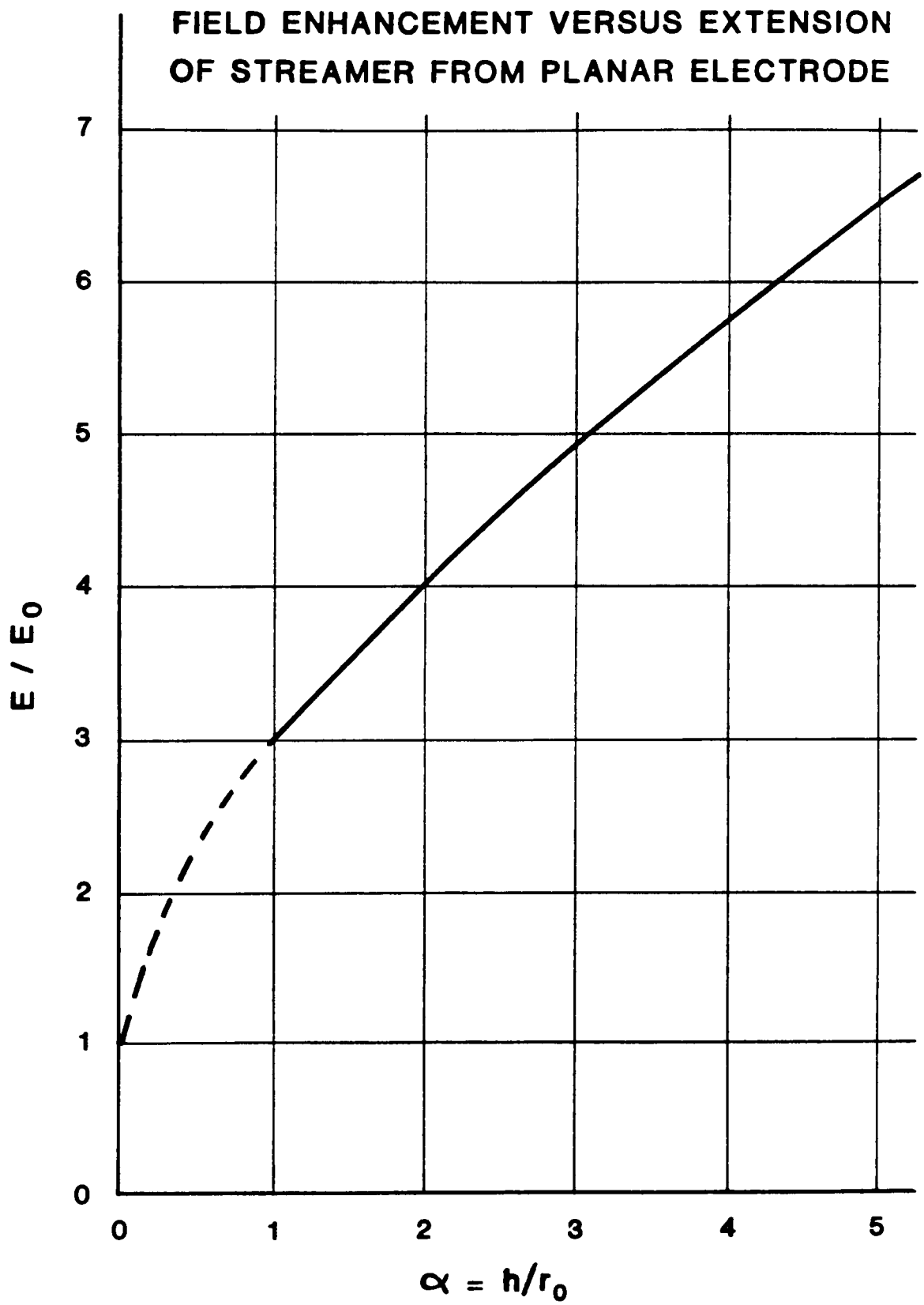
FIELD ENHANCEMENT VERSUS EXTENSION
OF STREAMER FROM PLANAR ELECTRODE
E / E0
0
1
2
3
4
5
6
7
0
1
2
3
4
5
α = h/r0

FIGURE A1

this result is familiar (e.g. from Jeans' Electromagnetism) as the field enhancement on a hemispherical boss on a plane. For $\alpha < 1$, a solution might be obtained by treating the streamer as an oblate hemispheroid. To represent this region, the dotted line in Figure A-1 is sketched by hand; it must pass through the point (0,1) as there is no field enhancement when the streamer vanishes. The result

$$E/E_o \simeq 2 + \alpha \qquad (12)$$

is taken as an approximation to the curve in Figure A-1; in the range $0.5 < \alpha < 5$ it is in error by no more than about 10%.

8.5 Model of Streamer Propagation in Uniform Field

In a uniform field it is believed to be the positive electrode that usually launches the breakdown streamer. The positive streamer velocity (equation 4)

$$\bar{u} = dx/dt = 90\ V^{1.75}\ \text{cm/us}$$

is interpreted in terms of the electric field at the streamer tip by using equation 10.

$$E = 0.25\ V/r_o$$

The velocity is then expressed as

$$\begin{aligned} u &= 90\ (4Er_o)^{1.75} \\ &\simeq 1000\ (Er_o)^{1.75} \end{aligned} \qquad (13)$$

For a streamer of length x in a uniform field F, the electric field at the tip is approximated by equation 12 as

$$E = F(2+x/r_o)$$

so that the velocity is given by

$$dx/dt = 1000\ F^{1.75}\ (2r_o+x)^{1.75} \qquad (14)$$

Equation 14 can be integrated from the launching of the streamer to breakdown. It is assumed that there is a threshold field, F_o, at which the streamer begins to grow, which in view of the discussion in section 8.3 is likely to be non-zero. It is also assumed that the streamer may grow not from a planar surface but from a protrusion, which is assigned an effective height x_o. It is not clear how well this latter assumption represents the actual situation, since the protrusion from which the streamer starts may have a radius and shape different from those of the streamer, so that the field configuration in the region of the protrusion may not necessarily be representable by an effective height x_o of a streamer-like protrusion. However, ignoring this reservation, the breakdown condition becomes

$$\int_{x_o}^{d} dx/(2r_o+x)^{1.75} = 1000\int_{F_o}^{F_B} F^{1.75}\ dt \qquad (15)$$

where d is the electrode spacing and F_B is the field at breakdown.

In order to be able to apply this equation, it is necessary to obtain values for F_o and x_o. This is done in the

succeeding sections by considering a particular configuration for which the breakdown is known from empirical results.

8.6 Estimates of Threshold Field and Protrusion Height

For a particular configuration in which F_o and x_o are fixed, equation 15 can be written

$$F^{1.75}\, dt = k, \text{ a constant} \tag{16}$$

To express the time-dependence of the breakdown field, suppose that breakdown occurs on a linearly rising voltage or field ramp given by

$$F = at \tag{17}$$

Equation 16 can then be written

$$a^{1.75}\int_{F_o/a}^{F_B/a} t^{1.75}\, dt = k$$

which on integration gives

$$F_B^{2.75} - F_o^{2.75} = 2.75\ ak \tag{18}$$

As a specific set of conditions, take the breakdown predicted by the empirical equation 3 for a 100 cm^2 electrode surface with an effective time (t_{eff}) of 0.25 us. The prediction is F_B = 0.54 MV/cm. The time that the voltage is greater than 63% of peak in the case of

a linear ramp is 37% of the time to breakdown, which is therefore 0.25/0.37 = 0.675 us. Hence

$$a = 0.54/0.675 = 0.80 \text{ MV/cm-us}$$

Inserting the values of a and F_B into equation 18 gives

$$k = 0.0835 - 0.455F_o^{2.75} \qquad (19)$$

Substituting for k in equation 18 gives the general result for voltage ramps with different rates of rise,

$$F_B = (1-1.25a)F_o^{2.75} + 0.23a \qquad (20)$$

The corresponding value of t_{eff} is given by

$$t_{eff} = 0.37\ F_B/a$$

Figure A-2 shows, for different assumed values of F_o, the relation between F_B and t_{eff} from equation 20, as the waveform rise rate a is varied to give t_{eff} values in the range from about 20 ns to 1 us. Each log-log plot is essentially a curve that at long breakdown times levels out at the threshold field, and at short breakdown times approaches a slope of 1/1.75 corresponding to the regime where the threshold field is unimportant compared with the breakdown field. As discussed in section 8.3, available data in this time range fits a relation F_B t_{eff} on average, corresponding to a slope of -1/3 in Figure A-2, but the time dependence and slope are thought to be numerically larger at short times and smaller at long times. The general trend of changing slope is present in all plots that result from different choices of F_B, but

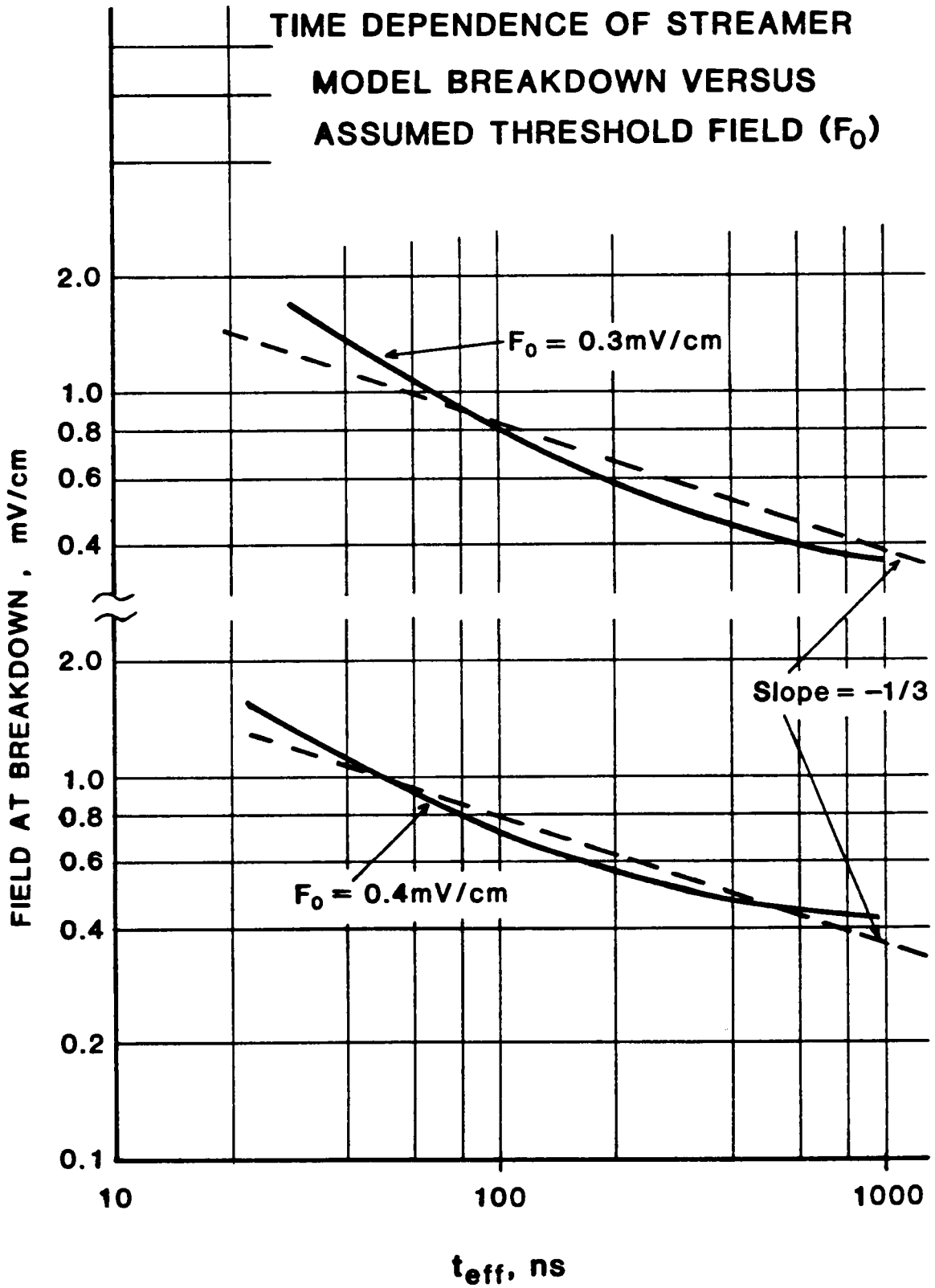
TIME DEPENDENCE OF STREAMER
MODEL BREAKDOWN VERSUS
ASSUMED THRESHOLD FIELD (F_0)
F_0 = 0.3mV/cm
F_0 = 0.4mV/cm
Slope = −1/3
FIELD AT BREAKDOWN, mV/cm
2.0
1.0
0.8
0.6
0.4
0.2
0.1
10
100
1000
t_{eff}, ns

FIGURE A2

in order to obtain the observed average slope of -1/3 it is necessary to choose $F_o \simeq 0.4$ MV/cm. This is a large fraction of the breakdown field of 0.54 MV/cm estimated for the 100 cm area at $t_{eff} = 0.25$ us.

Adopting the value $F_o = 0.4$ MV/cm, the resulting value of k from equation 19 is 0.047. Substituting this in equation 15 gives

$$\int_{x_o}^{d} dx/(2r_o+x)^{1.75} = 1000\ k = 47$$

For a typical spacing of d = 1 cm, this can be integrated to yield

$$1/(2r_o+x)^{0.75} \Big|_{1}^{x_o} = 63$$

or (21)

$$1/(x_o+2r_o)^{0.75} - 1/1(1+2r_o)^{0.75} = 63$$

Equation 21 can be plotted as a relation between r_o and x_o as shown in Figure A-3. This graph shows, in effect, what protrusion height must be assumed on the electrode as a function of the radius assumed for the streamer. For the streamer radius of 10 um suggested in section 8.3, the protrusion is about 20 um, which is comparable to the diameter of the streamer. If the streamer radius is assumed to be 20 um, however, no protrusion need be assumed; the streamer can be assumed to start from the flat surface.

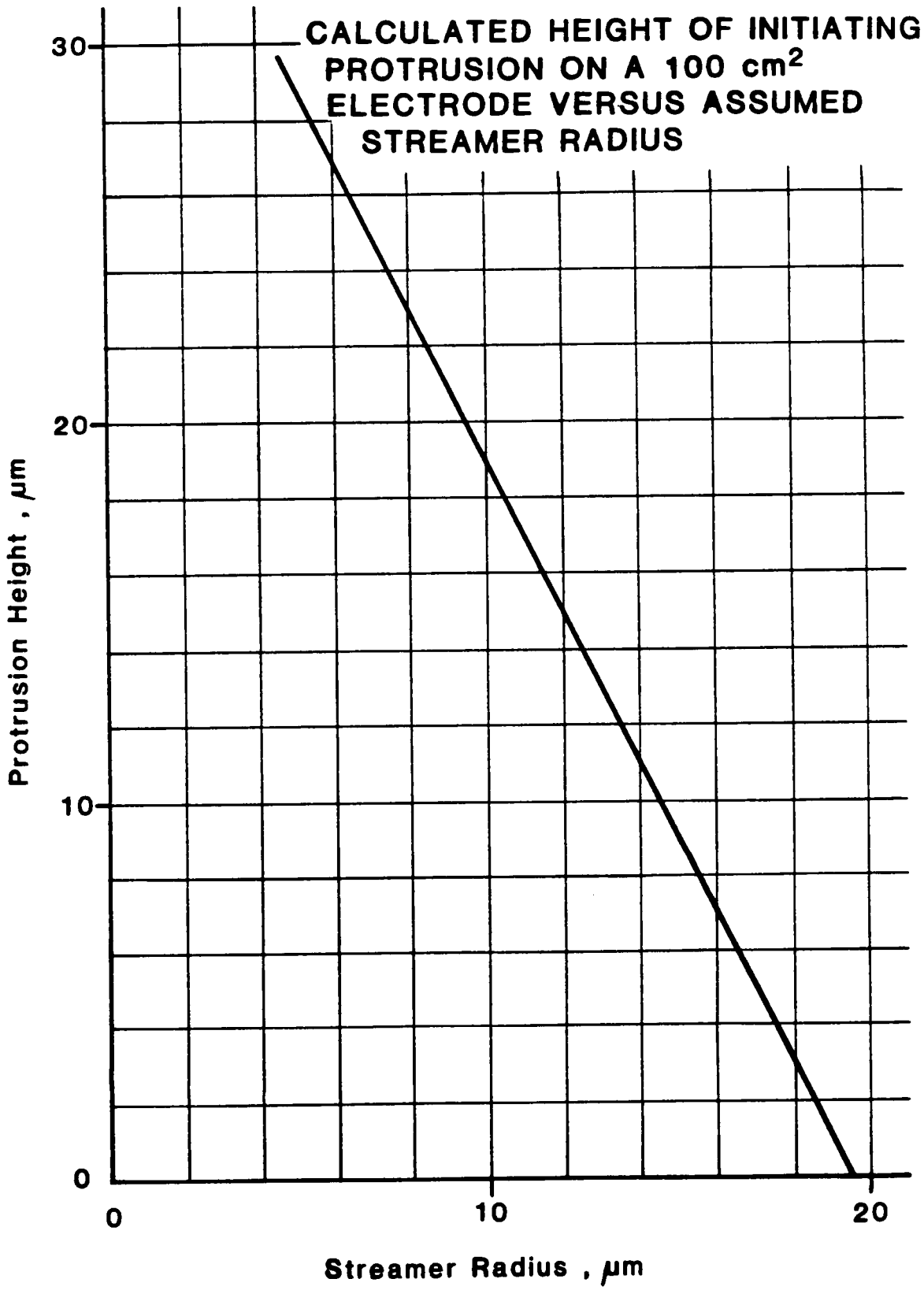
CALCULATED HEIGHT OF INITIATING PROTRUSION ON A 100 cm2 ELECTRODE VERSUS ASSUMED STREAMER RADIUS
30
20
10
0
Protrusion Height , μm
0
10
20
Streamer Radius , μm

FIGURE A3

8.7 Plausibility of the Streamer Model

Some comments can be made about extending the fit of the model from the 100 cm^2, t_{eff} 0.25 us, d = 1 cm example given to the general empirical data. First, equation 15 implies a dependence of breakdown field on electrode spacing, but because $d >> r_o$ the predicted dependence is extremely weak, and quite consistent with the data. Second, for different electrode areas the threshold field must always be assumed to be 70-75% of the breakdown field at t_{eff} = 0.25 us, in order to maintain a predicted time dependence that is consistent with experiments. This seems rather unlikely. Third, for different areas the variation of breakdown field with area requires the height of the controlling protrusion to increase very weakly with area; this seems quite plausible.

With respect to the threshold field, it seems likely that it is in fact lower, and that the weak time dependence of the uniform field configuration results from a stronger dependence of streamer velocity on voltage or field in the low fields that exist near the streamer tip in the controlling early stages. To improve the model developed here, it is desirable to make needle streamer velocity measurements at voltages well below the minimum of 150 kV used in Reference 3. These measurements should probably be made before testing the model, e.g. by applying it to predict breakdown levels of different field configurations or solid-liquid insulation, or by checking the predictions of streamer length versus time by photography.

8.8. Preliminary Comparison with Experiment

The model developed here allows a complete description of the development of a streamer that crosses a uniform field

gap. This description consists of a calculation of the streamer length as a function of time from the start of the pulse to breakdown.

Reference 9 contains photographs of a streamer-like growth in a nearly uniform field in transformer oil that bridges a 0.32 cm gap in four frames spread over 0.2 us. The authors of Reference 9 were contacted to obtain the applied voltage, 160 kV. Table A-I shows this author's interpretation of the photographs of Reference 9 to obtain an approximate velocity for the streamer at two different positions in the gap. Also shown in Table A-I is the velocity predicted for the particular streamer position by equation 14. In one instance, the agreement is very good, and in the other the disagreement is about a factor of two. Considering the need for more data to improve the model, the comparison is encouraging.

TABLE A-I

Streamer Length as a Function of Time for Oil Breakdown Photographed in Reference 9

Time, t (us)	Streamer Length, x (cm)	Mean Length $\bar{x}$ (cm)	Mean Velocity, $\bar{u}$ (cm/us)	Velocity from eq. 14 (cm/us)
0	0			
0.05	0.017			
		0.026	0.4	0.5
0.10	0.036			
		0.063	1.1	2.4
0.15	0.09			
0.20	0.32			

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