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ELECTRICAL INSULATORS IN A REACTOR ACCIDENT ENVIRONMENT

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ABSTRACT

Wire connections in a reactor containment generally are made by means of many hundreds of insulating blocks ("terminal blocks") which are protected by metal boxes. A broad investigation was conducted to determine what effect the heat, steam, and contamination resulting from a nuclear reactor accident would have on these terminal blocks. A comprehensive experimental program was performed at temperatures, pressures, and time constants characteristic of the Three Mile Island accident. A model was developed which predicts, within an error factor of 2, the probability of an electrical breakdown for a wide range of temperatures, contamination, and protective measures. "Normally dirty" terminals in a tightly closed protective box with a 6 mm "weephole" in a 480 V circuit had about one chance in 100 of suffering complete breakdown at Three Mile Island. If flow retarders or "breathers" narrowed the effective size of the weephole, breakdown was less likely by about a factor of 3. For a large scale steam breakout with a temperature of 170°C, however, the breakdown probability for an unprotected terminal would be about 30% at the same voltage.

Terminal blocks are probably the weakest links in a reactor's electrical system, and concern about their presence in safety-related circuits is fully justified. Some remedial measures and some improvements for future installations are proposed.

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ELECTRICAL INSULATORS IN A REACTOR ACCIDENT ENVIRONMENT

I. Introduction and Summary

A. Purpose and Program

Electrical insulators, mostly in the form of connection boards or "terminal blocks", can be exposed to a severe environment during an accident involving steam breakout in the containment of a reactor. The insulators will then permit increased leakage currents, present a noisy shunt to the circuit, and may suffer temporary or permanent electrical breakdown. The number of terminals in a reactor containment may be very large; at Three Mile Island Unit 2 (TMI-2), about 2700 terminals remain after 620 were replaced by splices. The purpose of the present work is a broad investigation of insulator deterioration under accident conditions to provide data for circuit analysis and to propose improvements in present and future installations.

In a comprehensive experimental program, more than 600 terminals were exposed for an average of five hours to heat, steam, varying power cycles, contamination, different protective arrangements, etc. The conditions were selected to imitate the Three Mile Island accident (i.e., temperatures below 90°C, blocks made of phenolics, and the contaminants most often boric acid and the standard containment spray). Direct impingement of steam on the terminal blocks was avoided. In many experiments the terminals were protected by enclosures, into which a pressure equilibrating drainage hole or "weephole" was cut. In combination with commercial tests under higher temperatures and with room temperature data from literature, our measurements permit a broad statistical description of insulator behavior over a wide range of accident conditions.

Our experiments do not take radiation into account; for TMI-2 conditions the influence of radiation on insulator breakdown appears to be negligible. Purely mechanical failures of terminals (sliding link breaks; mechanical cracks due to excessive tightening and/or thermal expansion) are not included in our considerations. These aggravate the situation and would of course enter into circuit reliability statistics.

B. Low-Voltage Surface Breakdown

It is essential for the interpretation of our data to develop an understanding of the underlying phenomenon: low-voltage surface breakdown (also called "tracking"). This degradation mechanism is very complex. Leakage or breakdown depends on a large number of parameters, such as material, voltage, temperature, measuring time (or rather voltage exposure time), humidity, and most importantly, contamination. Some of these parameters, as discussed in more detail in Section II, are of minor influence and most are quite well measurable and reproducible, but the dominant influence, contamination, does not fit in these categories. The great variety of contaminants possible in a reactor containment is discussed later. There are unexpected complications: the breakdown voltage not only has a minimum value but may have a maximum as well. Worst, of all, the observations are time and history dependent. It is not surprising, then, that our measurements show large fluctuations in leakage currents and our results have considerable error bars.

Section II is basically a literature survey of the state-of-the-knowledge about tracking at room temperature. With about fifty directly or indirectly quoted authors, there is no single result without at least one dissenting voice. Only "general consensus" exists. Section II includes comments about how our results fit this general picture.

An important simplification is achieved by introducing the surface resistivity, $\rho_s(\Omega)$, to classify and estimate the deterioration-breakdown process. For high surface resistances ($10^9\Omega$), breakdown requires high voltages (10^4V) and takes weeks at room temperature. For low surface resistances ($10^2\Omega$), a few hundred volts will cause a breakdown in fractions of a second. Severe changes in ρ_s occur quite readily: a change in humidity from 50-100%, or an increase in temperature by only 7°C, or a thumbprint on the surface, may each decrease the surface resistivity by a factor 10^3 or more.

Surface resistivity and surface breakdown are only weakly dependent on the insulator material. Phenomena observed and breakdown statistics derived for phenolics will therefore also apply well to other insulators.

C. Experimental Facilities

Two experimental arrangements were used; they are described in Section III. In principle, they resembled the well known facilities utilized for loss-of-coolant accident (LOCA) testing under IEEE qualification test standards. They were, however, as far as steam exposure is concerned, much simpler; simulating TMI-2 accident conditions, the system could work at atmospheric pressure, at lower temperature (86°C) than the IEEE Standards (177°C), and at slow (20 min.) temperature rise times.

For the first experiments, steam was generated in or injected into a large plastic box; contamination was added by a hot air operated nebulizer. The much improved second system used the steam exposure facilities of the Sandia environmental test group; impurities were added directly to the steam supply.

The data handling system used was quite powerful: 14 channels (12 for terminals, 2 for calibration resistors) could either be continuously read (singly) or sampled in one-minute steps. Additional channels recorded temperatures and dewpoint depression. Computer printouts and plots over three decades of leakage current (.1 to 100 mA) were obtained.

D. Experiments

As low-voltage breakdown for protected and relatively clean insulators is (fortunately) a rare event, a large number of experiments had to be performed to obtain a meaningful statistical description. All experiments were done under as high humidity as obtainable inside the chamber but outside the protective circuit boxes. The three kinds of phenolic blocks present in Three Mile Island Unit 2 were exposed. Voltage, temperature, and contamination were varied; the leakage currents to ground were measured over time spans from 4 to 6 hours. Three series of experiments were performed with the two sets of apparatus described above.

1. In preliminary measurements the temperature rose to about 43° (110°F) in about 20 minutes. Leakage currents and fluctuations increased with increasing humidity and temperature (as expected). Breakdowns occurred during this phase. When the temperature stabilized, the leakage currents as well as the noise dropped, often by one decade; this constitutes a healing phenomenon. A.C. voltages of 480V, 240V, and 120V were applied. Turning the voltage on after the humidity had risen increased current and noise noticeably well above those situations where the voltage had been applied before the experiment was started. Over two hundred terminals were measured; seven total breakdowns were observed; six of these were coincident.

2. Forced breakdown was studied by applying contaminants in solutions with an eye dropper. If the insulator was noticeably hotter than the contaminant, the contaminant droplet was simply blown off, clearly helped by the applied electric field, and no breakdown could be obtained. Otherwise, strong contaminants (such as the standard containment spray solution) produced breakdowns within seconds, as expected.

We were surprised to observe that broken-down terminals tend to regenerate when exposure to humidity and voltage ceases. Of 50 terminals broken down to a few ohms, 33 returned to 10 MΩ or more (measured with 4.5 volt ohmmeter) after drying for a few days with no voltages applied.

3. In a final experimental series, the Three Mile Island accident was closely imitated: the temperature rise was generated by injected steam and approached 86°C (186°F) in about 30 minutes. Contaminants were injected with the steam for the first 30 minutes of the first steam cycle. To incorporate the experiences of the preliminary tests, the terminals were

exposed to three steam cycles and five voltage cycles during five-hour experiments. Impurities were added at concentrations believed to have existed at Three Mile Island or taken from a general contamination listing. Readings for up to 12 terminals during each experiment were recorded every minute (some fast fluctuations were missed thereby). Three hundred and nineteen terminals were exposed to full cycle programs, and 108 additional ones to partial or altered programs. In part of the experiments, a protective enclosure with 6 mm weepholes was provided for the blocks. Twenty-three breakdowns were obtained, almost all at the beginning of the first or second voltage application. Average leakage resistances, mostly taken at 480V, varied from 5 MΩ for a well protected clean terminal to 200 kΩ for a dirty, unprotected terminal. Instantaneous values were occasionally lower by a factor 10 and, thus, possibly inadmissible for certain circuits.

The experiments, by definition, had to be made in a corrosive environment. Insulation failure (or contact failure) in the wiring system therefore could not be completely avoided. Close to 100 experiments had to be challenged and are not included in above experiment numbers.

The details of the experiments are described in Section IV.

E. Evaluation

Our measurements were used to develop a model which a) correlates the data with those obtained by other investigators, and b) permits breakdown and leakage resistance predictions for other temperatures, voltages, and conditions. The model, more extensively described in Section V, is based on an observation in the literature that low voltage breakdown (at room temperature) is essentially current dependent. We extend this fact to all temperatures, calculate an activation energy of approximately .31 eV for breakdown current, and find a reasonable fit ($\pm$50%) to the available observations. For illustration we quote a few estimates for TMI-2 conditions and terminals operated at 480 volts A.C.

The probability of an unprotected terminal (open or no box) breaking down under severe contamination (spray, no direct hit) is approximately 7%. In a protective box with a 6 mm weephole, the breakdown probability would be approximately .9% with average contamination (dust and dirt) and approximately .5% with low contamination.

For reactor accidents where temperatures approach 163°C (325°F), the breakdown probabilities corresponding to the above situations would have been approximately 30%, 14%, and 9%, respectively.

At room temperature and 100% humidity, our model, perhaps no longer well justified, predicts breakdown probabilities of well below 10^{-3}. (From the literature we know that it may take weeks to obtain a breakdown under these conditions.)

The model correlates breakdown probability with the average leakage current and therefore permits an estimate of terminal behavior if the applied voltage is lower (or higher). For medium and high contamination, we observe that the currents are ohmic, i.e., proportional to the voltage. A 120 volt circuit therefore has about one-fourth of the breakdown probability of a 480 volt circuit. For clean terminals this is, however, not applicable; the probability will be less (possibly much less) than one-fourth. Average leakage current also are predicted by the model; fluctuations (noise) are essentially proportional to them.

The evaluation also provides a considerable number of general observations which help understand, and thereby eventually may help mitigate, insulator deterioration:

1. The leakage currents through various terminals on the same block tend to be proportional: if one current rises due to some environmental influence, most of the others do also.

2. The above phenomenon expresses itself most vividly in multiple breakdowns, which are by no means rare. Breakdown of one terminal tends to cause a hot, partially ionized vapor cloud around its neighbors. This

is of considerable practical importance; a single dirty terminal may foul several neighbors.

3. If there is no power applied to a terminal, no leakage current will flow, the surface will not be current-heated, and thicker water layers will build up in high humidities. Sudden application of a voltage now finds lower surface resistivity; a higher current flows, and the breakdown probability is enhanced.

4. The corollary to this phenomenon is that long term application of power tends to dry out water layers, which decreases leakage currents and breakdown probabilities. This is always observed for highly contaminated insulators. For a very clean surface, however, the leakage current tends to increase with time: gradual tracking as described in Section II outpaces the drying process.

5. Insulators constituting or mounted on heat sinks (e.g., the containment wall) are most endangered; water vapor adsorption is enhanced there because of the lower temperature.

Comments on additional observations of interest will be included in Section VI.

F. Conclusions and Recommendations

We have investigated the behavior of contaminated insulators in a hot, humid environment. Our experimental results apply most directly to Three Mile Island type accidents but can be extrapolated to higher and lower temperatures; for accidents with irradiation in excess of 10^8 rads, the figures may have to be revised. A dominant influence of contamination is evident in all cases.

One of the main conclusions is that in a typical small steam breakout accident insulators do not cause problems if they are clean and protected by a tight box having (at worst) a small weephole. This holds up to the time the highly conductive containment spray is turned on. After spray application, high voltage (480V) control circuits which are cycled will be the first to show deterioration and breakdown. Terminals in boxes mounted on the (heat sink) containment wall will show leakage currents, noise, and an approximately 1% breakdown rate. When flow retarding breathers are used, the breakdowns occur less often. However, if a box lid is left open, or if a contact is very severely precontaminated, a considerable failure probability exists immediately at steam breakout time. The consequences of the deterioration depend, of course, on the circuit and may require detailed circuit analysis to assess. We recommend such analyses for at least some representative devices (e.g., pressurizer heaters) and instruments (noise-susceptible pressure gauges).

The above scenario changes severely for a large-scale steam breakout with high temperatures. For the design basis LOCA, about 14% of the protected terminals are expected to break down within the first 10 minutes. Therefore, terminals in boxes with weepholes should be avoided in new reactors in all circuits that could ever be of use during and after accidents. For existing reactors, the protection of terminal blocks should be improved. We recommend first cleaning (high pressure steam) and then tightening and sealing of boxes, decreasing or eliminating weepholes, or adding a weephole thermal closing device. It is also highly advisable to protect the terminal blocks from dust during construction. (We are not proposing hermetic sealing of all conduits and boxes because retardation of steam arrival is all that is needed; flow retarders in weepholes are therefore quite effective.)

Our investigations find no clear difference in behavior for different terminal block models. If there were one, the wide statistical spread of data would veil it. However, we are not stating that there are no differences between blocks. From the general physics of breakdown, blocks that can accumulate humidity and dirt in a screw cavity just between the connection point and the electrical ground certainly cannot be recommended. It may pay to consider a redesign that minimizes dirt accumulation on likely breakdown paths. This redesign could also improve the terminal separators for prevention of multiple breakdown. Mounting instructions should specify gloves or a post-installation cleaning requirement.

The considerable statistical data spread makes conclusions from low number experiments suspect.

Containments seem to harbor large amounts (kilogram quantities) of contaminants (acetone, carbon tetrachloride, detergents) which do not appear to have a reason for being present. A look at how these could be eliminated should be taken. Also, smoke from wire insulation is certainly dangerous; circuit overloads therefore have to be avoided.

Hydrogen is a molecular gas which at the temperatures in question has a very low degree of dissociation. Its adsorption should not materially affect deterioration. Unfortunately, our experiments showed three breakdowns under about one-half volume percent of H_2 in the steam chamber, a number barely justified by statistics. If hydrogen actually enhances breakdown, this would predict a strong influence by hydrogen breakouts on the electrical system. The phenomenon should be investigated further.

Finally, we would like to comment on the observed healing of tracks which are drying with the voltage off; satisfactory low-voltage impedance measurements after an accident do not guarantee that the circuit in question was operative during the accident.

Terminal blocks are apparently the weakest link of the electrical system inside a reactor containment building. The concern for their use in safety-related (1E) circuits is absolutely justified. While details could be only ascertained by a circuit analysis, pre-accident replacement of the blocks in safety-related circuits at Three Mile Island doubtlessly prevented some circuit breakdowns and therefore made the accident less severe.

II. Low-Voltage Surface Breakdown

A. Introduction

The important deterioration phenomenon for a terminal block is electrical damage to its surface in the presence of high humidity and contamination, possibly aggravated by high radiation doses. This is called surface breakdown.

This section discusses the state of knowledge of the applicable physics of low-voltage (<3000 volt) surface breakdown. The general information in this field is extensive[1,2] but often highly contradictory. We will emphasize materials of interest (phenolics) and conditions occurring in the reactor accident environment.

Surface breakdown results from formation of carbonized paths (tracking), accompanied sometimes at very low voltages by material removal (erosion). Unfortunately, the general aim of published investigations is different from that of this study. Previous researchers wanted to find a good and economical insulator material for such humid and contaminated environments as exist along power lines. Data on insulation deterioration versus time, which is important to us, are hard to find. High temperature and particularly radiation influence are not generally considered.

On the other hand, the nuclear utilities have exposed terminal blocks to a severe environment, e.g., a full LOCA simulation. What was determined, however, was only severe breakdown with "leakage" currents exceeding 1 or 10 amperes. These were go/no-go experiments. We can use the results as pegpoints, however.

To be able to combine the two pools of information, we have to understand the basic phenomena occurring during low-voltage breakdown.

B. General Mechanism

Surface tracking is the result of surface leakage currents. In a humid environment, moisture forms an electrolyte together with ionizeable contaminants or creates continuity between "sooty" particles. (Contaminants generally absorb moisture and ensure surface wetting and the formation of continuous surface films.) At higher humidities, the surface film becomes thicker, the conductance higher, and the tracking mechanism develops as follows.

The surface current heats and starts to evaporate the moisture film. Eventually electrical continuity will be destroyed at one location. A "dry band" forms; it is perpendicular to the current flow and very narrow (about 0.1 mm). Here the electric field exceeds the breakdown stress of the air, and mild surface arcing ("scintillation") ensues. The discharge, which is not visible but is audible with proper amplification, slowly heats, burns, and carbonizes the surface, creating a low resistivity region. Then a neighboring band forms, and carbon deposits grow and finally join to form a low-resistance circuit. Arcing becomes stronger toward the end of this process, as the series resistance of the surface layer gradually lessens. Finally (power supply permitting), very high currents may flow and hot (ard loud) arcs may develop.

Sometimes, the chemistry of insulator and contaminant permitting, new chemicals are formed by the tiny arcs; this may lead to material removal called "erosion." It occurs mostly at very low voltages and very high contamination. (We have regularly observed it under these conditions.) At high current (amperes), the discharges will be clearly visible. They should not be confused, however, with "dry arc" breakdown, which happens on essentially uncontaminated surfaces at very high field strengths, in very short times, and is more destructive than tracking.

Tracking has been the subject of studies for more than half a century. The older results are well summarized by Whitehead (1950).[1] In the past two decades the understanding of the phenomenon has been much improved by the introduction of the dry band concept described above, and by the application of controlled contamination. The newer developments were analyzed by Fava[2] in 1977. Many contradictory views still exist; we shall see that this is due to the large number of parameters entering an experiment, which prevents two experiments from being identical.

In the evaluation of the literature data, a complication is introduced by the fact that the authors use a wide variety of geometries for their investigations (concentric electrodes, flat plates, point contacts, and even a double cylindrical spiral). We have attempted to correct for geometry variations where possible; the data quoted are therefore sometimes not the values of the original publication.

C. Rough Classification of Regimes

Because of the large variations existing in the parameters (e.g., breakdown voltage, breakdown time, contamination, etc.) it is helpful to look at a rough classification of the parameter values characteristic of a breakdown situation.

The literature survey discloses that the breakdown phenomena and quantities correlate relatively well with the surface resistivity ρ_s (ohms) of the insulator and with the power density P_s (W/cm^2) deposited in the surface, although the correlations are not proportional. For our purposes, the values of ρ_s and P_s are taken at the beginning of the experiment; during deterioration, ρ_s will decrease strongly and P_s will increase.

In Table 1 we use ρ_s as the main parameter. The values in the Table represent orders of magnitude data only. We establish three regimes: (1) a reasonably clean surface with a high surface resistivity (regime a), (2) a highly contaminated insulator with a surface resistivity of a few hundred ohms (regime c), and the third regime, which may originate in regime a and terminate in regime c (regime b). For regime a, several thousand volts must be applied to initiate breakdown, and the development of a track may require weeks. For regime c, a few hundred volts may cause breakdown in a fraction of a second.

Table 1

Low-Voltage Breakdown
(Modified from Ref. 14)

Regime	a	b	c
Surface Resistivity ρ_s	10^9	10^5	10^2 Ohm
Breakdown Mechanism	Corona (Tracking)	Tracking (Erosion)	Arc
Breakdown Initiation Voltage	10^4	10^3	10^2 Volt
Breakdown Initiation Current	10^{-5}	10^{-3}	10^{-1} Amp
Surface Power Density P_s	10^{-3}	10	10^2 W/cm^2
Time to Breakdown	Weeks	Hours	Seconds
Breakdown Products	Ionization, Polar Compounds	Carbon	Carbon, Fused Filler

We will now discuss low-voltage breakdown in some detail. The immense variability of observations is correlated with the variability of surface resistivity, which we therefore use as our main descriptive parameter.

D. Surface Resistivity

Surface resistivity ρ_s is defined as the resistance of a square part of the surface measured between opposite sides. It is measured in ohms.

The concept of surface resistivity is a useful and well understood one for thin metallic layers. For surface electrolyte layers it suffers from a substantial paradox. Since the number of adsorbed layers on a surface versus humidity is known, we can calculate theoretically the surface conductivity from the carrier density and the respective mobility. However, it is found (McIlhagger and Salthouse,[3] quoting Chirkov) that the calculated values are smaller by a factor of 10^4 to 10^5 than the theoretical values. The favored explanation absolves the mobility and assumes that the dissociation of impurities is orders of magnitude lower on a surface than in bulk. (The phenomenon is gratifying, as we certainly prefer a high surface resistivity, which decreases the probability of breakdown. It complicates our theoretical considerations, however, as will be seen in Section V.)

We shall now discuss the various effects which determine or influence surface resistivity on terminal blocks. (Surprisingly, the material of the insulator has a very low and unknown influence on ρ_s.)

1. Humidity -- Possibly related to the above paradox is the very strong variation of surface resistivity with humidity. Yaeger and Morgan[4] found that while the electrolyte thickness increases by a factor of 10 to 100 for a change in relative humidity from 40% to 100% the surface resistance decreases by factors from 10^3 to 10^4. Similar changes are found by many other authors quoted in Ref. 3. The data are not uncontradicted, however. Chaikin,[5] cycling the humidity from 53% to 97% over a nylon-filled phenolic insulator, finds only a factor of 3, not 10^3 (See Figure 9 of Ref. 5). The discrepancies probably have to do with the various surface cleaning processes used, if any. Chaikin also made his measurements at voltages which are quite high for a surface resistance determination, namely 480 Volts. The high variability of surface resistivity with humidity is of minor concern to us: humidities of 98 to 100% are reached almost immediately during a steam breakout.

At constant humidity, the surface resistivity changes (mostly increases) with time. For organic materials (e.g., methyl methacrylate), Williams and Herman[6] find (See their Figure 7) a small decrease in ρ_s with no potential applied, and an increase by a factor 10 with 135 volts dc applied (dry bands may be forming). We find the same phenomenon at higher temperatures (Section III).

2. Temperature -- To make things more complicated, surface resistivity also depends strongly on surface temperature, which is difficult to measure in certain situations. Salthouse[7] (Figure 1) finds that for a temperature change of only 7°C the surface resistivity changes by 3 orders of magnitude. Surprisingly, the ratio is independent of humidity, i.e., independent of the surface layer thickness.

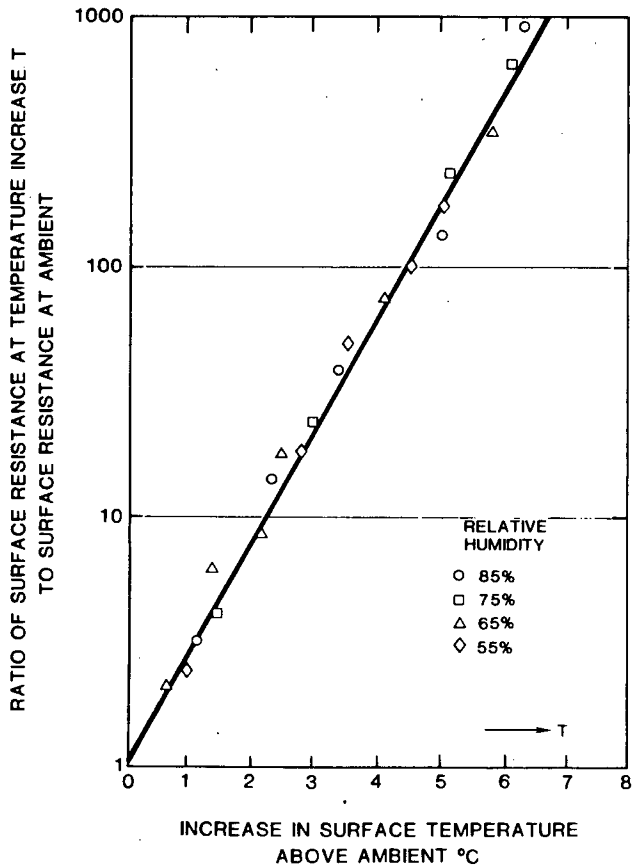


Figure 1. Surface Resistance Ratio vs Temperature Change
(From Ref. 7)

3. <u>Contamination</u> -- The influence of contamination is difficult to determine. While it is quite simple to measure average surface resistivity by measuring resistance with a low voltage and taking the geometry into account, it is another matter to reproduce surface contamination. Many investigators circumvent the problem by immersing the electrodes into an electrolyte and correlating to the bulk resistivity ρ (ohm-cm) rather than to the surface resistivity ρ_s (ohm). The "inclined plane liquid contamination test" (Mathes and McGowan[8]) is based on this approach. The results are quite reproducible, but somewhat challengeable. (There are three widely used outdoor insulator test methods; they do not correlate well[9] but are generally useful to develop improved materials and surface treatments.)

To achieve reproducibility for establishing statistics, we would have to reproduce contamination. This is difficult. A touch with a finger reduces the surface resistivity of "clean" amber by 80 percent.[10] Williams and Herman[6] found that natural perspiration (deposited on the insulator by pressing it against a human body) decreased surface resistivity by factors of 10^4 to 10^7. The authors also found that "handled" insulators all had about the same ρ_s independent of material, while "clean" insulators showed a wide diversity in performance. But what is clean? Recipes and methods for surface cleaning are legion, but none of them is guaranteed to lead to reproducible conditions.

Chaikin[5] investigated phenolic paper-based circuit boards. He measured surface resistance at 35 locations of a fingerprint-contaminated panel. At 97% relative humidity, surface resistivity varied from place-to-place by a factor of 4000 over the 4 x 6 inch panel. Strangely, Chaikin found applying three kinds of resin-alcohol solder fluxes did not degrade the phenolic panels. (Even stranger, solder fluxes seemed to protect the phenolic insulation from the otherwise degrading influence of collected dust.) Of great interest for reactor accident situations are Chaikin's observations of the influence of a sodium chloride aerosol:[5] alcohol-cleaned phenolic panels were not affected, steel wool cleaned samples were slightly deteriorated, and melamine insulators showed "severe degradation." If there is any silver in the electrode material, phenolic insulators exhibit extensive silver migration at voltages of the order of 500 V and high humidities.[6] At prolonged exposure to high humidities and elevated temperatures, fungi are prone to impair surface conductivity on phenolics.[11]

4. Times and Frequencies -- There is some agreement that the time required for a surface to reach equilibrium with the humidity of the surroundings is of the order of an hour.[3] Chaikin,[5] however, finds the relevant time interval to be of the order of minutes (see Figure 7 of this reference). In a steam breakout, diffusion is rapid due to the higher temperatures; a pseudo-equilibrium therefore should be established fast, e.g., in minutes.

There is a hysteresis effect found by E. Schroedinger, quoted by McIlhagger:[3] the values of surface resistivity found for rising humidity are higher than those for decreasing humidity.

Surface resistivity also depends on the measuring frequency. The only data available (Yaeger and Morgan[4]) were obtained for a pyrex glass surface. From 1 to 100 kHz the surface resistivity decreased by a factor of 3 at 50% relative humidity and by a factor of 220 for 96% humidity. The surface layer capacitance remained essentially constant. The phenomenon is unexpected (a bulk electrolyte does not behave that way) and unexplained. Polarization may be one of the underlying causes. The observation of course has a bearing on breakdown initiated by sharply rising voltage pulses.

After the above simplified discussion of our basic parameter ρ_s, we shall proceed to investigate the influence of the various circuit parameters on breakdown.

E. Voltage Dependence

Figure 2 is a circuit schematic which is useful in describing the current flow[12] caused by a gradually increasing voltage V across a moist surface. Resistor R_1 may be very large (10^8 ohms), R_2 is of megohm size, and R_3 represents the internal impedance of the voltage source.

First a minute current of the order of 10^{-9}A and linear with voltage will flow through the only available path, R_1, the resistance of the approximately uniform surface layer. At somewhat higher voltages R_1 becomes nonlinear, dry bands form, and R_1 increases. At a certain voltage V_i (which depends on time, as we remember from Table 1), microdischarges bridge the dry band. Resistor R_2 in series with a low impedance discharge path, as indicated in Figure 2, forms and controls current flow. Further increases in voltage or increases in time lead to breakdown across all or part of the insulator. A low impedance arc is formed. The current is now determined by R_3, the impedance of the outside circuit. The description is compatible with Table 1; it introduces the existence of an initiation voltage V_i.

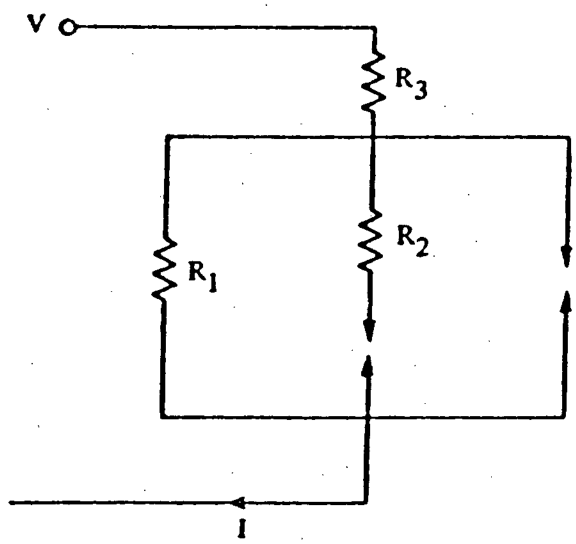


Figure 2. Equivalent Circuit for Low-Voltage Breakdown

Salthouse[12] succeeded in making reproducible measurements of the breakdown behavior for a special insulator (Eastman Chromagram Sheet) using cobalt chloride as an electrolyte and a concentric electrode arrangement. In Figure 3 the inception voltage V_i is plotted versus measured surface resistance; the associated surface resistivity ρ_s is about 1/3 of the plotted parameter. The graph, slightly extrapolated, makes it appear plausible that breakdown starts at around 500 V for a surface resistivity of 10^3 ohms; this is compatible with the behavior of contaminated phenolic insulators. An increase of the voltage at constant ρ_s is seen to lead to what Salthouse calls a "flashover;" here it means a visible spark across the dry band, not an arc between the electrodes. The behavior depicted by Figure 3 is generally found, although variations exist. In Figure 4 (from Mathes and McGowan[8]) the surface resistivity variation was obtained by using an ammonium chloride solution of varying concentration. The ordinate is therefore calibrated in the bulk resistivity (Ω-cm) pertaining to this solution. We see that the initiation voltage is different for different substrates (phenolic gives the worst results). The authors have also indicated that at the very low end of the tracking regime, erosion, (i.e., mass removal from the surface) occurs. At the high voltage end the electrolyte simply blows off, and no damage is observed in the time frame in which the data were taken (1 hour). This potential no-damage situation is a strongly complicating factor for damage prediction statistics.

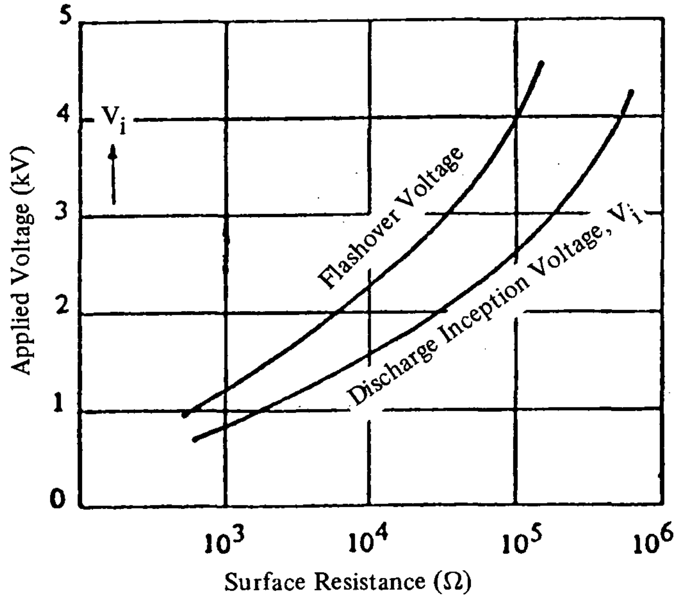


Figure 3. Variation in Breakdown Discharge Inception and Flashover Voltages With Surface Resistance

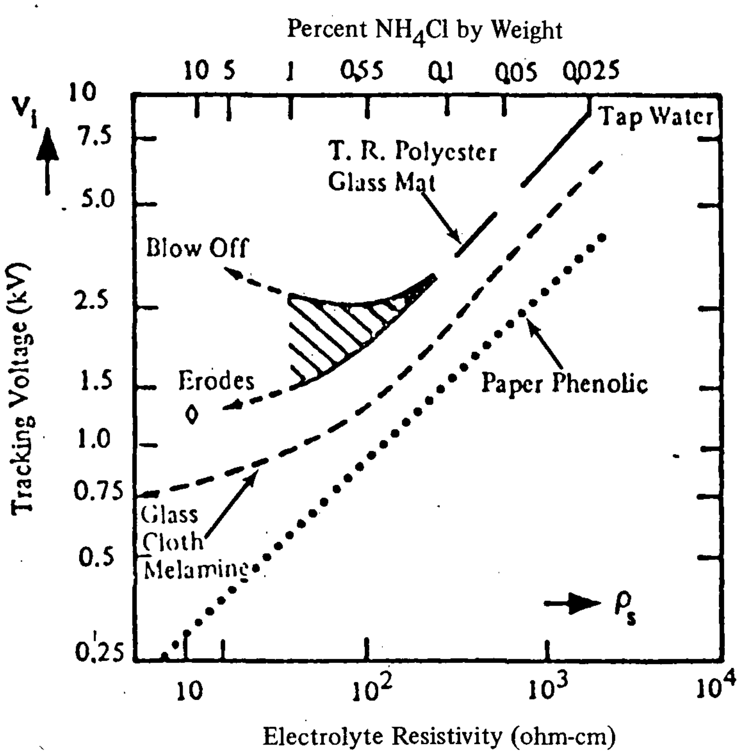


Figure 4. Discharge Inception Voltage vs Surface Layer Bulk Resistivity

It is appropriate at this time to comment on the use of a voltage rather than a field as the descriptive parameter for a breakdown situation. The primary breakdown parameter is the field across the dry band. This is determined by the voltage applied and the width of the dry band, not by the dimensions of the arrangement. This dry band width seems to be rather uniform, between 0.1 and 0.3 mm. Therefore, the voltage is a better parameter than the field between the electrodes. This is generally accepted. Wilkins and Billings,[13] e.g., find only minor variations in the initiation current (see below) with electrode spacing. Mathes and McGowan,[8] however, state that "in a number of cases" the initial voltage V_i is strictly proportional to the electrode spacing (see Figure 9 of this ref). An explanation may be related to the fact that in reference 13 the experiment time is measured in seconds, while in reference 8 it is measured in hours.

F. Current Dependence

Since the onset of breakdown is voltage dependent, one would expect a corresponding dependence on linear current density (measured in A/cm). Experimentally, however, a dependence on current (proper) is found. Wilkins and Billings[13] determined the onset of breakdown for paper/laminate phenolic at $I_B \approx 1.25$ mA. The authors find very little variation of this value with electrode spacing. They determine I_B by measuring the current, at which the time to breakdown decreases hyperbolically (Figure 5).

Comparing materials, it turns out that the value of I_B for phenolics is not near the bottom of the list, while the breakdown initiation voltage V_i is.

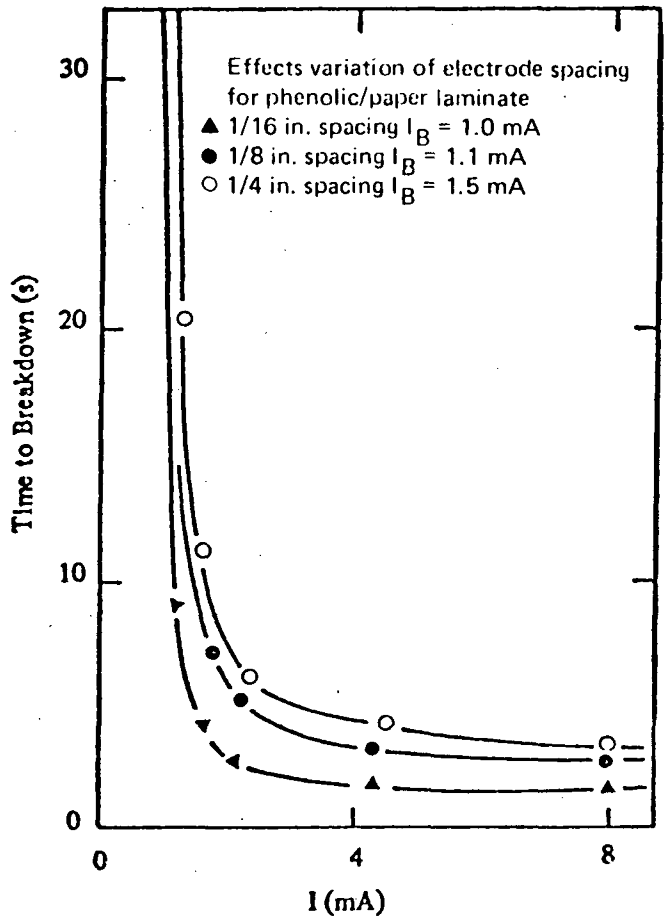


Figure 5. Time to Breakdown vs Current for Various Electrode Spacings

G. Surface Power Density

It is generally agreed that the destructive mechanism (i.e., tracking and erosion) is linked to thermal events. In fact, Wilkins and Billings[13] measured the surface temperature at the breakdown location and found good correlation with the decomposition temperature of the insulator. It is therefore not surprising that the surface power density P_s (W/cm^2) is a good measure for breakdown initiation. For phenolic with a surface resistivity of 3×10^4 ohms, the breakdown deposition is approximately 4 W/cm^2; for a surface resistivity of 10^2 ohms, the values are around 10 W/cm^2, according to Mandelcorn.[14] This is not completely in agreement with average figures quoted in Table 1; in the light of the considerable spread of all measurements the results seem reasonable, however.

As P_s is not easy to measure directly, additional details about its influence and its variations are omitted.

H. Conclusions

We have sketched important aspects of a very complex phenomenon, surface breakdown at low voltages. The complexity is not unexpected. Breakdown depends on six controllable independent parameters (base material, geometry, voltage, temperature, measuring time, and power supply impedance) and on at least two more difficult to control independent parameters (humidity and contamination); there certainly are others, such as surface cleaning methods, air ionization degree, etc. If we select only two values for each parameter we have 256 different combinations. Therefore, the truth cannot be simple and easy to arrive at.

Nevertheless, considerable understanding of both the phenomena and of the importance of the various parameters has been developed. For us, the following points seem to be important.

If several thousand volts are applied, an even slightly contaminated surface will suffer damage; it may take weeks, however. If only a few hundred volts are available, surface breakdown can occur in seconds under conditions of very severe contamination and high humidity. An essential problem for the Three Mile Island reactor accident case is therefore the determination of the accumulated contamination at accident time. Protective enclosures, weepholes sizes, and the presence or absence of flow retarders affect this accumulation.

The survey also predicts that considerable scatter of data has to be expected in an experimental determination of leakage resistance. This makes experimentation arduous and costly and the statistics of breakdown harder to establish.

Finally, from the discussed data it becomes evident that humidity and contamination alone are sufficient to explain observed terminal block breakdown during qualification measurements; it is felt that radiation exposure plays a minor role for the reliability of phenolic terminal boards. We shall return to this point in Section V.

III. Experimental Facilities

It was decided to simulate only temperature, pressure, and temperature rise time up to the TMI-2 accident environment. With a pressure of 1 atmosphere and temperatures less than 86°C (186°F), very simple experimental arrangements could be used, e.g., access to the insulators to be exposed could be obtained simply by opening a lid and sealing of pipes and cables was not a problem. In principle, of course, the arrangements resembled the more powerful facilities[15,16] which are designed to reach conditions existing during a large scale steam breakout.

A. Preliminary System

In a preliminary arrangement (Figure 6), low pressure steam was generated in a pyrex bottle and injected into a large plastic chamber. The chamber was instrumented with a hygrometer and a number of thermocouples; it accommodated one or two terminal blocks, each with 3 to 12 terminals. A heating element in the chamber controlled the temperature. Contaminants were added by dripping appropriate solutions through the steam jet, by dispersion of the solutions by means of a hot air-driven vaporizer, and, for a number of special experiments, by dripping the solution onto the block from an eye-dropper.

While the arrangement was necessary for the acquisition of experience and of preliminary data, it did not permit obtaining simultaneously the temperatures and relative humidities required for a TMI-2 accident simulation.

B. Improved System

A much improved second system used the steam exposure facility of the Sandia environmental test group. The exposure chamber had a volume of about .9 m^3; temperature and humidity could be controlled. Impurities were added directly to the steam supply by means of a venturi nozzle. The facility was programmed to automatically apply steam cycles which reached a peak temperature of 86°C (186°F) in about 25 minutes; this simulated Three Mile Island accident conditions.[17]

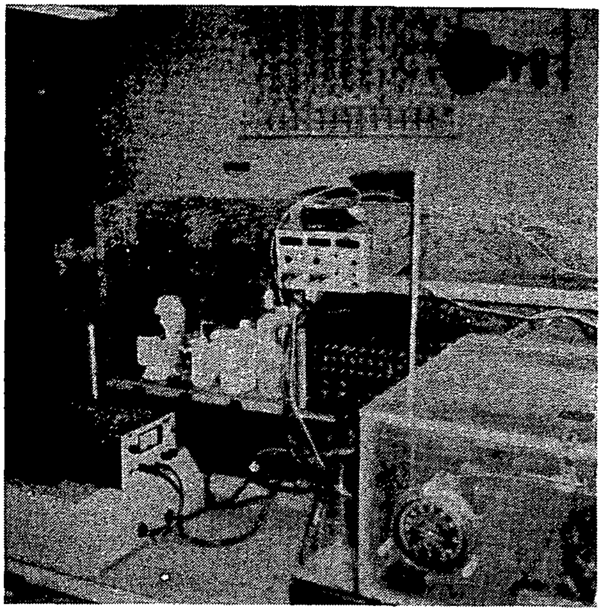
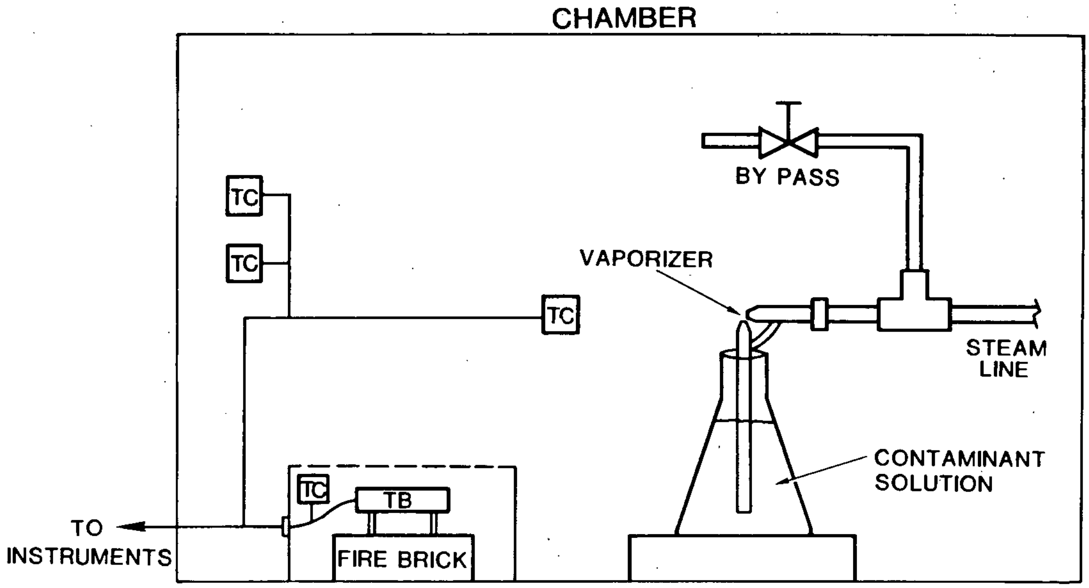


Figure 6. Experimental Setup 1. (Plastic environment box with Hygrometer right front, steam bottle to its left side, power supply left front, switching and measuring arrangements center rear).

Figures 7 and 8 show the interior of the steam chamber. The Erlenmeyer flask contains the contaminants dissolved in distilled water or tap water. The venturi nozzle on top, through which the steam enters, can be partly bypassed to regulate the rate of impurity dispersion. The protective box which contains the block (or blocks) shows a 6 mm weephole on the side. The box could be closed quite tightly with a lid. Figure 9 shows a terminal block (States Co. Model ZWM) and the associated cabling inside the protective box. The three terminal block modules used at TMI-2 are pictured in Figure 10; they all have metallic ground plates.



TB: TERMINAL BLOCK

TC = THERMOCOUPLE

Figure 7. Chamber Layout (From ref. 18)

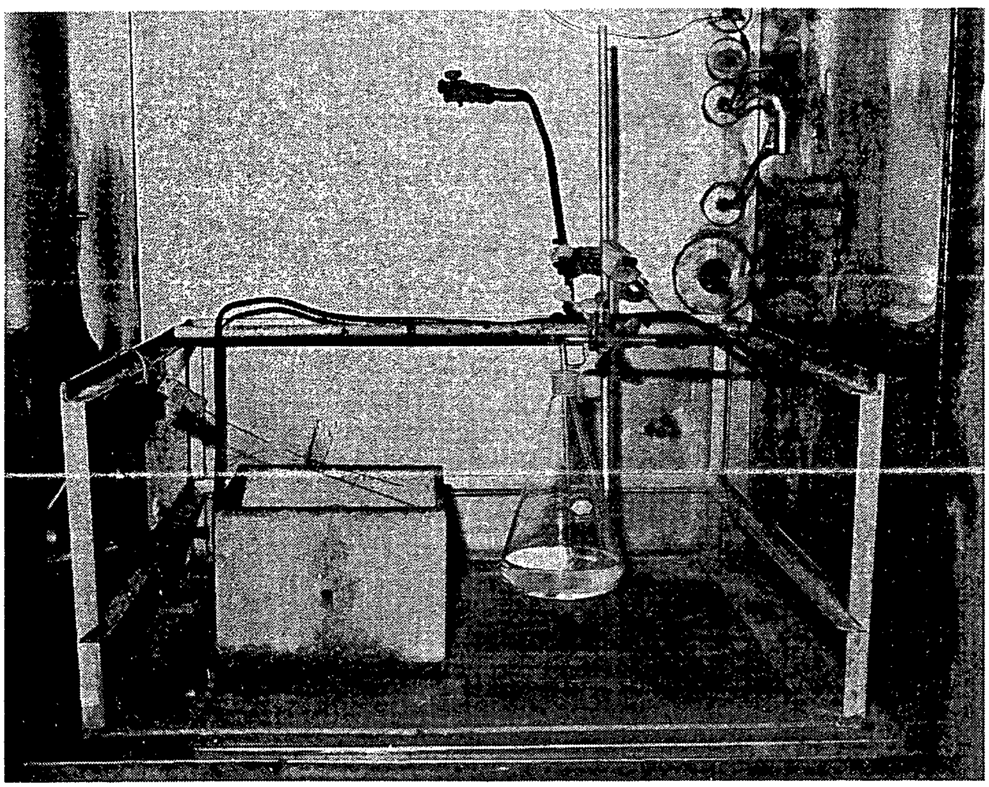


Figure 8. Steam Chamber Interior

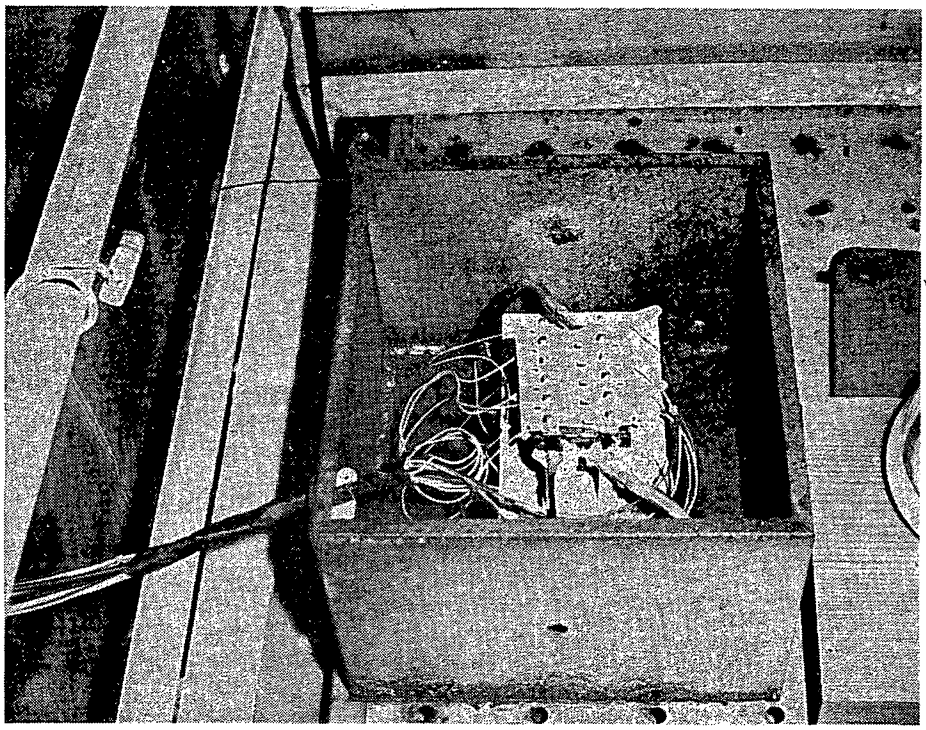


Figure 9. ZWM Terminal Block in Enclosure Box
(Lid Removed; Weephole on Side)

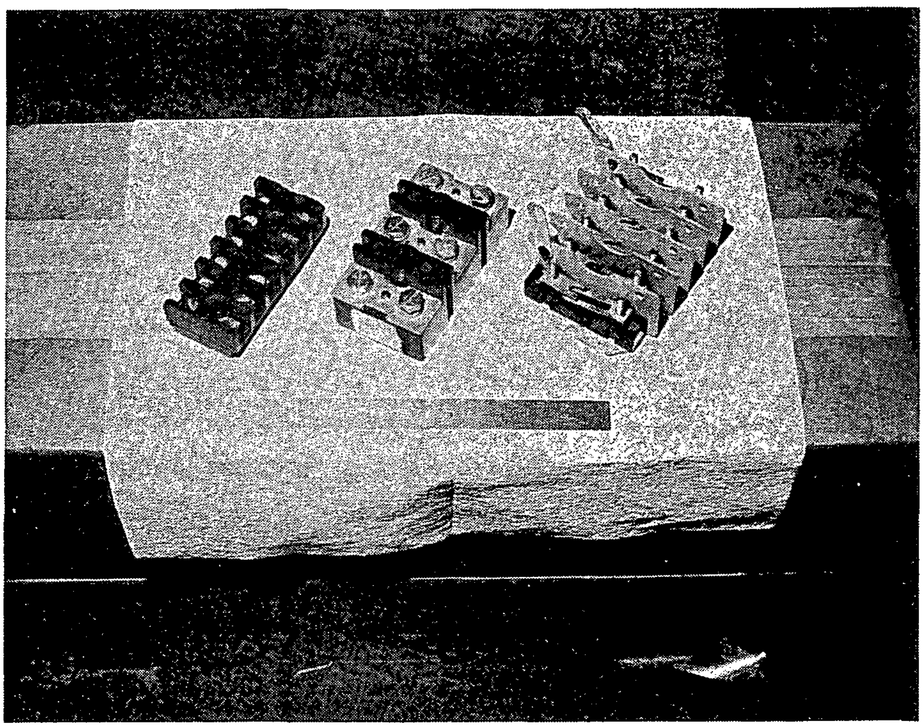


Figure 10. Terminal Block Models Used at Three Mile Island Unit Two.
Left to right: GE CR2960; GE CR151; States Co. ZWM 25006

C. Electrical Circuits

The electrical circuits used are straightforward. The basic principle is shown in Figure 11. The various terminals, with the ground plate at high voltage, are connected to an ac voltage source. Dropping resistors are switched sequentially to a voltmeter to permit measurement of the leakage currents.

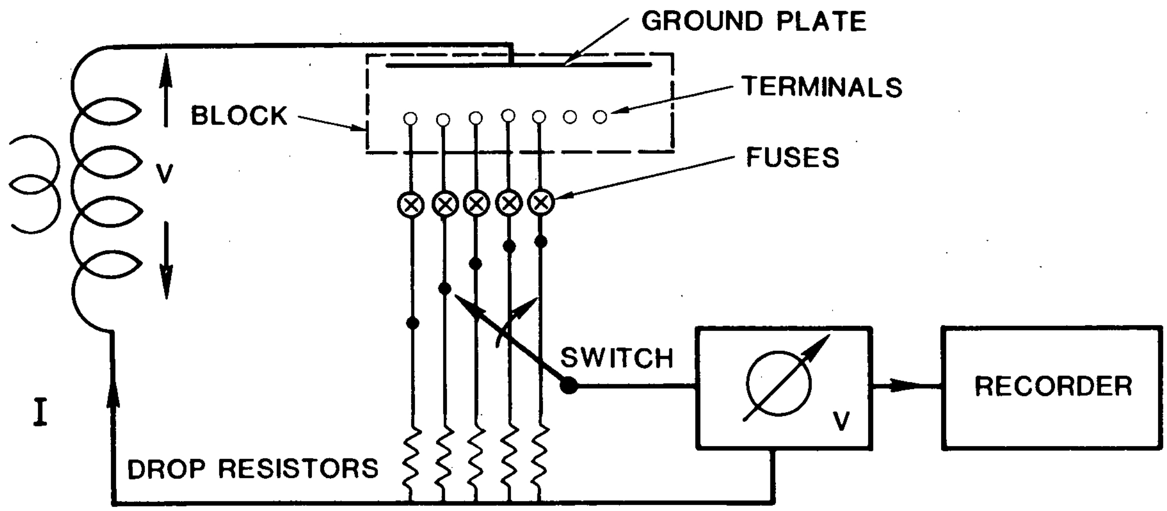


Figure 11. Basic Measurement Circuit

The circuits of Figure 11 eventually developed into an automated computer controlled system[18] which permitted programmed sampling of leakage currents and calibration resistors on 14 channels combined with automatic voltage cycling for groups of blocks, and automatic steam cycling with selectable cycle times. Figure 12 shows a schematic[18] of the essential components of the system. Channel sampling time could be varied from 40 seconds upward. The data were stored on tape for evaluation.

The electrical noise in the system was high (due to its physical location) and ranged from 20 to 30 μA. Since the leakage currents of interest were between .1 and 100 mA, the noise was acceptable, however.

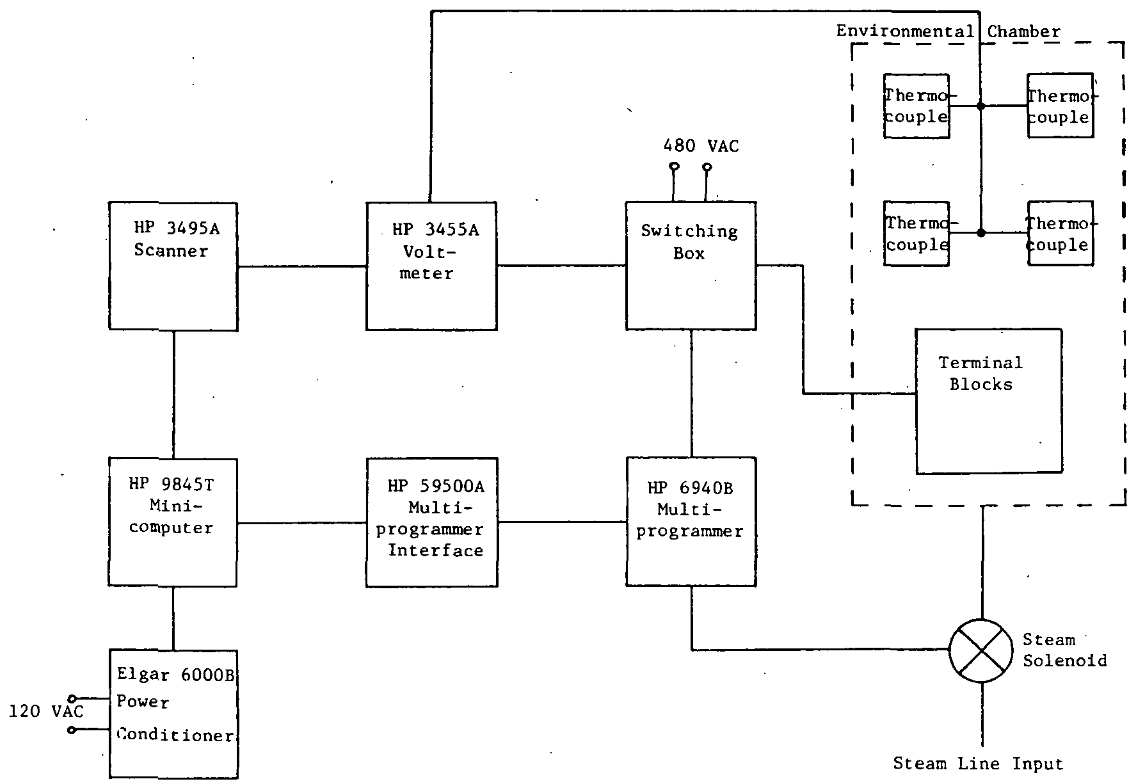


Figure 12. Block Diagram of Advanced Measuring System

IV. Experiments

Experiments were performed by exposing terminal blocks in the apparatus described above to various temperatures and humidities, and to a large variety of added contaminants. We shall first describe three groups of experiments and their gross results, and then add a discussion of the contamination procedures.

A. Low Temperature Measurements

The first series of experiments was performed using the equipment described in Section III A. Terminal blocks were exposed to humidities and/or temperatures as high as the arrangement would permit; contamination was added more or less at random. Voltages were varied from 120 to 480 volts ac.

It became evident very quickly that leakage currents fluctuate strongly, and breakdown occurs mostly on those terminals which draw the highest current. This is compatible with room temperature behavior. An unexpected observation was that currents through various terminals on the same block tended to be proportional; if one current increased, most of the currents through the neighboring terminals increased by the same percentage.

A short time sample measurement is shown in Figure 13. It was made at about 35°C (95°F) at a relative humidity rising from 70% to 90%. At time zero a 1000 ppm (parts per million) spray of room temperature boric acid was administered through the steam jet; as described above, the spray did not directly hit the blocks. The blocks had been handled before. One minute afterward, 480 volts was applied. The leakage current I (which without spray had been below 20 μA) rose rapidly to about 400 μA and then tapered off. The measurement was repeated with the spray preheated to about 150°F before being injected. Naturally, the effects were noticeably enhanced: the block was now cooler with respect to the steam-spray, and surface adsorption was faster. The terminal with the lowest resistance broke down after 3-1/2 minutes. The resulting ion and hot fluid cloud doubled the leakage currents through the other terminals for a minute. The current traces are clearly parallel, i.e., the currents are proportional.

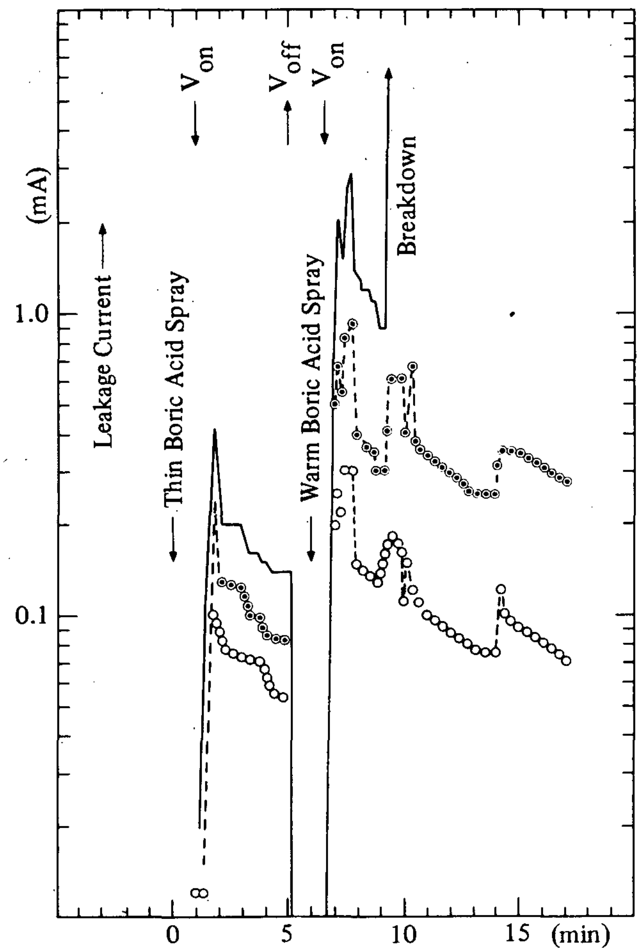


Figure 13. Leakage Current vs Time Showing Breakdown. (Block #2, Temp ≈ 95°F, Rel. Humidity 70-95%, V = 480 volts)

Not shown in Figure 13 are occasional very short current spikes (originated by dry band breakdown) of often less than .1 sec duration. These represent noise. The noise appeared to be 1/f type extending to 30 Hz.

Attempts to reproduce the measurements shown in Figure 13 in detail failed completely. Except for the one total breakdown, the main features (rapid rise, then decay; warm electrolyte more effective than cold one) were always observed, but the details were different. The instantaneous currents were about a factor 2 higher or lower; the average currents, however, stayed within ±30%. In light of the discussion in Section II, this is not surprising. The chemical mix was probably not exactly the same; the spray droplet size and distribution, as well as the air currents in the chamber, were certainly somewhat different; the handling history of the new blocks was unknown; and local temperature and humidity values were not exactly reproducible. The connecting wire harness was reused, and represented a changing source or sink for contaminants.

After about 40 preliminary experiments, many more systematic tests were conducted using the equipment of Figure 6. Each test lasted from five to seven hours. The initial rise of current and fluctuations again was observed; with time (after equilibrium was established), it was followed by a current and noise drop of about an order of magnitude. When the voltage was interrupted and reapplied, a strong current surge occurred. Breakdowns occurred during high current phases. The same observations were repeated in the final experimental series (described below).

From the observations, the following physical picture emerges: with rising relative humidity and steam warmer than the insulator, surface adsorption is rapid and strong. With equilibrium, the leakage current can start drying the surface; that is, a "healing" process begins.

In 38 long runs, more than 200 terminals were exposed. The ac voltage applied was usually 480 volts. Leakage current varied between 10 μA at steam admission to 4 mA prior to breakdown. Seven complete breakdowns were observed, six of them within a few seconds; multiple breakdowns are predicted by our physical model. The secondary current peaks shown in Figure 13 and discussed above are an indication of increased breakdown probability.

B. Forced Breakdowns

A series of additional experiments was designed to obtain preliminary information about the influence of specific contaminants (discussed in detail below) and to study broken-down insulators. Some 50 terminals were forced to break down by dripping contaminant solutions on their surface at various temperatures with voltages applied.

One initially surprising observation (which is, however, quite compatible with the physical picture sketched above) was the following: if the surface was noticeably hotter than the contaminant, the latter was simply blown off, in part by evaporation and in part by electrical forces. For suitably oriented surfaces, the Leidenfrost phenomenon (vibrating and migrating droplets) was seen. If the surface was cooler than the contaminant and slightly dirty or dusty, however, immediate breakdown occurred for conductive contaminants such as "containment spray."

All the broken-down insulators exhibited clearly visible carbon tracks, and some showed erosion. Unexpectedly, however, most of the tracks were not permanently conductive if voltage was removed and the blocks were dried. Of 50 forcibly broken-down blocks, 33 exhibited more than 10 MΩ resistance when measured with a standard 4.5 volt ohmmeter. Eight of the 33 terminals stayed above 10 MΩ at 200 volts. Much the same observations were made with regularly broken-down blocks, i.e., those exposed to our temperature-humidity cycle.

The findings have a bearing on postaccident circuit measurements such as those performed at Three Mile Island: circuit impedance may now be high, while a breakdown occurred during the accident.

C. Final Experiments

Based on the experience gained, an automated exposure program was established in the heavily instrumented facilities described in Section III B. To simulate the several steam breakouts at TMI-2, three sequential steam cycles, with 1-hour and 1/2-hour intermissions, were applied. Superimposed on these were voltage cycles such as would have occurred in control circuits. The interlacing of the cycles is shown in Figure 14. The first voltage application was provided for some terminals (I) a few minutes before steam turn-on, for other terminals (II) 20 minutes after steam application. Steam admission was automatically controlled such that the maximum chamber temperature (measured at three locations) was 86°C (186°F). The resulting temperature cycles also are shown in Figure 14. The quantity ΔT indicated in the figure is the wet bulb/dry bulb temperature difference; the curve means that 100% relative humidity was reached in about 5 minutes in the experimentation chamber (but not inside a protective enclosure). The typical (smoothed) leakage current is shown on the bottom of the figure; the drying-out phenomenon is clearly recognizable. The dashed trace (II) indicates the enhancement of the leakage current due to delayed voltage application.

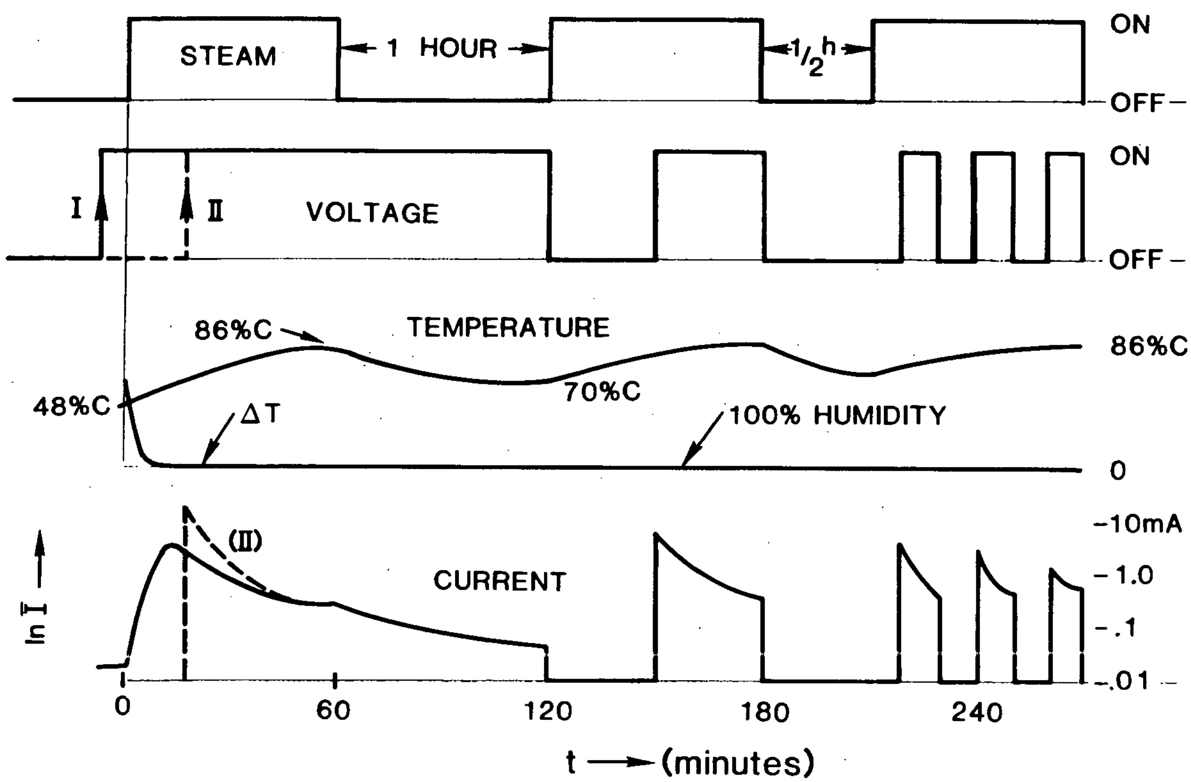


Figure 14. Steam, Voltage, and Temperature Cycles With Representative Leakage Current

Figure 15 shows a computer generated graph of the first 100 minutes of a leakage current measurement for 4 terminals; the terminal indicated by curve 5 had delayed voltage application. In this particular measurement the fluctuations were lower than usual, which makes the graph easier to read.

Data corresponding to those in Figure 15 were taken for 4-1/2 hours on 319 terminals; partial data were taken on 108 additional terminals. Voltage was usually 480 volts; occasionally it was 240 volts. On an average, each terminal was exposed to four sudden voltage applications. Twenty-three breakdowns were obtained, almost all of them within minutes of the beginning of the first and second voltage/steam cycle. Twenty-two of the breakdowns were for unprotected blocks with contamination applied.

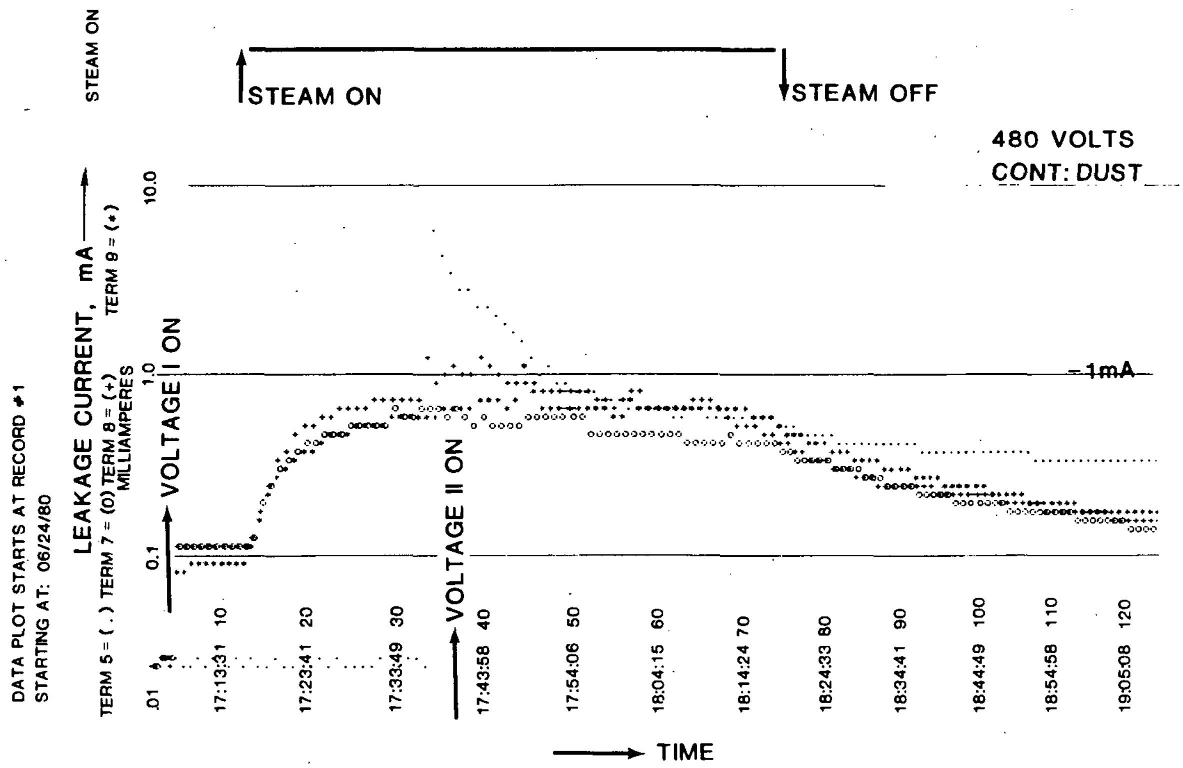


Figure 15. Computer Printout of Leakage Currents of Four Parallel Terminals, One With Delayed Voltage

D. Contamination

With the steam, voltage, and temperature cycles fixed, the main parameter to be selected is the contamination.

The working fluid of the reactor is thin (approximately 1000 ppM) boric acid; in a steam flash it will be dispersed over the containment. The containment spray[19] on the other hand is a quite caustic solution of boric acid, sodium thiosulfate, and sodium hydroxide. Hydrogen is added to the reactor fluid in small quantities; a massive outbreak due to a metal-water reaction occurred during the TMI-2 accident. Table 2 lists additional contaminants[20] which could enter the hydrogen recombiner; at least the same amount of impurities must at some time be present in the containment. In fact, the "conventional substances" at the bottom of the list seem to be present even without an accident. There is a strong suspicion that copious amounts of construction dirt and dust also can be found in the protective boxes.

Considering the general difficulities of making breakdown measurements, a very large number of experiments would be necessary to investigate the effects of contaminants systematically, especially if cooperative effects were to be considered. We limited the scope of our investigations to the following:

1. Boric acid solutions and containment spray solutions of actual concentration were dispersed directly by the methods described in Section III. In programmed experiments the dispersal occurred during the first 30 min.

2. For some of the chemicals of Table 2, the quantities listed were reduced by the volume ratio of the test chamber to the containment (3×10^{-5}) and dispersed as described.

3. Laboratory dust, admittedly not a clearly defined agent, was collected in corners and sprinkled by hand on the blocks. Dust was generally applied before the contaminant(s) under investigation.

4. Often contaminants were added in sequence; no clear collective effects were detected.

Table 2

Quantities of Contaminants Entering Hydrogen Recombiner System

Post-LOCA Contaminants That the Hydrogen Recombiner System Could be Exposed to:

Fission Product Inventory

Fission Products	Quantity Entering System (gm)	Fission Products	Quantity Entering System (gm)
Bromine	24	Antimony	0.0549
Iodine	352 (CH_3I)	Samarium	3.08
Cesium	96.2	Promethium	2.75
Rubidium	15.2	Yttrium	3.40
Tellurium	14.6	Praseodymium	6.49
Ruthenium	12.4	Neodymium	22.0
Technetium	5.08	Tin	1.82
Molybdenium	18.8	Chromium	0.159
Strontium	8.81	Iron	0.254
Barium	8.22	Nickel	0.086

Potential Conventional Air Contaminants

Conventional Substances	Amount Assumed Initially Airborne (gm)
Misc. Oils	3000
Lubricating Oil	3000
Acetone	2930
Carbon Tetrachloride	6000
Greases	3300
Wire Insulation (Smoke)	4540
Paint	5000
Carbon Monoxide	4540
Detergents	3600
Tobacco Smoke	454
Acetylene	454

It is believed that a reasonable simulation of the actual, but in detail unknown, situation was achieved. Hydrogen experiments could not be made at the high concentrations experienced during the TMI-2 accident because the facility did not permit this.

It was observed that compared to pure steam, the addition of even minor amounts (micrograms per cubic meter) of some chemicals led to observable increases in leakage current. A systematic compilation of all results is given in the next section.

V. Evaluation and Results

As already indicated, even the large number of measurements made is not sufficient to establish systematic statistics of breakdown versus all the parameters of interest. It would require about 50,000 tests, each several hours long, in order to: (1) vary the major and measurable parameters, such as voltage, temperature, humidity, geometry, chemical contaminants, and protective arrangement, and (2) perform enough experiments in each category to average out such unknown quantities as precontamination, history and detailed distribution of contamination, thickness distribution of adsorbed water layer, neighbor influence, steam flow patterns, air ionization, etc. Therefore, we will use the observations together with physical arguments to establish a simple "average breakdown model" which will correlate with our data. The model will be useful for making preictions, albeit with sizeable error bars.

A. The Model

It has been observed that low-voltage breakdowns are essentially current dependent,[13] at least at room temperature (Section II F). The information in Table 1 points in the same direction: breakdown depends on surface conductivity ($1/\rho_s$), and, for similar geometries, current is proportional to this quantity. There is a maximum current I_B for each configuration, which determines the irreversible onset of breakdown. For the various phenolics, I_B is between 1.1 and 1.5 mA at room temperature[13] (Figure 5).

We now define an average leakage current $\bar{I}_{AV}$, i.e., time averaged and experiment averaged for each essential parameter combination, and expect that the ratio $\bar{I}_{AV}/I_B$ is a measure of the breakdown probability of an average terminal. The model can then be carried through semi-analytically.

B. Breakdown Current

A difficulty seems to be introduced by the fact that the breakdown initiation current ("breakdown current") I_B is a function of temperature. This complication turns out to be a blessing in disguise as it forces us to establish a temperature dependent model suitable for interpolation and extrapolation.

We have shown in Section II that at room temperature the surface resistivity is about 10^5 times higher[3] than it would be for an ohmic conduction process. Since the mobility is absolved[3], we have to make the carrier density responsible, i.e., dissociation. Over the relatively small (300 K to 470 K) temperature range which concerns us, dissociation will be subject to an exponential activation process. We can define a temperature independent activation energy ΔE and describe conductivity, and therefore current variations, by

$$I_B = I_{BO} \exp(-\Delta E/kT) \quad (1)$$

where k is Boltzmann's constant. Since I_B/I_{BO} at room temperature is 10^{-5}, we can calculate ΔE simply; we find that $\Delta E \approx .31$ eV, a reasonable value in the light of our knowledge of semiconductor band gaps. Current I_B is plotted in Figure 16 over an inverse temperature scale for which Eq (1) gives a straight line. From the literature, we have $I_B = 1.3$ mA at room temperature. At 343 K (110°F), the curve predicts $I_B = 5$ mA, and at 386 K (186°F), we expect $I_B = 20$ mA. These values are very close to our experimental observations. For 463 K (325°F), our theory predicts 95 mA breakdown current, which is certainly not out of line with observations by Franklin Institute[21]. Equation (1) and our value of ΔE can be considered justified.

C. Average Leakage Current

The average leakage current $\bar{I}_{AV}$, to be defined below, is not expected to -- and does not -- follow an equation similar to Eq (1). The average currents, as do the instantaneous currents, depend on the local balance between water being adsorbed from the environment and water being evaporated, mostly due to current heating. The arriving water molecules are transported (barring direct impingement) by diffusion, and diffusion is strongly temperature dependent. This means that a temperature dependent factor has to be added to Eq (1). Everything else being equal, the leakage current will be relatively lower at lower temperatures than the slope of Eq (1) predicts. A glance at Figure 16, where experimental average leakage currents are plotted versus 1/T, shows that this is the case. Figure 16 is discussed more fully later; it is established with the data shown in Figure 17. The average leakage currents plotted in Figure 17 are experiment averages for blocks. First the algebraic average of the current $\bar{I}_v$ was determined for each of the eight to twelve terminals exposed together, i.e.,

$$\bar{I}_v = \frac{1}{t_o} \int_o^{t_o} I(t)dt \quad ; \qquad (2a)$$

the determination was made by computer integration or by graphical integration. Then the results for all terminals on the block were averaged by

$$\bar{I} = \frac{1}{n} \sum_1^n I_v \quad ; \qquad (n = 8 \text{ to } 12) \quad . \qquad (2b)$$

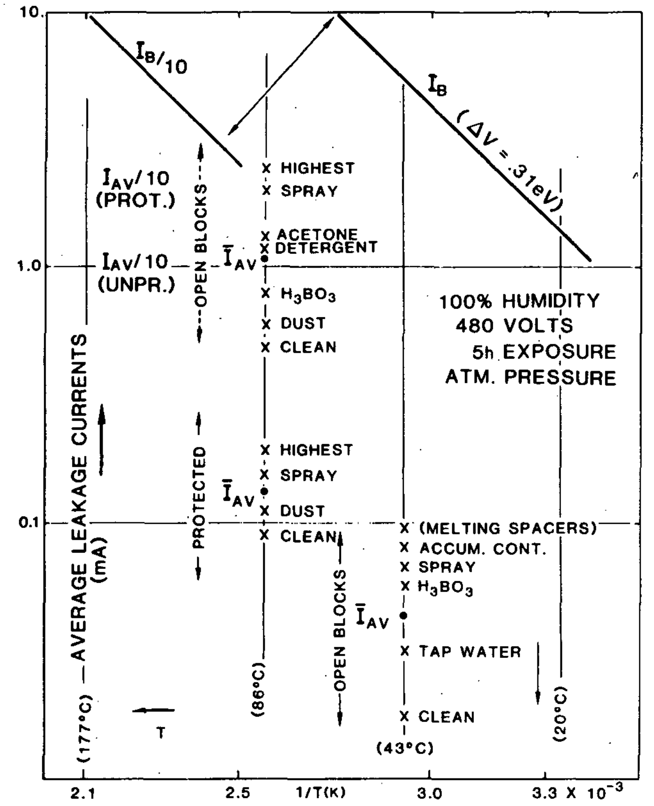


Figure 16

Leakage Current Distribution

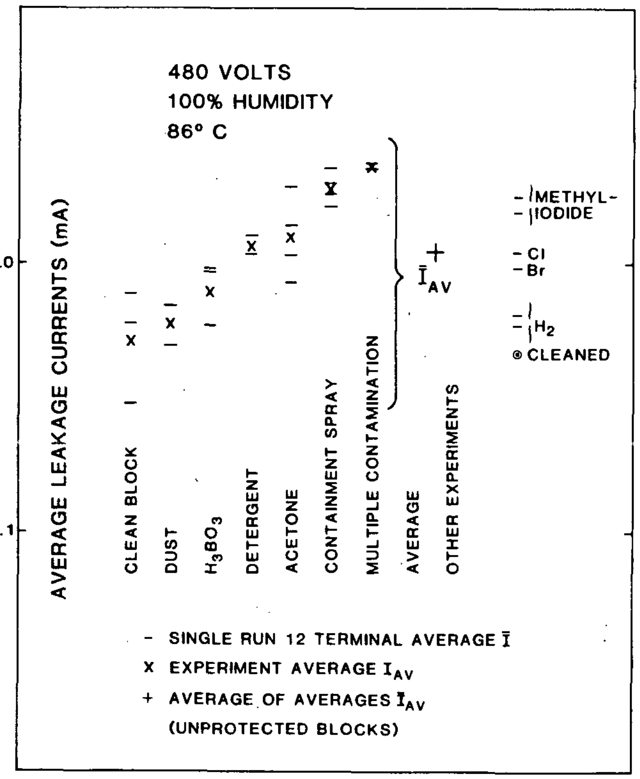


Figure 17

Impurity Ranking

The terminals contributing to $\bar{I}$ were all exposed to an "identical" environment and had comparable histories. Values of $\bar{I}$ are plotted in Figure 17 for different (prime) contaminants, arranged in such a way that the more effective chemicals progress to the right. Also entered in Figure 17 are (as crossmarks) the group averages I_{AV} of all blocks exposed (mainly) to the same contaminant. Since the plot is logarithmic, the geometric average was selected, namely

$$I_{AV} = (\bar{I}_1 \cdot \bar{I}_2 \cdot \cdot \cdot \bar{I}_n)^{1/n} \quad ; \tag{3}$$

linear averaging would not have altered the results materially. A final geometric group average $\bar{I}_{AV}$, formed from the I_{AV} values, characterizes all experiments made at the same voltage, temperature, and diffusion condition (i.e., protected or non-protected blocks). The values in Figure 17 are for 480 volt energization, for TMI-2 temperature, and for unprotected blocks. Similar compilations were made for other experimental conditions. All values are plotted in Figure 16 below our curve for the breakdown current. Figure 16, which is more fully discussed in Section VI, contains one of the main results of our study, the average leakage currents and their approximate spread with contamination.

D. Breakdown Probability

From $\bar{I}_{AV}$ and I_B we now define an average breakdown probability

$$P_{AV} = K \cdot \frac{\bar{I}_{AV}}{I_B} \quad . \tag{4}$$

The physical meaning of P_{AV} is the probability of complete breakdown for a terminal with average (or with unknown) contamination. K is an adjustable parameter used to improve compatibility with experimental results; it should be near unity. We find, however, that optimum agreement with experimental data is achieved for K = 1.4. We will use this value in Eq (4), fully aware that resulting agreements with experiments will seem unrealistically precise.

We now use Eq (4) to calculate three probability values for each measurement group and enter them as triangles into Figure 18, which is a plot of probability of complete breakdown versus inverse temperature. The three values are P_{AV}, corresponding to $\bar{I}_{AV}$ in Figure 16, the probability pertaining to the optimum conditions (marked "clean block"), and the probability pertaining to the worst case ("highest contamination").

These semitheoretical values have to be correlated with direct experimental data. In Table 3 our measured data, which were acquired with the methods described in Section IV, are listed, together with values from commercial sources at high temperatures (163°C or 325°F) and a room temperature estimate.

Table 3

Breakdown Statistics for Terminal Blocks
(480 Volts, 100% rel. Humidity, 5 hours exposure)

Temperature	Number of Experiments		Breakdowns	Probability
163°C = 325°F (Commercial Tests)	Protected*	28	4	.14
	Open	20	6	.30
	Overall	48	10	.21
86°C = 186°F (Three Mile Island 2)	Protected*	112	1	.009
	Open	315	22	.07
	Overall	427	23	.054
43°C = 110°F (Laboratory)	Protected*	42	0	$<10^{-3}$
	Open	170	2(+4 multiples)	.012
	Overall	212	2	.009
Room Temp.				$\sim 10^{-5}$

*6 mm weephole

Some comments are in order here, because the commercial experiments were made under conditions different from ours. The available data on these measurements (Franklin Institute, Westinghouse Canada) are listed in Table 4. Conditions similar to the IEEE specified design accident environment[19] (large break LOCA) were used. Relative humidity was, like ours, 100%. The pressure was very much higher than ours; this should be of minor influence, as diffusion is essentially pressure independent. The fast initial temperature rise prescribed by the IEEE encourages breakdown. The admixture of contaminants was more conservative than ours, however. Voltages used were sometimes higher (by 40 volts) than 480 volts, but the temperatures were often lower (290°F instead of 325°F). The exposure time was longer than ours, but almost all breakdowns occurred early in the test. Overall, we are justified in comparing this family of experiments with ours, considering the +50%/-30% error margin we have applied to all predictions.

Table 4

Commercial Breakdown Data
(100% Humidity, 285°F-325°F, 480-600 Volts ac)

Experimenter	Blocks	Number of Terminals Protected	Number of Terminals Unprotected	Number of Breakdowns
Franklin Inst., for N.E. Utilities Ref: 22, 23, 24, 25	Marathon (Open)		4	2
	Westinghouse (Open)		2	0
	GE, 25 mm Weephole	2		0
Franklin Inst., for CYAP Ref: 26	GE, Westinghouse, KULKA, Al Box	6		3
	GE, Westinghouse, KULKA, Steel Box	6		0
	GE, Westinghouse, KULKA, Steel Box	6		1
	GE, Westinghouse, KULKA, Steel Box	6		0
Westinghouse Canada Ref: 27, 28	Culter Hammer (600 Volts)		12	4
	Penn Union		2	0
	GE, Al Box, 1 in. weephole	2		0
	GE, Al Box	2		0
Not Included in Evaluation				
Franklin Inst., for Weidmueller Terminations Ref: 21	Weidmueller, Tight Box Melamine - Voltage Lowered During Experiments to Avoid Breakdown	25		0

Table 3 also contains a room temperature estimate. At this temperature (where steam is water vapor) the breakdown probability is very low. From Table 1 we see that 480 volts is probably under the threshold voltage for breakdown except for the dirtiest surface. Observed breakdowns take weeks to occur; the breakdown probability P_{AV} is estimated as 10^{-5} with an uncertainty factor of 10 on either side of it. For protected terminals, P_{AV} would be still lower.

We finally enter, from Table 3, the experimental breakdown probabilities (P_{AV}) for protected and for unprotected terminals into Figure 18 and connect the data points by free-form curves. We know that these curves must have horizontal asymptotes for P = 100% and effective vertical asymptotes (for P = 10^{-4} to 10^{-6}) at room temperature. The general shape of the curves is therefore well determined by two or three real data points, and certainly so within our wide error limits.

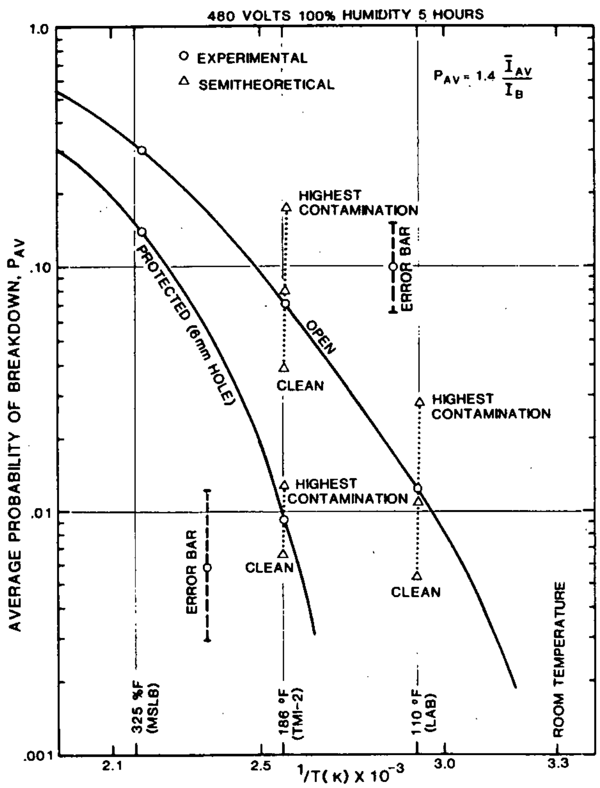


Figure 18. Average Probability of Breakdown vs Inverse Temperature

As stated above, the experimental data (with our adjustment factor K = 1.4) fit the expected value points for average conditions surprisingly well. Our model appears viable, although it has a number of shortcomings which are discussed later.

VI. Conclusions and Recommendations

Figures 17 and 18 and Table 3 contain the main results of our investigation. Their importance and their limitations are discussed below.

A. Discussion of Results

For 100% relative humidity and a potential difference of 480 volts, Figure 18 represents the temperature dependence of the average total-breakdown probability of a phenolic terminal block for two cases. In the first case (upper curve), the insulator is open to the environment but is not directly hit by steam or spray. In the second case, the block is protected by an "average" (i.e., not hermetically sealed) enclosure with a 6 mm (1/4") weephole. If the protection is increased by a 2 mm flow retarder in the weephole, the applicable curve would be lower by a factor of two or three. At higher temperatures (left side of plot), the curves tend to approach each other: diffusion through the weephole becomes so fast that any protection effect decreases. At lower temperatures, breakdown probability becomes negligible even in a humid environment. The curves are for average (or unknown) contamination. For higher contamination the curves shift upward, in very severe situations by a factor of two. For low contamination an equivalent decrease is predicted. Contamination degrees such as "highest" or "clean block" are not rigorous but, rather, practical designations.

There are two kinds of data in Figure 18. Firstly, the experimental points (open dots) suffer from the shortcomings of low number statistics for situations where breakdowns are rare, i.e., on the right and lower side of the graph; at 110°F, as Table 3 shows, there were only two independent breakdowns after eliminating multiple events, and there was only one breakdown inside a box under TMI-2 accident conditions. Secondly, the semitheoretical points (triangles) obtained from correlation with our model have been determined by multiple averaging from highly fluctuating data. Considerable error bars are therefore indicated and, for prediction, have to be attached to the curve values: +50%/-30% at the higher probabilities and a factor of two at the lower end of the curves.

B. Application of the Model

The model represented by the curves establishes correlation between breakdown probability, which is extremely hard to measure, and average leakage current, which is quite easy to determine. The correlation is useful in both directions. Commercially, e.g., average leakage currents $(\bar{I}_{AV})$ have not been published, but the breakdown probabilities have been measured reasonably well. Therefore, from Eq. (4) and Table 3 we can estimate the average leakage currents at 325°F, and find 20 mA for an unprotected terminal and 9 mA for an insulator in a box with a weephole. The values are entered in Figure 16.

More importantly, the model permits parameter scaling, with certain precautions. We have found, e.g., that in our measurement leakage current for high and average contamination were ohmic, i.e., leakage currents are proportional to voltage, and probability then scales with voltage. At 240 volts we expect half the breakdown probability, and at 120 volt a quarter of the 480 volt values. For insulators approaching the designation "clean", this model is not applicable; currents here, and therefore probabilities, decrease much faster than linearly with voltage.

The capability to estimate electrical total breakdown probabilities and to establish average leakage current is needed for the analysis of circuit behavior under accident conditions. Fluctuations were observed to be generally proportional to leakage current, so we have now a means of estimating maximum instantaneous current (3 to 5 times average) and noise (1/f noise with average current value, $\bar{I}_{AV}$, at 1 Hz and extending to 30 Hz).

C. Shortcomings of the Model

The work reported, while apparently very broad, has some shortcomings in addition to its strongly statistical nature.

1. Neither in our nor in the high temperature commercial measurements were the insulators exposed to radiation during the experiment. The bulk

properties of phenolics are not affected by deposition of less than 10^7 rads.[29] Up to this exposure the only concern is for surface effects, i.e., essentially radiolysis occurring in the surface water layer. The problem was addressed theoretically, using literature data (see Appendix A). It was found that for TMI-2 accident conditions, the effect of radiolysis is negligible on surface conductivity, and therefore on breakdown. For radiation depositions of 10^8 rads or more, the above findings may have to be reevaluated.

2. Hydrogen gas is present in molecular form in the reactor fluid. During an accident, massive outbreaks can occur. But H_2 is a very stable molecule; the dissociation up to 470K is very small. No indication could be found in the literature that solvated H_2 contributes to surface conductivity. Surprisingly, at an addition of about one half volume percent of H_2, three terminals (previously contaminated with spray or acetone) broke down, a number not expected from statistics. Unfortunately, a facility for higher concentration hydrogen experiments was not available.

3. The hydrogen puzzle raises the question of the completeness of our investigation; not all the chemicals in Table 2 were tried, nor were collective effects systematically investigated.

4. From the physics of breakdown, one would expect to see response variations with terminal block design. Blocks with screwholes, e.g., in which liquid and dirt can accumulate, should break down more often than clean designs where breakdown paths are only statistically formed. This effect showed up clearly in our forced breakdown experiment (Section IVB), but was barely recognizable in steam exposure experiments because it was veiled by statistics.

5. Mechanical damage to blocks seems to be quite common. Cracks, in which contaminated water can accumulate, will increase the breakdown probability.

6. Breakdown and deterioration can be very circuit specific: a 50 K leakage path may completely eliminate one circuit and have no effect whatsoever on another.

Most of the above phenomena have a tendency to aggravate the terminal block problem; our evaluation is therefore optimistic. Even so, it points out that terminal blocks in a containment can cause considerable problems during an accident or even just with a small steam leak occurring.[31]

D. Recommendations

The results of our study indicate that the following recommendations for reducing or eliminating the danger from terminal block deterioration are warranted:

1. For existing reactors, steam cleaning of terminal blocks with subsequent alcohol washing is recommended, especially if considerable amounts of dust are found in the protective box or if an accident has occurred. A very highly contaminated block, cleaned this way and sealed with RTV, was regenerated completely and functioned like a new block during a steam cycle; the measurement is indicated on the right of Figure 17. As a single very dirty terminal is prone to take its neighbors along in breakdown, cleaning of contamination spots is important.

2. The protective boxes in the containment should be inspected for loose, open, or missing lids. The boxes should be tightened, and the weepholes should be eliminated, decreased in diameter (e.g., by insertion of flow retarders), or equipped with some kind of bimetallic closing device which automatically activates at high temperatures.

3. For new reactors or for thorough retrofit situations, elimination of terminal boxes as in safety-related circuits (as already accomplished at TMI) should be considered for all those circuits which are of conceivable use during and after an accident.

During construction, cleanliness and dust protection should be emphasized--gloves may have to be used or a postcleaning requirement may have to be established.

4. Special attention should be given to penetration boxes and instrument boxes on the containment wall; they are connected to a heat sink, and the blocks inside will suffer higher water adsorption. High voltage circuits (480V) and those circuits where the power is cycled are most endangered.

5. Circuit overloads leading to insulation burns have to be avoided; smoke from burning wire insulation enhances breakdown.

6. Terminal blocks should not be mounted in such a way that condensate can collect in screwholes close to a potential breakdown path. Separators with a low melting point should be avoided. It may be advisable to perform a re-design study to make blocks more breakdown resistant.

7. For accident analysis, it should be kept in mind that broken-down blocks may heal. Low voltage postaccident tests do not permit conclusions concerning the behavior of a circuit during the accident.

8. Large amounts of effective contaminants (Table 2) seem to exist in containments, without clear reason. Consideration should be give to eliminating most of them.

9. The screening tests performed at the behest of the USNRC[30] are quite meaningful in general; however, due to the highly statistical nature of breakdowns, they should not be used for detailed decisions.

10. For a complete assessment of terminal block malfunctioning, a detailed circuit analysis has to be performed.

References

1. S. Whitehead, Dielectric Breakdown of Solids, Clarendon Press. Oxford, 1950 (See Chapter "Surface Breakdown").

2. R. A. Fava in "Treatise on Materials Science and Technology", Vol. 10, "Properties of Solid Polymeric Materials", Part B, Edited by M. Schulz. Academic Press, NY, 1977.

3. D. S. McIlhagger and E. C. Salthouse, Proc. Inst. El. Eng. 112, p. 1468, 1965.

4. W. A. Yaeger and S. O. Morgan, J. Phys. Chem. 35, p. 2026, 1931.

5. S. W. Chaikin, IRE Transactions QC-6, p. 57, 1956.

6. T. C. Williams and D. B. Herrmann, IRE Transactions QC-6, p. 11, 1956.

7. E. C. Salthouse, Proc. Inst. El., Eng. 115, p. 1707, 1968.

8. K. N. Mathes and L. J. McGowan, Proc. AIEE 80, Part 3, p. 281, 1961.

9. M. J. Billings, et.al., IEEE Transactions on El. Insulation, E13, p. 33, 1968.

10. E. Liste, Z. Phys. 62, p. 646, 1930.

11. J. S. Dryden and P. T. Wilson, Australian J. Appl. Science 1, p. 97, 1950.

12. E. C. Salthouse, IEEE Conference on Dielectric Materials, Measurements and Applications, p. 245, July 1970.

13. R. Wilkins and M. J. Billings, Proc. IEEE, 116, p. 1777, 1969.

14. L. Mandelcorn, Proc. AIEE 80, Part 3, P. 481, 1961.

15. See, e.g., Franklin Institute Reports F-C 4033-3, January 1975, and I-C 4911-1, January 1978.

16. L. L. Bonzon, "LOCA/MLSB Simulation Facility and HIACA", Sandia Internal Memorandum, 1/23/80.

17. Nuclear Safety Analysis Center, Report NSAC-1, July 1979 (see Attached Accident History Graphs).

18. J. L. Johnson, "Terminal Block Testing: Hardware Implementation," Sandia Labs Internal Memorandum, 6/5/80.

19. IEEE Standard for Qualifying Class 1 E Equipment for Nuclear Power Stations, IEEE 323, 1974.

20. TMI-2 Final Safety Assessment Report (FSAR) Table 6.2-16, p. 6.2-81.

21. Franklin Institute (for Weidmueller Terminations), Report F-C5205-1, October 1979.

22. Franklin Institute Research Laboratories, Report F-C4911-1, January 1978.

23. USNRC, Minutes of Meeting on Feb. 1, 1978, Docket No. 50-29, Feb. 3, 1979 (sic).

24. USNRC, Summary of Meeting on Jan. 29, 1978, Docket No. 50-2134, Jan. 30, 1978.

25. General Electric Company, Letter to Metropolitan Edison Co., GP-8-58, Oct. 10, 1978.

26. USNRC, Summary of Meeting on March 23, 1978, Docket No. 50-213, March 30, 1978.

27. Indiana and Michigan Power Company, Letter to Office of Nuclear Reactor Regulation, Docket No. 50-316, DPR #74, March 22, 1978.

28. Donald C. Cook Nuclear Plant Unit #2, Docket No. 50-316, undated.

29. J. E. Gover, Personal Communication.

30. USNRC Bulletin 78-02, January 30, 1978.

31. See, e.g., USNRC, IE Circular No. 80-15, June 20, 1980.

APPENDIX A

Radiolysis and Surface Conductivity

During nuclear reactor excursions, insulating surfaces are exposed both to high humidity and to sizeable doses of radiation. The thin water layer on the insulator is then partially ionized by radiolysis. Some of the ions (H^+ and OH^-) have a relatively high mobility in an electric field and may generate surface conductivity and thus contribute to electrical breakdown.

We will discuss the pertinent physical phenomena and provide a general estimate of the resulting conductivity. For the special case of the TMI-2 accident, numerical figures will be furnished. We assume a pure water layer without chemical contamination on the insulating surface.

An essential parameter is the thickness δ of the water skin. It is a function of relative humidity (Figure A1). For glass as substrate,[A-1] δ varies from 17 to 120 monolayers, if the humidity varies from 90% to 97%. There is indication[A-2] that for phenolic surfaces approximately the same values apply. For the TMI-2 situation, the insulators of concern are mounted in a protective "penetration box" with a weephole. We estimate that with unplugged weepholes the humidity inside the boxes varies from 60% to 97%. Therefore, the layer thickness varies between 4 and 120 monolayers, i.e., between 32 and 960 x 10^{-8} cm. These figures are of course not valid if there is direct spray impingement, dripping, or liquid collection in design features such as screwholes.

The complex reactions in irradiated water are analyzed in some detail by Baker and Limatainen.[A-3] Of importance for us are not the copious molecular products formed, but the ionized radicals, mainly H^+ and OH^-, which have the highest mobilities. The authors define a factor G_R which describes the number of radicals which "leave the tracks of the ionizing radiation" for each 100 eV absorbed. In the absence of other data for assessing electrical phenomena, we shall use the G_R values for analyzing the conductivity increase (or leakage resistance) under radiation.

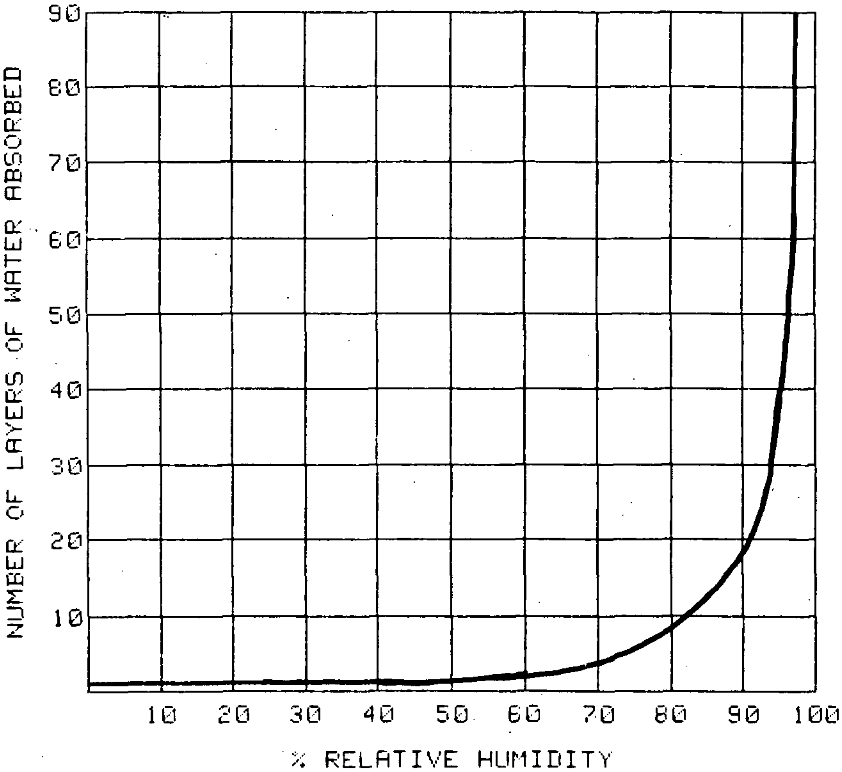


Figure A1. Number of Adsorbed Water Layers vs Relative Humidity

For water moderated reactors the energy deposition is mainly caused by γ-rays.[A-4] Depending on reactor design, G_R values vary between a low value of .4 and a maximum of 2.7 radicals per 100 eV. If r rads/sec = r x 6.25 x 10^{13} eV/sec gr impinge on 1 ccm (= 1 gr) of water, the number of ionized carriers formed in this volume is

$$n = 6.25 \times 10^{11} \times G_R \cdot r/cm^3 \cdot sec, \qquad \text{(A-1)}$$

according to the above definition of G_R.

To calculate the resulting conductivity σ, we need to know the average lifetime τ(sec) and the average mobility μ(cm^2/V sec) of the generated ionic carriers. The values for both quantities are known to be strongly dependent on the thickness δ, which for our case is sometimes of the order of the mean free path of molecular motion. This fact increases the lifetime τ and decreases the mobility μ in a manner which is not well understood, but as these quantities enter the equation for σ as a product, we feel we can use bulk values for our estimate. Lifetime τ then may be taken between 10^{-3} and 10^{-1} seconds, and mobility μ between 10^{-5} and 10^{-7} cm^2/V sec. We find, therefore,

$$\sigma = q \cdot n\tau \cdot \mu \; (\Omega^{-1}cm^{-1}) \tag{A-2}$$

where q is the elementary charge, 1.6×10^{-19} A·sec.

We can now finally calculate the resistance R of a strip on the surface which is a cm long and b cm wide, $R = a/b\delta\sigma$, and find, using Eqs. (A-1) and (A-2):

$$R \approx \frac{1.6 \times 10^{-12}\, a}{b\delta q\, G_R \cdot r\, \tau\, \mu} \; . \tag{A-3}$$

For terminal blocks in the TMI reactor, $a \approx b$ and the two quantities cancel. Of course, the worst (i.e., smallest) leakage resistance is obtained for the maximum parameter values in the denominator. The maximum radiation deposition outside the reactor vessel, but inside the containment, observed at TMI was 6000 rads/hour = 1.67 rads/sec.[A-5] Using this and the other maximum parameter values listed above, we find a leakage resistance of $R \approx 2 \times 10^{16}\Omega$. Hydrolysis alone therefore causes very little leakage. Even if we modify our figures for δ, G_R, r, τ, and μ by one order of magnitude each in the unfavorable direction, R is still $\approx 2 \times 10^{11}\Omega$. At 500 volts or less, the effect therefore is negligible with respect to the circuit impedances involved. The same conclusion is obtained if we take secondary electrons reflected from bulk collisions into account,[A-6] which may change the results from Eq. (A-3) by a factor of 500. Our calculations are of course only valid if linearity and linear superposition holds. This is highly likely for parameters of the order of our considerations.

References for Appendix A

1. Yaeger and Morgan, J. Phys. Chem. 35, p. 2026, 1931.

2. McIlhagger and Salthouse, Proc. Inst. El. Eng. 112, p. 1469, 1965.

3. Baker and Linatainen, "Chemical Reactions," in "Technology of Nuclear Reactor Safety, Vol. 2, p. 470, MIL Press, Cambridge, MA, 1973.

4. Hart, McDonnell and Gordon, "Decomposition of Boric Acid Solutions by Reactor Radiation," Proceedings of the First U.N. International Conference on Peaceful Uses of Atomic Energy, Geneva, 1955, Vol. 7, p. 593.

5. P. Yarrington, Oral Communciation.

6. J. Castle, Oral Communication.

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