UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

#5

FOIA-83-767

August 10, 1981

OFFICE OF THE
COMMISSIONER

MEMORANDUM FOR: Executive Director for Operations ✓

FROM: John Ahearne [signature]

SUBJECT: QUESTIONS CONCERNING RIL No. 123: ELECTRICAL TERMINAL BLOCKS

REFERENCE: NUREG/CR-1682

I would appreciate your providing me some information regarding the evaluation and recommendations of this July 2, 1981 Research Information Letter. In particular:

(1) The RIL recommends "All nuclear power plants using terminal blocks in circuits important to safety within the reactor containment should be inspected to verify that all terminal blocks are enclosed in a protective enclosure."

(2) "All terminal blocks utilized in systems important to safety should be cleaned at least once after construction and possibly periodically thereafter."

(3) "Procedures should be established to keep the terminal blocks clean, and appropriate guidelines should be issued to maintenance personnel regarding the removal of enclosure covers and the cleanliness of terminal blocks. For example, fingerprints on terminal blocks significantly increase the probability of a low-voltage breakdown failure."

The first recommendation is for an inspection. The second and third recommendations are for possible changes in procedures. What is I&E doing with respect to these recommendations, which address actions with respect to currently licensed plants? IE

The RIL also recommends "For new plants, it is recommended that terminal blocks be eliminated, placed in a hermetically sealed enclosure

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when used in electric equipment important to safety, or moved outside of containment." The RIL requests prompt examination by NRR. I would appreciate knowing NRR's position on this recommendation, in particular, which of the following three correctly describes NRR's position (any would be adequate; I do not see that there is an alternative, adequate position). First, the licensees are doing this; second, NRR is not sure Research is correct and they are doing __________________ to verify Research's position; or, NRR knows Research's position is incorrect, because __________________________.

cc: Chairman Palladino

83-767

UNITED STATES
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JUL 2 1981

MEMORANDUM FOR: Harold R. Denton, Director
Office of Nuclear Reactor Regulation

Victor Stello, Director
Office of Inspection and Enforcement

FROM: Robert B. Minogue, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER # 123 PERFORMANCE OF ELECTRICAL TERMINAL BLOCKS EXPOSED TO A LOCA OR STEAM ENVIRONMENT

INTRODUCTION

This memorandum transmits a summary of the results of a completed portion of the NRC Qualification Testing Evaluation (QTE) Program relating to the adequacy of currently utilized electrical terminal blocks when exposed to loss-of-coolant accident (LOCA) or steam line break conditions in a reactor containment. (See Reference on page 9.)

Electrical connections in nuclear power plants are made with electrical connectors, permanent splices and terminal blocks. Research has been conducted on both electrical connectors and splices, and reported previously.

The terminal blocks utilized in nuclear power plants are usually mounted in non-hermetically sealed enclosures with pressure relief or liquid drainage holes. A generic assessment of electrical terminal blocks was conducted using blocks of the type installed at TMI-2 as an example. Based upon a cursory review of other terminal blocks used in nuclear power plants, the conclusions reached as a result of this research and the recommendations made in this Research Information Letter are pertinent to all terminal blocks that may be exposed to LOCA or steam line break conditions.

The research consisted of a series of about 600 experiments on TMI-2 terminal blocks under different steam containment and enclosure environments. Failure modes were identified and a model was developed that predicts the probability of an electrical breakdown failure under combined environmental effects of several accident conditions. It was concluded that terminal blocks utilized in currently operating nuclear power plants should be cleaned and covered at all times, and that, for future plants, terminal blocks should be mounted in hermetic enclosures.

BACKGROUND

Prior to the TMI-2 accident, about 600 of the 3,000 electrical terminal block connections inside the TMI-2 containment were replaced with permanent splices. This change was prompted by deficiencies in the LOCA qualification of electric equipment important to safety previously discovered in the QTE research program. Specifically, the previous research resulted in an I&E bulletin requesting a review of electric equipment important to safety required to operate during a LOCA. The terminal blocks at TMI-2 associated with this type of equipment had not been adequately qualified for LOCA operation and were replaced by permanent splices that had been qualified.

The question was posed by RES management as to whether or not the TMI-2 accident could have been worse if the terminal blocks had not been replaced. Also, since terminal blocks were suspected of being a weak portion of many systems important to safety, it was decided to perform an assessment of the adequacy of terminal blocks to function during loss-of-coolant and steam line break accidents. Accordingly, the scope of the study was expanded to include a wider range of accident environments than TMI-2.

The long-range plan for the QTE program calls for a design verification study of electric equipment important to safety to begin in FY 82. Since this design verification program is still under review by NRR and RES, it was felt that the terminal block study would serve as a pilot project for the planned program, helping to evaluate its usefulness.

TESTS

Testing was conducted on GE CR151 and GE CR 2960 and States Co. ZWM 25006 terminal blocks under varying conditions. The review of previous work showed that the important parameters affecting the terminal block leakage current are relative humidity, temperature, terminal voltage, contamination, and the terminal block geometry and method of installation. Based upon radiation data available on the insulating materials used in the terminal blocks, radiation testing was not included as a test parameter.

Although there is no previous work suggesting adverse effects caused by hydrogen, some scoping tests were conducted with a low concentration of hydrogen which was introduced into the test chamber. These tests were conducted because of the hydrogen release during the TMI-2 accident.

Data were obtained at 110°F. and 186°F., and supplemented by data from the literature at 326°F. Voltage was varied between 120, 240 and 480 volts between terminal and ground and leakage currents were measured. The effect of surface contamination was also studied. The contaminants were those that would be in the containment spray and the reactor coolant, or have been detected in power plants under normal operation. Tests were conducted with both enclosed and open terminal blocks. The tests with the enclosed terminals had a 6mm drainage (pressure relief) hole in the enclosure which is representative of field installations.

The humidity was maintained as high as possible in the test chamber and was approximately 100% for all tests. Because TMI-2 type accidents were of primary concern, the pressure was maintained at one atmosphere. This made it possible to use low pressure test chambers and simplified the problem of introducing contaminants and making measurements and observations. Contaminants were introduced by addition to the steam jet and, in some tests, by direct application to the terminals.

The failure criterion was the terminal to ground leakage current. Failure was judged to occur when a significant increase in leakage current occurred. This increase in leakage current would result in an irreversible short circuit. Most of the data obtained was for cases where failure had not occurred. These data were used to validate a statistical model that was postulated to predict terminal block failure rate.

RESULTS

As a consequence of the relative simplicity of the test apparatus and test method, considerable data were obtained. However, these tests cannot be used as a basis for qualification of terminal blocks for any a full LOCA accident sequence. The purpose of the testing was to identify failure modes and determine the probability of significant degradation or failure when subject to a TMI-2 type accident environment. However, the test results and interpretation can be applied to a broader accident spectrum.

At the voltages in use in electric equipment important to safety that include terminal blocks (equal to or less than 480 volts), the usual high-voltage insulator failure mode is not relevant. However, it is possible to experience a surface breakdown at these lower voltages if the terminal block is exposed to certain accident environments. Although the physical process of this low-voltage breakdown, which is sometimes referred to as "tracking," is complex, the result is a reduction in resistivity from terminal to ground or terminal to terminal caused by a path or track of degraded insulating material containing free carbon. This relatively low-voltage breakdown of phenolic type insulating materials has been noted and analyzed by others. Although there is no definite conclusion as to the exact physical and chemical process leading to the material degradation, the following is a plausible explanation that reflects the current consensus of opinion and correlates, to considerable extent, with the observed degradation.

In the presence of moisture and contamination, a conducting path in the form of a surface film is generated between the terminal and ground (or between the terminals). This is evidenced by a leakage current which, under normal dry conditions, would be a few microamperes with a 480-volt potential between the terminal and ground, and under wet conditions could be as high as a few milliamperes. The heat resulting from the leakage current flow evaporates a portion of the conducting film, forming localized, narrow "dry bands" which tend to be oriented perpendicular to the normal leakage current flow. When the "dry band" is formed, the leakage current is reduced, and a higher voltage difference develops across the band. The electric field resulting from this voltage difference can cause a breakdown on the surface of the phenolic material if the "dry band" width is narrow. This breakdown will result in an electric discharge on the surface or in the air above the surface. In either case, the energy associated with this discharge damages the surface of the terminal block, leaving a residue or "track" of carbon on the surface of the block. For the subject study, these complicating physical processes were taken into account by knowing that the degradation from the low-voltage breakdown would result in a gross loss of surface resistivity and a corresponding increase in leakage current. The leakage current is the parameter which directly affects circuit performance and, therefore, was utilized as the degradation parameter for this study.

For low values of leakage current, the low-voltage breakdown mechanism is reversible in that if the voltage is removed, there will be no carbon residue. However, for a leakage current greater than one to one and a half milliamperes at room temperature, the process is irreversible in that, if the applied voltage is sustained, an eventual failure will occur. This has been shown to be true for phenolic materials of the type used in the terminal blocks tested at room temperature. At higher temperatures, the critical value of leakage current increases. At least, to a first approximation, this conclusion was correlated in this research. It was these critical values of leakage current that were taken as the indicator of probable failure.

Although the generation of carbon residue was referred to above as representing permanent damage, it was noted that in many cases, if the voltage were removed and the terminal block allowed to dry, the terminal to ground resistivity would return to its nominal value before the test. This means that we cannot judge TMI-2 terminal blocks' performances by measurements made after the accident, nor can we judge LOCA qualification of terminal blocks by post-LOCA test measurements.

A review of the literature and also a comparison of the data from the three types of terminal blocks tested show little dependence of leakage current on the phenolic material in the terminal block, and, in fact, this is consistent with the "dry band" mechanism postulated. For this reason, the results from this research should generally apply to all terminal blocks of similar geometry and using similar phenolic insulating materials.

The low-voltage surface breakdown effect is strongly dependent on the ambient level of relative humidity. The effect was not studied for levels of relative humidity less than 100% as this was considered to be outside the scope of work for this program. In any event, we are not aware of terminal block failures during normal plant operation. However, during an accident of the type experienced at TMI-2, the relative humidity is close to 100%, and it was at this level that all the terminal block tests were made.

The low-voltage surface breakdown effect is also strongly dependent on temperature. As mentioned above, the critical value of leakage current varies with temperature. Also, the measured value of leakage current can be expected to increase with temperature, since the resistivity of all conducting films is reduced with increasing temperature. This effect is the result of the increased dissociation of the charge carriers at higher temperature. Also, the water film inventory on the terminal block is affected by the water absorbed from and evaporated into the air surrounding the terminals. The combined effect of these influences results in a greater probability of terminal block failure with increasing temperature.

The low-voltage surface breakdown effect is also dependent on contaminants that are deposited on the phenolic surface. The contaminants can be deposited on the terminal blocks during normal operation or from the reactor coolant and/or during a loss-of-coolant accident. In any case, the presence of moisture and certain contaminants result in significantly higher values of leakage current. Specifically, boric acid, containment spray, detergents, acetone, methyl iodide, chlorine, bromine, and dust collected in the test laboratory were all used as contaminants. Liquid contaminants were introduced into the steam spray, while solid contaminants were placed on the terminal block phenolic material before the experiment.

Hydrogen can be expected*to be present during a loss-of-coolant accident but its influence on terminal block failure was not completely examined experimentally. Due to the stability of the hydrogen molecule, a significant effect on change in resistivity would not be anticipated, and, in fact, there are no data in the literature to indicate that hydrogen would effect the surface resistivity. However, a few scoping tests were conducted with contaminated terminal blocks exposed to one half (volume) percent hydrogen. During these tests some failures were detected, following the application of the hydrogen, that were not statistically anticipated.

A statistical failure model was developed that assumes that the failure rate, as evidenced by a significant excess in terminal-to-ground leakage current, is proportional to the measured average leakage current divided by the value of leakage current above which the degradation process is irreversible. The average leakage current was based on measurements from about 10 terminals per terminal block and for a number of terminal blocks exposed to nearly identical conditions. This average was then empirically matched to the measured failure rate and the proportionality constant adjusted to provide optimum match to the measured failure rate data.

*Even if the LOCA is terminated, successfully, below the Zr-H_2O reaction threshold, PWRs operate with a small amount of dissolved H_2 in the coolant.

Using this approach, failure probabilities were calculated as a function of temperature for various levels and types of contamination and for enclosed and open terminal blocks. The protected terminal blocks were in a non-hermetically sealed enclosure with a 6mm drainage hold. The open terminal blocks were exposed to the steam environment without permitting direct impingement. The estimated error associated with the probabilities obtained with this model ranges from about ±50% at full LOCA conditions to about ±100% at conditions typical of the TMI-2 accident. The following specific results were obtained from the model relating breakdown probability to the measured block leakage current:

1. Figure 1 and Table I show, in summary form, the results of the experiments and the conclusions drawn by use of the probability model.

   The data relate the probability of terminal-to-ground low-voltage breakdown as a function of the inverse temperature. Curves are drawn through experimental data points for both the open and enclosed terminal blocks. Also, data are shown for various conditions of relative contamination at 186°F. (TMI-2 peak containment emperature) and at 100°F. for both the open and enclosed terminal blocks. All experimental data and model predictions are for an approximate 100% relative humidity condition in the test chamber and for 480 volts applied between the terminals and ground.

   The curves drawn through the experimental data represent an average contamination in that they are a composite of both clean and contaminated terminal blocks.

   These data show that, under a full LOCA condition, the probability of failure is 14% for a non-hermetically sealed terminal block with a 6mm drainage hold. As can be seen (from Fig. 1), this failure probability is higher if the terminal blocks are unusually dirty or left uncovered. Table I shows a summary of the data obtained including the terminal failures detected.

2. Based on the research conducted and a review of the literature, the probability of terminal breakdown for terminal blocks with a moderate amount of contamination is approximately proportional to the applied terminal voltage. This conclusion is valid at least to 480 volts where the prime failure mode is still the low-voltage breakdown phenomenon. Data were obtained from 120 to 480 volts. At least to a first approximation, this conclusion should also be valid below 120 volts.

   (a) Increasing levels of contamination result in a greater probability of low-voltage breakdown failure. The failure probability of a contaminated terminal block can be at least a factor of three times as high as that for a clean block.

(b) The increase in failure rate as a function of temperature is quite high. For example, the difference in failure rate between a TMI-2 type accident and a full LOCA could be as much as a factor of 10.

3. An important conclusion to be derived from this research is that terminal blocks have the potential of being a significant problem during a LOCA that might not be found by a qualification test as required in Regulatory Guide 1.89. For example, a qualification test would be conducted on one or, at most, a few terminal blocks. At full LOCA temperature of 326° F. there is a 14% probability of failure with a protected terminal block in a non-hermetically sealed enclosure with a 6mm weephole. It is, therefore, quite probable that a breakdown failure would not occur during the qualification test. Furthermore, the terminal block is much more likely to be clean during the LOCA test than during an accident in a plant.

   Also, because of the tendency for terminal block degradation to be reduced or eliminated after the surface has dried, it is essential to have the qualification measurements made when the terminals are exposed to the accident environment.

   The following are the specific areas not covered in this research:

   (a) As previously stated, radiation effects were not examined. The available data show that there is no gross damage to the phenolic material utilized in the terminal blocks studies below 10^7R. Since the study was directed primarily at the TMI-2 accident, radiation was not included as a test parameter.

   (b) Only a limited number of tests with hydrogen as a contaminant were conducted. Unfortunately, these limited data do not correlate with the expected hydrogen results, and no firm conclusions can be drawn from this part of the investigation.

4. No attempt was made to test all generic terminal blocks, and the failure rate may vary significantly for different designs. This is particularly true for terminal blocks where the mechanical design of the terminal block and mounting is different from the designs that were tested. For example, holes and cracks where liquid can accumulate could significantly change the conclusions drawn. The difference between horizontal and vertical mounting could also affect the results. Also, the terminal blocks tested utilized a similar phenolic base insulating material. There is some evidence that different insulating materials are less susceptible to a low-voltage breakdown under the conditions considered in this research.

5. No attempt was made to correlate the terminal block low-voltage breakdown failure with mechanical damage. However, IE has noted some damage of terminal blocks due to improper installation.

EVALUATION AND RECOMMENDATIONS

Terminal blocks are used extensively in systems important to safety. Based on our limited review in this area, it appears that the environmental factors influencing the low-voltage breakdown failure mode are not controlled by current practice and probably are not even monitored in nuclear power plants. It also appears that certain installation and maintenance procedures that have a strong influence on failure rate are not covered by normal quality assurance practices. This is probably due to the general lack of appreciation of the vulnerability of terminal blocks to a low-voltage breakdown during a LOCA. The following recommendations may be drawn from this research:

1. All nuclear power plants using terminal blocks in circuits important to safety within the reactor containment should be inspected to verify that all terminal blocks are enclosed in a protective enclosure. If the enclosure is not hermetically sealed, it should be checked to verify that the cover is securely fastened and that the drainage hole is located on the bottom.

2. All terminal blocks utilized in systems important to safety should be cleaned at least once after construction and possibly periodically thereafter. This cleaning could be accomplished during scheduled plant shutdowns. One method of cleaning that has been effective in the laboratory is to use a steam jet followed by an application of alcohol. However, the applicability of using this method in an operating plant has not been examined and there may be a better way to clean the terminal blocks installed in a plant.

3. Procedures should be established to keep the terminal blocks clean, and appropriate guidelines should be issued to maintenance personnel regarding the removal of enclosure covers and the cleanliness of terminal blocks. For example, fingerprints on terminal blocks significantly increase the probability of a low-voltage breakdown failure. Enclosure covers should be in place at all times when actual work is not being performed, since the terminals are more likely to fail during a LOCA in the uncovered condition. Also, the terminal blocks are more likely to become contaminated with the enclosure removed making the more vulnerable to failure even after the enclosure is replaced.

[illegible]
V. Stello

JUL 2 1981

4. For new plants, it is recommended that terminal blocks be eliminated, placed in a hermetically sealed enclosure when used in electric equipment important to safety, or moved outside of containment. This recommendation is based on a generic evaluation of a particular type of terminal block. It may be possible that a different type of terminal block, utilizing different geometry and/or insulating material, can be shown to have a low enough failure probability that a non-hermetically sealed enclosure can be used.

We recommend that these research results, be promptly factored into the ongoing equipment qualification program. The timing on application to operating reactors should be a function of the research typicality; we believe that this should be explored promptly by NRR.

Original Signed by

Denwood F. Ross, Jr.

Robert B. Minogue, Director
Office of Nuclear Regulatory Research

Enclosures: Figure 1
Table I

Reference: U.S. Nuclear Regulatory Commission, "Electrical Insulators in a Reactor Accident Environment," SAND80-1957 (NUREG/CR-1682), January 1981. Available for purchase from National Technical Information Service, Springfield, Virginia 22161.

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RECORD NOTE: This RIL was reviewed by the QTE review group and Tosztoczy (NRR) Rutherford (I&E), Thomas (I&E), Sullivan (RES), and Bonzon, SANDIA Laboratories. All comments have been incorporated.

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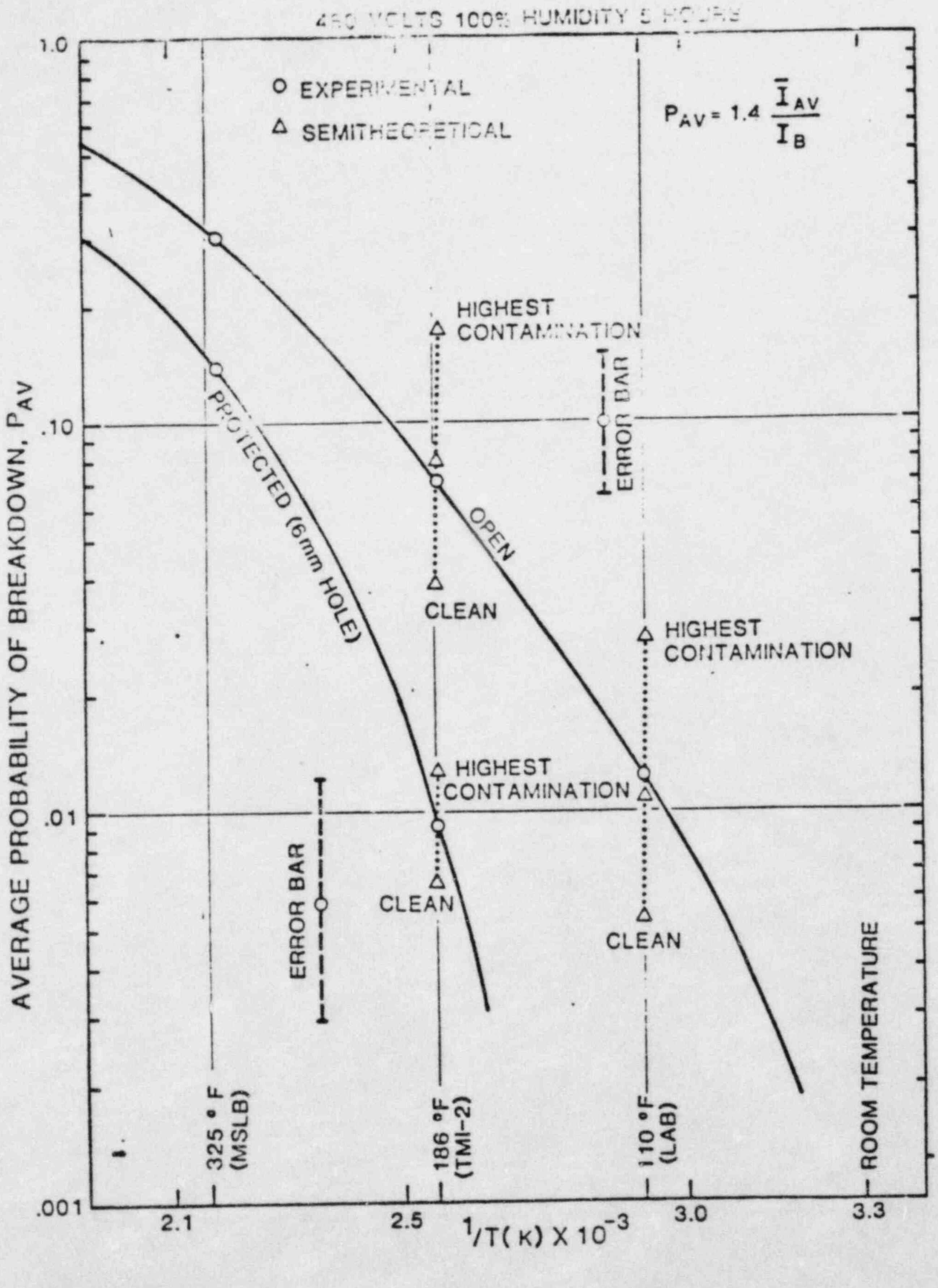
TABLE I

Breakdown Statistics for Terminal Blocks

(480 Volts, 100% rel. Humidity, 5 hours exposure)

Temperature	Number of Experiments		Breakdowns	Probability
163^{0} C = 325^{0} F (Commercial Tests)	Protected*	28	4	.14
	Open	20	6	.30
	Overall	48	10	.21
86^{0} C = 186^{0} F (Three Mile Island 2)	Protected*	112	1	.009
	Open	315	22	.07
	Overall	427	23	.054
43^{0} C = 110^{0} 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



480 VOLTS 100% HUMIDITY 5 HOURS
O EXPERIMENTAL
Δ SEMITHEORETICAL
$P_{AV} = 1.4 \frac{\bar{I}_{AV}}{I_B}$
AVERAGE PROBABILITY OF BREAKDOWN, P_{AV}
1.0
.10
.01
.001
HIGHEST CONTAMINATION
ERROR BAR
PROTECTED (6mm HOLE)
OPEN
CLEAN
HIGHEST CONTAMINATION
HIGHEST CONTAMINATION
ERROR BAR
CLEAN
CLEAN
325 °F (MSLB)
186 °F (TMI-2)
110 °F (LAB)
ROOM TEMPERATURE
2.1
2.5
3.0
3.3
$^1/T(K) \times 10^{-3}$

Fig. 1