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An Assessment of Terminal Blocks in the Nuclear Power Industry

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AN ASSESSMENT OF TERMINAL BLOCKS IN THE NUCLEAR POWER INDUSTRY

September 1984

Charles M. Craft

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Albuquerque, NM 87185
operated by
Sandia Corporation
for the
U. S. Department of Energy

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Abstract

The primary application of terminal blocks in the nuclear power industry is instrumentation and control (I&C) circuits. The performance of these circuits can be degraded by low level leakage currents and low insulation resistance (IR) between conductors or to ground. Analyses of these circuits show that terminal blocks, when exposed to steam environments, experience leakage currents and low surface IR levels sufficient to affect some I&C applications. Since the mechanism reducing surface IR (conductive surface moisture films) is primarily controlled by external environmental factors, the degradation of terminal block performance is mostly independent of terminal block design. Testing shows that potential methods of reducing surface leakage currents will not reduce them sufficiently to prevent terminal blocks from affecting I&C circuits. Therefore, terminal blocks can cause erroneous indications or actions of the I&C circuits in which they are a component. Most of the present qualification tests of terminal blocks do not address the issue of low level leakage currents, and hence do not demonstrate that terminal blocks will operate properly in I&C circui

Table of Contents

Table of Contents
(continued)

Table of Contents
(continued)

List of Figures

List of Figures
(continued)

List of Figures
(continued)

List of Tables

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Executive Summary

Terminal blocks are used in nuclear power plant Class 1E and non-Class 1E circuits inside and outside containment. Applications range from low voltage instrumentation and control (I&C) circuits to 480 Vac power circuits. Most terminal blocks are used in the low power I&C circuits. The most prevalently used terminal blocks are General Electric EB series and CR-151 series, Weidmuller SAK types, Westinghouse 542247 types, States Type NT and Type ZWM, and Buchanan NQB series. All of these terminal blocks may be found in both inside and outside containment applications. Approximately 50 percent of the utilities are planning to continue using terminal blocks in Class 1E applications inside containment. Those utilities choosing to continue use of terminal blocks operate mostly older plants with a large number of installed terminal blocks. However, some of the newer plants will also use terminal blocks. Alternately, some utilities have chosen to remove all explicit* terminal blocks in Class 1E applications inside containment, and others are removing them from selected applications (e.g., transmitter applications) or locations (e.g., below submergence level). The major trend for new plants is to use splices inside containment.

The two major terminal blocks designs (one-piece and sectional) are in approximately equal usage. Of the 57 distinct models of terminal blocks tabulated in Section 1.3.3, 32 are of sectional construction and 25 are of one-piece construction. However, one-piece terminal blocks are probably more numerous in absolute terms since they are specified by a larger number of plants. To characterize terminal block types as a percentage of the total population is difficult, since data for the quantity of each type, as well as the total population of terminal blocks, are not readily available.

Since 1977, there have been a number of test programs sponsored by both utilities and terminal block manufacturers that have been used to support the qualification of terminal blocks. These tests generally age the terminal blocks using Arrhenius techniques or the 10°C rule, expose them to a seismic and vibration test, and then conduct a Loss of Coolant Accident (LOCA) or a High Energy Line Break (HELB) simulation. Functional evaluations normally consist of insulation resistance (IR) measurements and conductor continuity checks following each of the several sequentially applied environmental stresses (i.e., thermal aging, radiation exposure, seismic and vibration simulation, and LOCA/HELB simulation). Although the acceptance criteria for the functional tests were not always specifically stated, all of the industry test reports reviewed by us indicate that the terminal blocks performed satisfactorily during the functional IR tests subsequent to each type of exposure. In some of these tests, measurements of the variation in terminal block performance during these tests were not made. In other tests, megohmmeter measurements were made at various points during the test with the block unpowered. The typical method used

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* The term explicit refers to terminal blocks which are not an integral part of larger pieces of equipment such as electrical penetrations or motor operators.

to monitor terminal block performance during the LOCA/HELB simulation was via fuses in the circuits that provided potential to the terminals of the terminal block. These fuses were sized to fail at leakage currents between 1 A and 24 A depending on the test specification. Acceptance criteria during LOCA/HELB simulation were based on the terminal block's ability to carry the specified voltage and current without failing these fuses. During some of the tests, the fuses in the circuits for one or more terminal blocks failed once or twice and were replaced. Sometimes for a given terminal block, the fuse continued to fail; in those cases, the terminal block was removed from the test. The test reports do not specify the number of times that a fuse was allowed to fail or the number of terminal blocks in the test lot that could be removed from the circuit before the terminal blocks were deemed to have failed the test. Using fuses in this manner has two drawbacks: first, the failure of a fuse is only a single point criterion that shows only that leakage currents were at least as large as the rated value of the fuse for the time necessary to fail the fuse; and second, the sizing of the fuses to "large" values provides no information about low level leakage currents. As shown by the analysis of applications that may use terminal blocks, low level leakage currents on the order of milliamperes can affect low power instrumentation and control circuits. These circuits are the primary terminal block applications, and, therefore, the test acceptance criteria are not, in this respect, germane to most terminal block applications.

Surface leakage currents are the primary mechanism by which terminal blocks contribute to I&C circuit degradation. During Sandia's tests of terminal blocks in a simulated LOCA environment [1], insulation resistance at 4 Vdc, 45 Vdc, and 125 Vdc fell to 10^2 to 10^5 ohms from initial values of 10^8 to 10^{10} ohms. At 45 Vdc leakage currents were on the order of 0.1 to 10 mA. These values are sufficiently large to affect some 4 to 20 mA instrumentation circuits by 0.3 to 185 percent with a nominal effect of 0.5 to 45 percent at their midrange (12 mA). At 4 Vdc insulation resistance ranged from 5×10^3 to 7×10^4 ohms. These values could affect RTD circuits by 0.3 to 9 percent. At 125 Vdc, the IRs were comparable or slightly higher (1/2 to 1 order of magnitude) than at 45 Vdc. During the cooldown periods to 95°C and during the post-test ambient temperature period, the insulation resistance increased to 10^6 to 10^8 ohms, but not to the pre-test levels of 10^8 to 10^{10} ohms. This behavior illustrates three points: first, the similarity between cooldown and post-test IR values indicates that the same conduction mechanism is probably occurring during these periods; second, IR recovery to a higher value after exposure indicates that a transient phenomenon is responsible for the low IR values during the steam exposure; and third, that some permanent degradation of the terminal block insulation resistance occurs. A conductive moisture film is the most probable explanation for the transient phenomenon. During cooldown periods, the residual heat of the terminal block keeps its temperature and the temperature of the film higher than the temperature of surrounding environment. The film's vapor pressure will exceed the partial pressure of water in the surrounding atmosphere and hence the film will vaporize, improving the terminal block's IR. Similarly, in post-test environments the film will evaporate and the IR will increase.

A model of film formation which predicts leakage currents that are consistent with the observed experimental results is presented. This model accounts for Joule heating of the film and the various heat loss mechanisms that exist. Interpretation of the results of the model and the Sandia test results [1] indicate that qualification testing at voltage levels above those of actual use may be nonconservative with respect to leakage currents.

All tested terminal blocks performed similarly in a steam environment, though some designs experienced IRs consistently lower than other designs. The formation of surface moisture films appears to be mostly independent of terminal block design. Three potential methods for reducing the magnitude of surface leakage currents (cleaning, sealing, and coating) will probably not reduce leakage currents to a level acceptable for I&C applications. We must, therefore, conclude that leakage currents observed during LOCA testing of terminal blocks can cause erroneous indications or actions of the low power I&C circuits in which they are a component. Most of the present qualification tests do not address the primary failure mode (low level leakage currents) and therefore do not demonstrate that terminal blocks will operate properly in I&C circuit.

1.0 INTRODUCTION

1.1 Background

Terminal blocks are used in nuclear power plant Class 1E and non-Class 1E circuits inside and outside containment. Their past widespread application in critical circuits and their potential for causing common mode failure lead to questions concerning their effect on nuclear plant safety. Motivated by questions arising from the accident at Three Mile Island (TMI), the NRC requested that Sandia National Laboratories investigate terminal block performance in TMI conditions. The results of this work by Stuetzer [2] indicated that terminal blocks could potentially affect plant safety by undergoing low voltage surface breakdown at voltages between one hundred and five hundred volts. Stuetzer also pointed out the highly statistical nature of terminal block breakdown and the influence of many complex, nonreproducible parameters. Therefore, to minimize variability, Stuetzer employed a controlled laboratory environment to investigate terminal block behavior. Most of his work was conducted at 480 Vac and used experimental configurations that were not typical of actual nuclear plant installations. On this basis, the work was attacked as nonrepresentative of actual industry practices. The results, however, did raise sufficient concern that a more thorough review of the terminal block issue was deemed necessary. This document and a companion report [1] present the results of the follow-on study.

1.2 Objectives

There were three rather broad objectives to the terminal block review. These were:

(1) Investigate the failure and degradation modes of terminal blocks in a configuration that was typical of actual plant installations, uses, and conditions.

(2) Assess the impact of the terminal block failure and degradation modes on nuclear power plant circuit performance.

(3) Develop the technical bases for judging the safety significance of terminal blocks.

1.3 Terminal Blocks in the Nuclear Power Industry

1.3.1 Why Terminal Blocks?

Terminal blocks are used as a method for connecting electrical circuits. They provide a convenient, low-cost method of making cable junctions. They are easily installed and provide provide maintenance and calibration access to the circuit by allowing circuit elements to be quickly and efficiently isolated. They are especially convenient for maintenance in areas where anti-contamination clothing encumbers personnel. For these and other reasons, the utilities prefer terminal blocks as a means of making circuit connections, particularly for

low-voltage, low-power applications. The arguments against the use of terminal blocks are generally the dynamic regulatory environment and the desire to avoid qualification problems.

1.3.2 Terminal Block Usage

The use of terminal blocks is universal throughout the nuclear industry for outside containment applications. Inside containment, terminal blocks are employed widely in older plants and in some newer plants, though the current trend for new plants is to use splices inside containment. Based on a 1981-1982 survey of 25 utilities and data in the Electric Power Research Institute (EPRI) Equipment Qualification Data Bank (EQDB) and the NRC's EQDB [3,4], approximately 50 percent of the utilities will continue to use terminal blocks in Class 1E applications inside containment. These utilities are pursuing two approaches to retaining terminal blocks: (1) qualify already installed blocks so as to avoid an extensive and costly replacement effort and (2) replace the terminal blocks with ones qualified by a vendor or another utility. Some of the utilities which are replacing terminal blocks with qualified splices are continuing to use terminal blocks in outside containment applications, and some will continue to use terminal blocks in non-Class 1E applications inside containment. Some utilities are following a policy of selective terminal block replacement, with a major criteria for replacement being the location of the terminal block relative to submergence level. Plants utilizing splices inside containment are not totally exempt from in-containment terminal blocks in Class 1E applications. Many pieces of equipment (e.g., Limitorque valve operators and some electrical penetrations) contain terminal blocks as integral components. These are "implicit" terminal blocks as opposed to the "explicit" terminal blocks which the utilities are removing.

It is difficult, if not impossible, to say that terminal blocks will or will not be used in plants still to be built and/or licensed. The decision between terminal blocks or splices depends somewhat on the preference of the utility and their Architect/Engineer (A/E). Other factors in the decision are the availability of qualified terminal blocks, and the stage of construction. These other reasons tend to be argued in either direction depending on the inclination of the utility and the A/E.

Table 1-1 summarizes the available data on terminal blocks being used in 73 of the 77 operating plants and 17 of the 68 planned or under construction plants.[5] No information was obtained from the other plants. The primary sources of data used to compile these tables were the EPRI EQDB, the NRC's EQDB [3,4] and the survey of 25 utilities. The two data bases derive their major input from the utilities' I&E Bulletin 79-01B submissions and subsequent updates and contain essentially duplicate information. The EPRI data base, however, has been regularly updated and expanded, whereas the NRC's data base has remained relatively static since 1981. One of the limitations to both data bases is that the inputs are generally limited to the utilities' Class 1E equipment; this limitation is in keeping with the intended objective of the data base, but does not permit a complete characterization of component usage within

a plant. Further, the location of equipment is only provided as inside or outside containment. No detailed locations are given. As a result any generic tests of terminal blocks must use generalized, very conservative environments. Little information is available in the data bases to tie down specific applications of the terminal blocks. To overcome these weaknesses, the survey of 25 utilities was made. Corporate headquarters or site personnel were contacted depending on the organization of the utility. The quality of the information was limited in most cases to the personal knowledge of the people contacted. No physical inspection of facilities was conducted.

TABLE 1-1

Summary of Terminal Block Usage by Plant

Plant	Manufacturer	Model	Location
Beaver Valley 1	Buchanan	0511, 0211	IC
	Marathon	1500 series	
	Penn Union	Series 1000	IC
Big Rock Point	General Electric	EB-25, CR-15NT	IC
	Westinghouse	542247, 805432	IC
	Weidmuller	DK-4, SAKR	
Braidwood 1 & 2	Marathon	1600 NUC	IC
	Penn Union	No Model Number given	
Browns Ferry 1, 2, 3	General Electric	EB-25	
Brunswick 1 & 2	Curtis	Type L	IC
	General Electric	EB-5, EB-25,	IC/OC
		CR-151D3	OC
	Weidmuller	SAK Types	IC
Byron 1 & 2	Marathon	1600 NUC	IC
	Penn Union	No Model Number given	
Calvert Cliffs 1 & 2	Buchanan	B112	IC
	Marathon	1600 series	IC
	Weidmuller	SAKS	IC
	Westinghouse	542247	IC
Comanche Peak 1 & 2	Weidmuller	SAK6N, SAK10	IC/OC
Cooper	Buchanan	0514	IC
	General Electric	EB-5, EB-25	IC
		CR-151A6	

TABLE 1-1
(cont)

Summary of Terminal Block Usage by Plant

Plant	Manufacturer	Model	Location
Crystal River 3	Kulka	5TB, 7TB	
	States	NT	OC
Davis Besse 1	Stanwick	Type G	IC
D.C. Cook 1 & 2	No Terminal Blocks in 1E circuits inside containment		
Dresden 1, 2 & 3	Allen Bradley	No model given (to be replaced)	IC
	Buchanan	NQB series (replacements)	IC
Duane Arnold	General Electric	EB-5, EB-25 (to be replaced)	IC/OC
	Buchanan	NQB series (replacements)	IC
Edwin I. Hatch 1 & 2	Buchanan	515,212,222	IC
	States	ZWM	
Fermi 2	Weidmuller	SAK Types	OC
Fitzpatrick	General Electric	EB-5, EB-25	IC
	Marathon	No Model No. given	
	Square D	Class 9080	IC
Fort Calhoun 1	States	M25014, M25016, M25018, M25112 (Type NT)	IC
Grand Gulf 1 & 2	Buchanan	0222, 0524	
	Cinch Jones	8-141	
	General Electric	EB-5, EB-25, CR2960SY139C CR-151D101	
	Kulka	5TB, 7TB, 1[illegible]TB, 27TB, 600J-J, 601J-J, 60[illegible]J-J, 603J-J, 604J-J	
Haddam Neck	General Electric	EB-25	IC
	Marathon	6012	
	Westinghouse	805432	IC
	Weidmuller	SAK Types	IC/OC
Indian Point 2	Westinghouse	542247	IC

TABLE 1-1
(cont)

Summary of Terminal Block Usage by Plant

Plant	Manufacturer	Model	Location
Indian Point 3	Westinghouse	542247	IC
Joseph M. Farley 1 & 2	States	ZWM	IC
Kewaunee	General Electric	EB-5, EB-25	IC
LaCrosse	Buchanan	218	IC
LaSalle 1 & 2	Buchanan	NQ3 series	IC
Limerick 1 & 2	No Terminal Blocks in 1E Circuits Inside Containment		
McGuire 1 & 2	States	ZWM	OC
	Weidmuller	AKZ-4	OC
Maine Yankee	General Electric	CR-151B	IC
	Square D	Class 9080-CBx (1828-C1?) (to be replaced)	IC
	Weidmuller	SAK Types (replacements)	IC
Millstone 1	General Electric	EB-25	IC
Millstone 2	Weidmuller	SAK-4	IC/OC
Monticello	Allen Bradley	1492-CD3	OC
	General Electric	CR-151D3	OC
Nine Mile Point 1	General Electric	EB-5, EB-25	IC
North Anna 1 & 2	Connectron	NSS3	IC
	General Electric	EB-5, EB-25	OC
	Marathon	2[illegible], 1500 series	OC
	Thermoelectric	Type 32-25	OC
Nuclear One 1 & 2	General Electric	EB-5, EB-25	
Oconee 1, 2, 3	States	M25004, M25008, M25012 (Type NT) SLS-8	OC
Oyster Creek 1	General Electric	EB series (to be replaced)	
	Weidmuller	SAK4 (replacement)	OC/(IC?)

TABLE 2-1
(cont)

Summary of Terminal Block Usage by Plant

Plant	Manufacturer	Model	Location
Palisades	Weidmuller	DK-4, SAKR	
	Westinghouse	805432	IC
Peachbottom 2 & 3	General Electric	CR-151 series	OC
	Buchanan	2B100 series	IC/OC
	Marathon	1600 series	OC
	Weidmuller	SAK Types	OC
Pilgrim 1	General Electric	EB-25, CR-151 series	
Point Beach 1 & 2	Square D	77701, 77710	OC
	States	M25012, M25006 (Type NT)	OC
Prairie Island 1 & 2	Allen Bradley	1492-CD3 (nylon)	IC
Quad Cities 1 & 2	Allen Bradley	No model given (to be replaced)	IC
	Buchanan	NQB series (replacement)	IC
Rancho Seco	Kulka	7TB	IC
	Square D	Type G, 9080-CBx, (1828-C19)	IC
Robert E. Ginna	Westinghouse	542247	IC
	States	Type NT	OC
H. B. Robinson 2	General Electric	EB-5, EB-25	OC
Salem 1 & 2	Buchanan	28112N	IC
	Cinch Jones	Various	IC/OC
San Onofre 2 & 3	No Terminal Blocks in 1E Circuits Inside Containment		
Seabrook 1 & 2	Weidmuller	SAK Types	IC/OC
Sequoyah 1 & 2	General Electric	EB-5, EB-25, CR-151B	
	Westinghouse	805430(?)	
	Cutler Hammer	10987	
St. Lucie 1 & 2	General Electric	EB-5, CR-151D101	OC

TABLE 1-1
(cont)

Summary of Terminal Block Usage by Plant

Plant	Manufacturer	Model	Location
Surry 1 & 2	Connectron	WSS3	OC
	General Electric	EB-5, EB-25	OC
	Marathon	200, 1500 series	OC
	Thermoelectric	Type 32-25	OC
	Weidmuller	SAK Types	IC
TMI-1	States	NT, ZWM	IC
	Weidmuller	SAK Types	IC
Trojan	General Electric	EB-5, CR-151	IC
	Square D	828(phenolic)	IC
Turkey Point 3 & 4	General Electric	EB-5	OC
Vermont Yankee	Buchanan	0222	IC
	States	Type NT	IC
WNP-2	Weidmuller	SAK Types Other Weidmuller Products	IC
	General Electric	CR-151B, CR2960SY139	OC OC
Yankee Rowe	Westinghouse	542247	IC
	Weidmuller	SAK Types	
Zion 1 & 2	Marathon	Pro Type EM-215/6000,	IC
		Pro Type EM-47150/6000	IC

1.3.3 Terminal Block Applications

Terminal blocks are used predominantly in two types of circuits: instrumentation and control circuits. Selected plants also employ terminal blocks explicitly in 480 Vac power circuits, but this practice is limited to 10 percent or less of the plants.

The instrumentation circuits are typically RTD circuits, which are low voltage (4 Vdc or less) and low current (1 mA or less), or

transmitter circuits* (4-20 mA at 24-50 Vdc). Control circuits are typically solenoid valve circuits, motor-operator control circuits, or status indication circuits and are normally 120 Vac or 125 Vdc and 1 A to 2 A or less.

The physical location of terminal blocks varies depending on the need to junction cables. Two of the most typical locations are at containment penetrations and near equipment. At these points, field wiring must be terminated and connected to the penetration or to the instrument or control device pigtail.

Electrically, the terminal blocks are typically adjacent to the instrument or control device and are separated only by the resistance of the intervening cable. As will be seen, this means that terminal block faults can be viewed as impedances in parallel with the input of the instrument or control device and their effects can be analyzed as such.

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* Due to the susceptibility of transmitter circuits to leakage current, most utilities are now employing splices in these circuits or are planning to change to splices within the near future.

2.0 TERMINAL BLOCK LIFE CYCLE

2.1 Terminal Block Design

Terminal blocks are considered to be "off-the-shelf" items with designs that have not changed for many years. The two basic types of designs are one-piece and sectional. The primary distinguishing feature of the one-piece terminal block is that the insulating material which forms all of the barriers and the support for all electrical terminals is a single piece of molded insulating material. The number of terminals is fixed by the molding. Mounting plates or channels do not comprise part of the one-piece terminal block design, and the block is typically mounted directly to the enclosure structure.

The primary feature of the sectional terminal block is that each section is an individual unit of insulating material and conductor. Each of these sections may or may not have one inter-terminal barrier as part of each section's molding. If the barrier is separate, it will be held in place by alignment tabs. The sections are mounted on a channel or base plate to form a multi-terminal terminal block assembly. The sections are either individually attached to the mounting plate, or they are gang-mounted using a mating dovetail-like arrangement between the sections and mounting channel. Special end-pieces keep the sections from sliding off of the channel.

Figures 2-1 and 2-2 illustrate typical one-piece and sectional terminal block configurations, respectively. The sectional construction has a gap between sections from the top surface of the terminal block to the mounting rail. This gap does not exist in the one-piece terminal blocks. The width of the gap depends on how tightly the end pieces compress the sections together. Given the proper conditions, this gap has the potential to retain a moisture film that could be a conducting path to ground.

Of the terminal block models reported in Table 1-1, 25 models were identified as one-piece and 32 as sectional. However, in terms of quantity installed, there are probably more one-piece than sectional terminal blocks in use simply because the majority of plants specify one-piece terminal blocks.

All terminal blocks have squared corners, crevices, and other convoluted surfaces which may retain deposits of contaminants and would be difficult to clean. Further, these designs make use of conformal coatings ineffective because a complete coating is difficult to achieve with the many concealed areas.

2.1.1 Terminal Block Materials

For the terminal blocks listed in Table 1-1, five insulating materials were identified. Phenolic with either a glass or cellulose filler is the primary material used for the insulation (39 of 57 models used this material) and alkyd, melamine, diallyl phthalate, and nylon

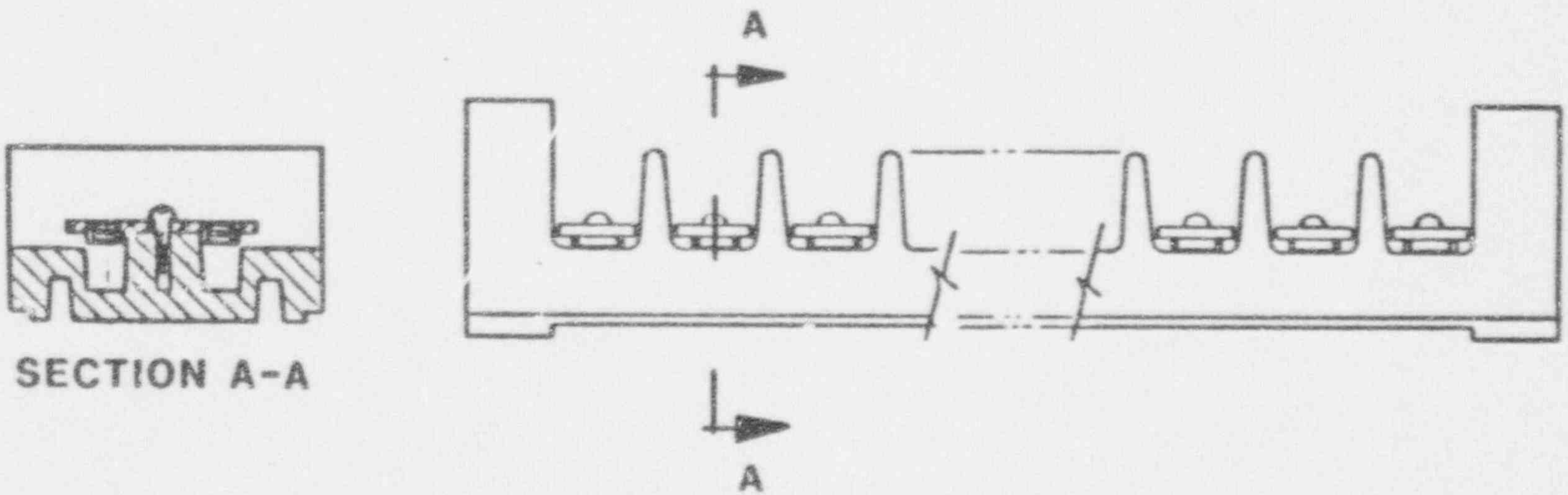

Figure 2-1: Typical Configuration for a One-Piece Terminal Block

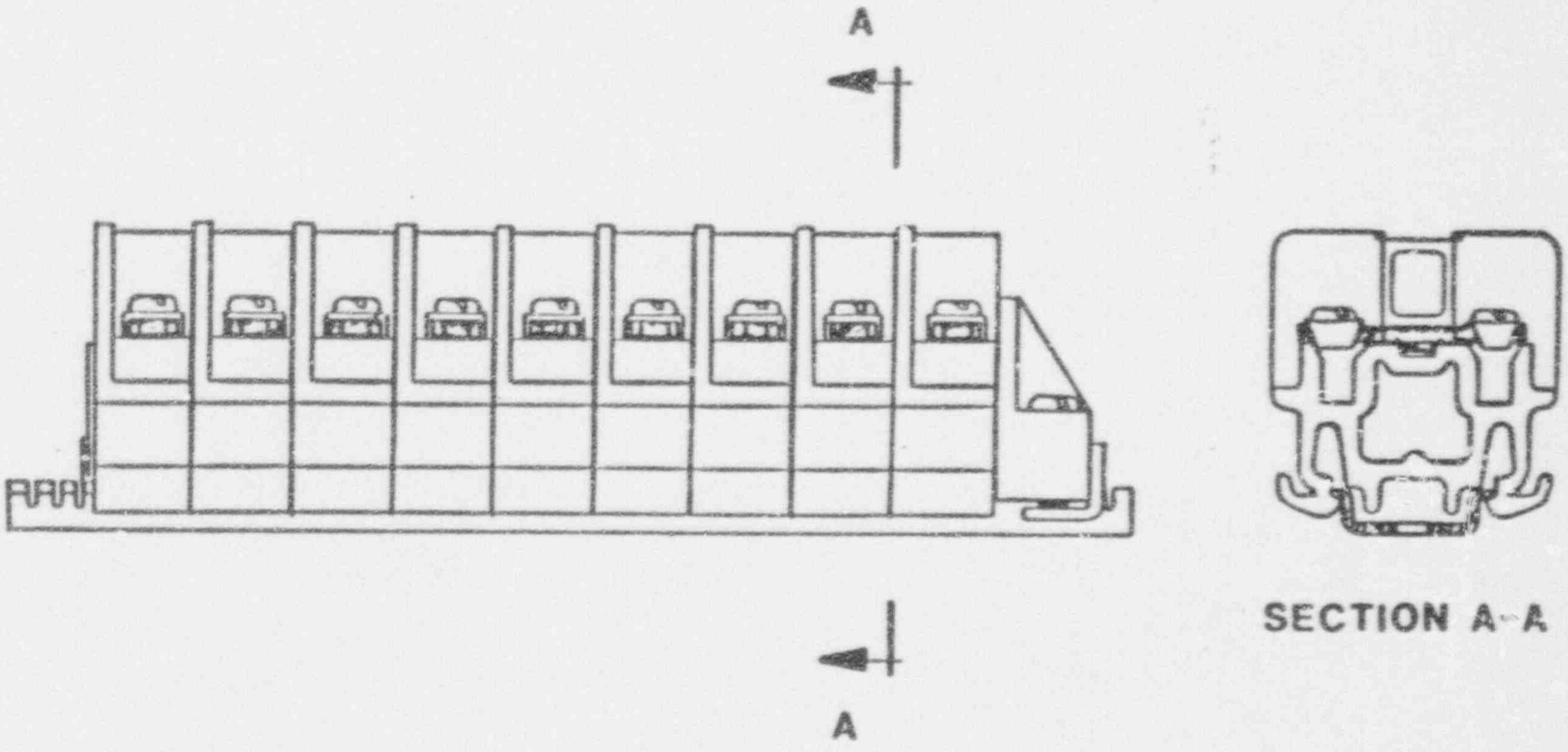

Figure 2-2: Typical Configuration for a Sectional Terminal Block

(five or fewer models each) make up the remainder. These materials are normally chosen because of cost considerations, moldability, and their relatively good electrical insulation properties. Table 2-1 summarizes some of the relevant properties for generic formulations of these materials. Product literature for models which utilize phenolic insulation indicates a maximum service temperature of 150°C (302°F).[9,10,11,12,13] This value is in agreement with Table 2-1. Qualification tests of terminal blocks for nuclear service [14,15,16,17,18,19,20,21] typically age samples between 120°C (248°F) and 165°C (329°F) and subsequently expose them to accident profiles that reach sustained temperatures of 170°C (338°F). The specimens tested survive these thermal environments showing only minor degradation. Thus, from a thermal standpoint, the selection of a phenolic or other polymeric material rated at a 150°C (302°F) service temperature is reasonable for nuclear application.

Radiation sensitivity is influenced by insulator fill material. Westinghouse Research Laboratories, in reference to Westinghouse terminal blocks, evaluated the radiation properties of phenolics as follows [22]:

> "Cellulose-filled phenolics...are less radiation resistant, in general, than unfilled or mineral-filled phenolics. Information on paper-, paper-laminate, and linen-filled phenolics indicates that they all begin to degrade at approximately 5 x 10^5 rads. The most radiation sensitive properties, elongation and impact strength, are reduced by 25% at doses from 3 to 8 x 10^6 rads. The [cellulose-filled phenolics] will probably exhibit similar behavior. Electrical properties are not affected by doses < 2 x 10^7 rads."

One manufacturer experienced a failure of their cellulose filled melamine terminal blocks during radiation and steam testing which is possibly attributable to radiation effects. They experienced cracking of the terminal block insulation material. The postulated mechanism was that radiation degraded the surface resin material and perhaps opened the structure sufficiently to allow moisture to be absorbed into the filler. Subsequently, when the high temperature accident transient was applied, this moisture vaporized, pressurizing the interior of the insulation in a time frame short enough to prevent pressure equilibration. Hence, the material cracked to relieve the stress.

The selection of a fill material typically affects the radiation tolerance of a material by plus or minus one to two orders of magnitude [6] with organic fillers such as cellulose decreasing radiation tolerance and mineral or glass fillers increasing tolerance. The radiation doses quoted in Table 2-1 are for degradation of mechanical properties such as flexural or tensile strength. It has been known for some time that the electrical properties of many polymeric materials, such as volume resistivity, dielectric strength, and arc resistance, appear to be unchanged by radiation levels which cause extensive physical damage to the material.[23] Thus, with proper selection of fill material (e.g.,

Table 2-1

Typical Radiation Damage Thresholds and Maximum Service Temperatures for Five Insulating Materials Used in Terminal Blocks Found in U.S. Nuclear Power Plants

Insulating Material	Radiation Damage Threshold (Rads(C)) [6]	Service Temperature °C (°F) [7]
Phenolics		
glass filled	10^{10}	160-190 (320-374)
cellulose filled	10^{8}-10^{9}	120-220 (248-428)
Alkyd		
glass filled	10^{9}	149-191 (300-376)
cellulose filled	10^{8}	191 (376)
Melamine (Resin)	10^{8}	
glass filled	10^{9}	204 (399)
cellulose filled	10^{7}	99-150 (210-302)
Diallyl Phthalate		
glass filled	10^{8}	204 (399)
cellulose filled	10^{7}	160 (320)
Nylon 61	10^{5}-10^{6}	130 (266) [8]

glass), the radiation levels quoted in Table 2-1 indicate that there will be minimal effect on the insulating materials normally used for terminal blocks by nuclear plant radiation doses (estimated doses: 5×10^{7} rad operating life and estimated 1.5×10^{8} rad accident).

The metallic terminals are typically stable to temperature and radiation levels which exceed the aging and accident environments postulated for nuclear power plants. Thus, we would not expect degraded performance of the conducting material based on pure radiation and/or temperature effects. There is, however, potential for material interaction problems such as corrosion or galvanic action to occur. The selection of metal coatings and base conductor material should be such that these effects are minimized in both the normal operating environment (e.g., 80-110°F and 10-100% RH) and the postulated accident environments which include steam and chemicals. One specific example would be to avoid the use of cadmium as plating material because in a steam-chemical spray environment it may be a reactant in a galvanic reaction.

2.1.2 Quality Assurance in Terminal Block Design

The manufacturer's quality assurance manuals reviewed by us [24,25,26] do indicate that design reviews are conducted by the their engineering organizations. The manuals are vague concerning what specifically is reviewed, but they do explicitly cover such items as drawing control, change control, compliance with applicable standards and regulations, and analysis of tolerances and dimensions. It is not clear whether or not consideration is given to appropriate material selection, material compatibility, or terminal block designs to reduce leakage currents or contamination. Apparently, some of these considerations are addressed as evidenced by a trend towards the use of glass-filled phenolics, the elimination of cadmium-plated conducting parts in terminal blocks for nuclear applications, and new designs to increase conductor separation.

2.2 Terminal Block Manufacture

2.2.1 Manufacturing Process

There are several processes applicable to the manufacture of terminal blocks. These include injection, transfer, and compression molding. As long as the Quality Assurance/Quality Control (QA/QC) programs assure that specified raw materials are used, that molds conform to specification, and that processes and assembly operations function correctly, there should be little reason to suspect the manufacture of terminal blocks as contributory to the failure and degradation modes. One potential area may be the use of mold release and the retention of a residue on the insulation surface which could affect performance. Based on our limited experience in procuring terminal blocks from nine manufacturers, we found no observable variations or defects and all were in conformance with catalog specifications. For a simple item such as terminal blocks, one would expect this type of reproducibility and quality.

2.2.2 Quality Assurance in Manufacture

The quality assurance manuals [24,25,26] vary in the thoroughness with which they describe the QA programs applicable to the manufacturing process. Some are sufficiently detailed to outlined the inspection programs which include inspection of the first production unit, last ten production units, and ten production units per case. The manuals also vary in the thoroughness of their stated raw material segregation, traceability, and receiving inspection requirements. Those vendors claiming compliance with 10 CFR 50, Appendix B appear to have good material control, lot traceability, verification that production units match design, and production line quality control. In general, the QA applied by the vendors to the manufacturing process appears to adequately meets the requirements for nuclear application.

2.3 Terminal Block Selection, Procurement, and Installation

2.3.1 Role of Architect/Engineering (A/E) Firms

The issue of terminal block selection, procurement, and installation was discussed with three (Bechtel, Burns and Roe, and Sargent and Lundy) of approximately twelve A/E firms participating in nuclear plant design. Though not a large sample in terms of total number of A/E firms participating in nuclear plant construction, these firms represent slightly more than 50 percent of the 140 planned and operating plants in the U.S. Generally, the A/Es function in a key advisory role in deciding whether or not to use terminal blocks and what terminal blocks to use. As the funding agency and the licensee, the utility retains final responsibility over the decision, but the policy and practices of the A/Es bear on the final choice. The A/E firms call out in the design specification when terminal blocks will be used and what makes or models are acceptable. Typically, an A/E might specify a particular make and model with purchasing to be done on an "or equivalent" basis. It is not clear, however, who makes the determination of what constitutes "or equivalent" or what criteria are used to make the determination. No other detailed controls over procurement or selection of terminal blocks are in place. On site, the A/Es do not provide any specific quality assurance function for terminal blocks except as might be provided in site quality assurance plans.

2.3.2 Construction and Installation Practices

Construction procedures are not normally written by the A/E unless they are also the constructor. The A/Es do, however, review and comment on the construction procedures and thus play an important role in determining how a component will be installed. The installation procedures we have reviewed give minimum clearances for terminal blocks, how cables are to be terminated, how wires are to be labelled, etc. Terminal block orientation within the enclosure was not mentioned nor was the entry direction for bringing wiring into the box. There is an effort to keep like voltages and applications on the same terminal block. For example, a single solenoid valve's power, actuation signal and indication signal might typically be on the same terminal block, but a pressure transmitter circuit or an RTD circuit would not also be on that block. There is also an effort to segregate applications by electrical box. For example, several transmitter circuits may all be on different terminal blocks but within the same enclosure, while terminal blocks in RTD circuits would be in a different enclosure.

The construction procedures are important in determining the installation quality assurance program since they document the basis for inspection and control. Typical quality control checks might include assuring that qualified terminal blocks are used in Class 1E applications and that installation procedures are followed with respect to spacing, circuit continuity, and wiring technique. As evidenced by the utility and A/E surveys, no written procedural check for cleanliness is made except to insure that large foreign objects do not remain in the electrical enclosures.

Terminal blocks are typically installed in a National Electrical Manufacturers Association (NEMA) Class 4 enclosure.* However, selected plants use enclosures fabricated to a company specification which may or may not meet NEMA-4 specifications. Other plants have different NEMA class boxes in use. All new construction that we are aware of employs NEMA-4 enclosures.

The conduit entries are normally made with conduit terminations that have neoprene or other organic material as seals. These entries may penetrate the box from the top, side, or bottom, but typically are top or side entries. There is no provision made to trap and drain condensate in the conduit to prevent it from flowing down the interstitial space between the cable and conduit and entering the box. The sealing of the conduit entry and exit points is utility dependent. Some utilities have sealed them with materials like Room Temperature Vulcanizing (RTV) sealant or Red Glypt™; however, most utilities have not sealed the conduit entries. All but one of the utilities contacted indicated that a 1/4" to 1/2" diameter weep hole is drilled in the bottom of the electrical enclosures. The primary reason for this hole is to permit condensation which accumulates under normal operating environments to drain from the box. The utilities also indicated that the weep hole will allow rapid pressure equilibration during a LOCA steam pressurization of the external atmosphere. To our knowledge, flow retarders are not installed in these holes.

2.4 Inspections and Maintenance

2.4.1 Utility Inspections and Maintenance

Most utilities surveyed indicated that no special maintenance or QA activities occur with respect to terminal blocks subsequent to installation. When circuit maintenance is performed, a visual inspection is made. If Class 1E circuits are involved, a check is made to assure proper reconnection of the circuits. No specific check for cleanliness is made. However, one utility that we are aware of, has modified its installation procedures for terminal blocks so that when new terminal boxes are installed or old terminal boxes are modified, the terminal blocks therein are cleaned with deionized water and allowed to air dry.

2.4.2 NRC Inspection Activities

The following comments are based on discussions with Region II and Region IV personnel and a review of NRC Inspection and Enforcement (I&E) inspection procedures.[28] During construction, NRC inspectors review the terminal block qualification documentation and verify whether or

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*NEMA-4 enclosures are intended for indoor or outdoor use primarily to provide a degree of protection against wind blown dust and rain, splashing water, and hose-directed water.[27] The lid gasket is normally neoprene and it is incumbent upon the installer to use conduit terminators that maintain the integrity of the box.

not the blocks are installed in accordance with the way they were qualified. For example, if the qualification was for non-harsh environment areas, then the blocks must be installed in non-harsh environment areas. They check the enclosures to assure compliance with the manner in which the blocks were protected during qualification.

With respect to the terminal blocks themselves, there are no stringent inspection procedures. They do examine the installation to assure that the blocks are correctly installed in accordance with construction procedures, that the terminals and cable terminations are tight, that the blocks are not cracked or broken, that the electrical enclosures are dry and nothing is stored in them, and that no stress is imparted to the blocks by the cable. They also check cleanliness, but the degree of cleanliness is a personal judgment decision. NRC/I&E Inspection Procedure 51063C [28] simply says that after installation... "cable trays, junction boxes, etc. [should be] reasonably free of debris." No specific standards for cleanliness exists other than the general housekeeping standards, ANSI N45.2.3 and IEEE 336-1977.[29,30] These standards address cleanliness only generally and do not reference any specific type of equipment or standard to be applied. IEEE 336 simply refers to ANSI N45.2.3, stating that housekeeping should be in accordance with ANSI N45.2.3. ANSI N45.2.3 sets up zones with different degrees of cleanliness and access requirements for each. For operational plants, no explicit standard addressing cleanliness exists. Only to the extent that ANSI N45.2.3 carries over does a standard exist for operational plant cleanliness.

The NRC inspectors expect a different degree of cleanliness depending on the type of equipment in the enclosure. For example, enclosures with relays require a higher degree of cleanliness than enclosures with simple terminal blocks. Surface dust is almost always present.

Inspectors do not regularly inspect terminal blocks in operational plants. However, this does not mean that terminal blocks are never inspected, but rather that they are not an explicit point on an inspection agenda.

2.5 Summary

The above sections highlight that terminal blocks are considered an "off-the-shelf" component with relatively few requirements that must be met. Their designs have been relatively static for a long period of time. Their simple, passive nature coupled with the industry's familiarity and traditional use of terminal blocks, has led to a relatively methodical approach in their selection, installation, inspection, and maintenance. QA activities designed specifically to assure adequate and appropriate attention to terminal blocks in these phases of their life cycle have not been diligently pursued, perhaps due to a lack of consideration about the relative importance of terminal blocks.

3.0 TESTING OF TERMINAL BLOCKS

3.1 Standard Industry Tests

All terminal blocks that we are aware of comply with the provisions of UL Standard 1059 [31] or NEMA Standard ICS-4-1977.[32] These standards specify minimum terminal spacing and insulation dimensions, properties to be considered in material selection, standard temperature rise at rated current, criteria for wire pull out, marking standards, connection types, and dielectric-voltage withstand test criteria. The standards and tests to assure compliance are designed to provide a high grade, industrial application product, which they do. In addition, some vendor catalogs quote that their insulating material fall in one of four flammability categories defined by UL Standard 94.[33] Other tests for tracking index [34,35] or arc resistance [36] are generally not quoted by the terminal block vendors, though original manufacturers of the insulating materials may have data available. Reference 7 tabulates electrical properties for many generic polymer materials such as the phenolics, melamines and alkyds used for terminal block insulations.

3.2 Nuclear Qualification Tests

Since 197?, there have been a number of test programs sponsored by both utilities and terminal block manufacturers that have been used to support qualification of terminal blocks.[14,15,16,17,18,19,20,21] These tests generally consisted of thermally aging terminal blocks using Arrhenius techniques or the 10°C rule, exposing the terminal block to normal vibration and seismic tests, and then conducting a LOCA/HELB simulation. Functional tests normally consisted of insulation resistance (IR) measurements and conductor continuity checks subsequent to each of the sequentially applied environmental stresses (i.e., thermal aging, radiation exposure, seismic tests, LOCA/HELB simulation.)

All industry test reports reviewed by us indicated that the terminal blocks passed the functional IR tests subsequent to each type of exposure. Measurements of the variations in terminal block performance during these tests with the blocks powered were generally not conducted, though many of the tests removed power from the blocks and made megohmmeter measurements during the LOCA simulation. The typical method used to monitor terminal block performance during the LOCA/HELB simulation was via fuses in the circuit providing potential to the terminal block. These fuses were sized to fail at leakage currents between 1 A to 24 A depending on the test specification. Acceptance criteria were based on the terminal block's ability to carry the specified voltage and current. During most of the tests, the fuses in the circuits to one or more terminal blocks failed once or twice and were replaced. Sometimes with a given terminal block, the fuse continued to fail; in that case, the terminal block was removed from the test. An important point which is not specified in any of the reports was how often a fuse was allowed to fail or how many terminal blocks were allowed to be removed from the test before the test lot was determined to have failed. Only the Washington Public Power Supply System test of

Weidmuller blocks in a post-LOCA soak environment [18] and the Phonix test of their own blocks [19] made definitive measurements of leakage currents during the tests in addition to the fusing techniques.

Using fuses to monitor during-test performance has two drawbacks: first, the failure of a fuse is only a single point criterion that shows that leakage currents were at least as large as the rated value of the fuse for the time necessary to fail the fuse; and second, the sizing of the fuses to "large" values provides no information about low level leakage currents. As shown by analyses in Section 8, low level leakage currents can affect low power, instrumentation and control circuits. These circuits are the primary terminal block applications, and, therefore, the acceptance criteria were not, in this respect, germane to the majority of terminal block applications.

Table 3-1 provides a brief comparison and summary of some industry terminal block qualification reports, and the following sections give a more detailed synopsis of each.

3.2.1 Franklin Research Center's Test of Buchanan Terminal Blocks for Philadelphia Electric Company [14]

This test series consisted of two phases, A and B. Each is discussed in turn.

In Phase A, six Buchanan terminal blocks were evaluated (2 each 2B104 and 4 each 2B108). These blocks are similar except for number of terminals (4 and 8). The insulating material for these terminal blocks is a filled phenolic. No further details on the material such as fill material or phenolic formulation were available. Two terminal blocks were subjected to 100 Mrads Co-60 gamma radiation and then thermally aged at 136°C (277°F) for 160 hours, two terminal blocks were subjected to 50 Mrads Co-60 irradiation and not thermally age, and two were neither irradiated nor thermally aged. All terminal blocks were then subjected to a 14-day steam/demineralized water spray (S/D) environment to simulate a LOCA exposure. During the S/D exposure, the blocks were installed in either steel compartments or vented aluminum boxes of Philadelphia Electric design; the terminal blocks were energized with 150 Vac and 12.5 A. If more than 1 A of leakage current was required to maintain the specified potential, the specimen was removed from the circuit. During the LOCA test, four specimens had to be deenergized for a 0.9-hour period when suspected flooding of the test chamber occurred; the two other specimens had to be deenergized for a 16-hour period when insulation resistance was low and leakage currents high; and one of these latter two terminal blocks had to be deenergized permanently 4.9 days into the S/D exposure, apparently due to the blockage of the drain hole which permitted liquid to partially submerge the terminal block. IR was measured before and after each sequential test and at selected times during S/D exposure. The circuits had to be deenergized to make the IR measurements. No failure criteria were promulgated for IR readings. Initial IR measured 10^8 ohms or greater at 500 Vdc for all specimens and there was insignificant change after gamma and thermal exposures. Early in the S/D exposure, the IR for all samples dropped to less than

Table 3-1
Comparison of Some Indu y LOCA Simulations for Terminal Block Qualification

Utility/ Test Lab	TB ID	No. Tested	Acceptance Criteria	Power	Megohmmeter Measurements (ohms) (500 Vdc unless noted) During LOCA	Post-LOCA	Special Notes	Length of LOCA Exposure	Ref.
Philadelphia Electric/ FRC*	Buchanan 2B104 2B108	 2 4	Ability to carry specified current at specified voltage.	150 Vac 12.5 A	$<5\times10^4$ at 50 Vdc	10^2 to 10^{12}	One block removed from test at 4.9 days. Others removed at various times.	14 d	14 Phase A
Philadelphia Electric/ FRC*	Buchanan 2B108 Marathon 1608	 3 2	Ability to carry specified current at specified voltage.	150 Vac 12.5 A	$<5\times10^5$ at 50 Vdc	$<5\times10^4$ at 50 Vdc to $<5\times10^5$ at 50 Vdc	One TB removed from from test after 5.1 hours.	7d	14 Phase B
Generic/ FRC*	Buchanan NQB106 NQB112 NQB106S NQB112S NQO Series	 1 1 1 1 1	Maintain potential of 120 V and current of 25 A.	120 Vac 25 A	$<5\times10^4$ at 10 V to 2×10^{12} at 500 V	Post-test hipot test	During LOCA, leakage currents were < 200 mA to < 5 mA for all terminal blocks together.	7 d	15
Generic/ Wyle (Huntsville)	Marathon 1600 NUC 1500 NUC 142 NUC	 6 6 6	Leakage currents less than 12 A, or 18 A, or 24 A. Monitored by fuse.	132 Vac, 33 A 264 Vac, 33 A 528 Vac, 33 A	None	$<5\times10^5$ for all 528 V boxes	Blew 25 A fuse on 528 Vac specimens. Removed from test. Blew 18 A fuse on 264 Vac specimens. Replaced fuse and continued.	30 d	16
Generic/ FRC*	Weidmuller SAK Types	5	Maintain 600 Vac and 20 A with leakage current less than 1 A. Monitored by fuse.	600 Vac 20 A	None	2.4×10^7 to 1.5×10^8 at 500 Vdc	Voltage reduced to 150 V when spray introduced to maintain leakage current less than 1 A.	29 hr	17

*FRC = Franklin Research Center

Table 3-1 (continued)
Comparison of Some Industry LOCA Simulations for Terminal Block Qualification

Utility/ Test Lab	TB ID	No. Tested	Acceptance Criteria	Power	Megohmmeter Measurements (ohms) (500 Vdc unless noted) During LOCA	Post-LOCA	Special Notes	Length of LOCA Exposure	Ref.
WPPSS/Wyle (Norco)	Weidmuller SAK Types (same TBs as tested by Weidmuller, Ref. 3)	5	1 A Leakage current Monitored by fuse and discrete time monitoring of leakage currents.	600 Vac 20 A	None	1.2×10^{5} to 5.0×10^{10}	Measured leakage current during test. Test was only a post-test LOCA soak. 230°F and 20 psig, 100% relative humidity. No steam.	32 d	18
Generic/ Wyle (Norco)	Phonix SSK Series Ceramic RKK Series Ceramic SSK Series Melamine K Series Polyester (2 Types)	30 units exposed to LOCA	None specified	420 Vac 20 A 48 Vdc 24 Vdc	None Reported		2 superheated steam periods. No leakage current measurements of DC circuits. < 40 mA to > 700 mA current observed in 420 Vac case	24 hr	19
Commonwealth Edison/Wyle (Huntsville)	Marathon Series 6000 Series 1600	2 2	Leakage current less than 10 A. Monitored by fuse.	175 Vac 15 A	None	$< 1.[illegible]\times10^{6}$** to 2.2×10^{12} at 500 Vac **Off scale low. Measurement with Digitial Multimeter read 3.6 ohms	Some periods of superheat in accident exposure. One block exceeded 10 A leakage current--shorted to ground.	36.9 hr	20
Generic/ Westinghouse	Curtis BT Cinch Jones 541 Westinghouse 542-247 Marathon 1500		None Specified	600 Vac	8×10^{3} to 5×10^{5}	2×10^{10} to 2.3×10^{11}	Leakage currents not monitored during test with blocks powered.	~ 21 hr	21

*FRC = Franklin Research Center

5×10^4 ohms at 10 Vdc, but then recovered to less than 5×10^5 ohms at 50 Vdc for the remainder of the S/D exposure. After the S/D exposure, the IR varied from 120 ohms to 10^{12} ohms at 500 Vdc. Leakage currents were not monitored during the S/D exposure.

Post-LOCA simulation observations by Franklin Research Center were:

a) After gamma radiation (50 Mrad or 100 Mrad air equivalent dose depending on sample)

Dark deposits on metal parts of TBs

b) After thermal aging (136°C (277°F) for 160 h)

Green deposits on TB mounting screws
Oily residue inside box
Thick, gray, crusty deposits on terminals

c) After steam/deionized water exposure (14 days)

Conduit seals marginal
Box gaskets marginal (EPR rubber)
Marker strips deteriorated
Cable insulation split, swollen, stuck together
Rust color sediment
White and tan deposits on all metals parts of the TBs
Debris from test materials clogging drain holes

Phase B of the FRC/Philadelphia Electric test exposed three Buchanan 2B108 and two Marathon 1608 terminal blocks to 26 Mrad (air) gamma irradiation and a 7-day steam/demineralized (S/D) exposure. No thermal aging was conducted. As in Phase A, the blocks were installed in either a steel compartment or vented aluminum boxes of Philadelphia Electric design.

Insulation resistance was measured before and after each environment and during S/D exposure. Again, the circuits were deenergized to make the IR measurements. Initial IR at 500 Vdc was greater than 10^9 ohms and no significant change was noted after gamma radiation. During the S/D exposure, the IR for all specimens measured less than 5×10^5 ohms at 50 Vdc. The Phase A test reported IR values as less than 5×10^4 ohms; the factor of ten discrepancy was not explained.* After the S/D exposure, the IR of one Marathon and one Buchanan terminal block measured less than 5×10^5 ohms at 50 Vdc. The IRs of two Buchanan terminal blocks were not measured after S/D (no reason stated). One Marathon terminal block was deenergized 5.1 hours into the test. After the test, the IR of this block measured less than 5×10^4 ohms at 50 Vdc. The

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* Different megohmmeters were used in each test. They presumably had different lower limit values and hence the IRs of the TBs could have been the same. All that is positively known is that in both Phase A and Phase B the IRs went below the range of the meter.

report postulates that the reason for the low IR which caused the block's removal from the test was the presence of conductive moisture and/or deposits on the molding ridges between the energized terminals and the box. The acceptance criteria for the Phase B test as stated in the test plan was "when the...insulation is degraded to the extent that the specimen is no longer capable of carrying the specified current at the specified voltage." A more precise definition of acceptance criteria was not given.

3.2.7 Franklin Research Center's Test of Buchanan Terminal Blocks for Control Products Division of Amerace Corporation [15]

Twelve one-piece, NQB series terminal blocks and three assemblies of selected NQO sectional terminal blocks were exposed to thermal aging (165°C (329°F), 39.6 days for NQB samples and 121°C (250°F) for 8.3 days for NQO samples), gamma irradiation (200 Mrad at 0.56 Mrad/hr, Co-60), vibration aging (10 pairs of acceleration and frequency between 0.03 and 0.74 g's and 3 and 60 Hz with 15-minute dwell at each acceleration-frequency pair), and seismic fragility tests (five 30-second dwells at greater than operating basis earthquake (OBE) levels with a peak acceleration of 5.5 g's between 2.5 and 13 Hz and one 30-second dwell at greater than safe shutdown earthquake (SSE) level with a peak acceleration of 8 g's between 2.5 and 13 Hz). Four of the NQB series samples and one of the NQO assemblies were then submitted to a 7-day steam and chemical spray exposure.

The terminal blocks were protected by NEMA-4 enclosures. The samples were energized with 120 Vac and 25 A except during the period when IR measurements were made. IR measurements after the thermal aging were greater than 1.4×10^{12} ohms, and after the gamma irradiation they were greater than 5.1×10^{11} ohms. Similar results were obtained after the seismic and vibration tests. During the steam/chemical spray exposure, the one-piece terminal blocks experienced variations in IR from 3×10^5 ohms at 10 Vdc to 2×10^{12} ohms at 500 Vdc. The sectional terminal blocks experienced IR variations from less than 5×10^4 ohms at 10 Vdc to 1.9×10^9 ohms at 500 Vdc. Though leakage currents were not measured for each terminal block individually, nor were they recorded throughout the test, the test report makes the following statement which we assume is based on periodic meter readings: "The leakage/charging currents which energized the specimens at 120 V were less than 200 mA during the dwells at 174°C (346°F). The leakage/charging currents decreased to less than 5 mA for the remaining portions of the steam/chemical spray exposure." The specimens withstood a 5-minute 2200 V high potential withstand test after the steam/chemical spray exposure. Acceptance criteria were not specifically mentioned, though reference was made to the maintenance of 120 Vac and 25 A.

3.2.3 Wyle Laboratory's Test of Marathon Terminal Blocks for Marathon Special Products [16]

Three sets of terminal blocks, each consisting of two Series 1600 NUC terminal blocks, two Series 1500 NUC terminal blocks, and two Series 142 NUC terminal blocks were tested. The blocks were protected in NEMA-4 enclosures. The test sequence was radiation exposure (200 Mrads at 0.58 Mrad/hr), thermal aging (120°C (248°F) for 18.5 days), vibration aging (0.1 g peak acceleration between 5 to 200 Hz), seismic simulation (5 OBE and 2 SSE) and LOCA simulation.

The planned accident simulation consisted of two 174°C (345°F), 50 psig steam plateaus each of 3 hours duration, followed by a 42 hour plateau at 163°C (325°F), 83 psig, and a 28-day, 3 hours plateau at 144°C (291°F), 45 psig. The two initial steam plateaus had initial ramps to 196°C (384°F), which lasted momentarily and then retreated to 174°C (345°F) in approximately 2 minutes. It should be noted that the 174°C (345°F), 50 psig condition is 26 C° (47 F°) superheated, while the other two temperature-pressure periods are saturated. Chemical spray was applied throughout the 30-day exposure. Arrhenius techniques were used to compress a one-year accident profile to a 30-day simulation. Each set of terminal blocks was powered at different voltage levels. One set was powered at 132 Vac, 33 A; one set at 264 Vac, 33 A; and one set at 528 Vac, 33 A. The acceptance criteria specified that 10^6 ohms was to be the minimum allowable IR for the functional tests and that during the accident exposure the 132 Vac specimens should not exceed 12 A leakage current, the 264 Vac specimens should not exceed 18 A leakage current, and the 528 Vac specimens should not exceed 24 A leakage current. Functional IR measurements were made initially and subsequent to each sequential exposure. The pre-test baseline measurements ranged from 10^9 to 10^{10} ohms; subsequent to the radiation exposure, the IRs varied between 2.4×10^9 and 3×10^{10} ohms; subsequent to the thermal aging, IR values varied between 10^{11} and 1.2×10^{12} ohms. Similar values were obtained after the vibration and seismic tests. During the first LOCA ramp, the leakage current for the 528 Vac terminal blocks exceeded 25 A and failed the fuse used to monitor the leakage currents. Also, the 18 A fuse in one of the 264 Vac circuits failed but did not fail a second time after it was replaced. During the second steam ramp, the 25 A fuse in the 528 Vac circuit failed again and the 528 Vac specimens were removed from the test. Leakage currents were monitored daily by using a clamp-on current probe for the specimens that remained in the test, though these readings are not reported other than to say that they were below the acceptance criteria. Also during the accident exposure, a power failure occurred which deenergized all terminal blocks. When power was reapplied approximately 15 minutes later, it was turned on abruptly and all leakage current fuses failed. This same phenomenon was observed in the Sandia tests [1] where rapid changes in applied voltages caused severe drops in terminal block IR. The post-accident IR functional tests yielded values between less than 5×10^5 ohms for the 528 Vac specimens to 1.2×10^{10} ohms for the other specimens. There were, however, a large number of 10^7-10^8 ohm readings which indicated that, in general, the IRs did not recover to the pre-accident levels.

3.2.4 Franklin Research Center's Test of Weidmuller Terminal Blocks for Weidmuller Terminations, Inc. [17]

Five terminal block assemblies each containing five SAK series terminal blocks were tested. The terminal blocks were molded of a glass-filled phenolic material. The terminal blocks were thermally aged (140°C for 7 days), exposed to 200 Mrad (air equivalent) Co-60 gamma dose at less than 1 Mrad/hr, vibrationally aged (3 to 60 Hz), and subjected to a multifrequency seismic vibration (1 to 40 Hz) which included five 30-second dwells at OBE levels and one 30-second dwell at SSE levels. The specimens were then divided into two groups and mounted in NEMA-4 enclosures. Each test group was then separately subjected to a 29-hour steam/chemical spray exposure to simulate a LOCA environment. The profile for one group reached a maximum temperature of 246°C (475°F) and 70 psig (89 C° (161 F°) superheat) and then retreated to 185°C (365°F) after 6 minutes and to 174°C (345°F) after 14 minutes into each of the peaks. The 174°C (345°F) periods lasted for approximately 3 hours and were at saturation pressure. After the second 174°C (345°F) period, two additional temperature plateaus completed the profile: 164°C (328°F) for 9 hours and 156°C (312°F) for 17 hours. Again, both of these plateaus were at saturation conditions. The peak temperature reached by the second group was 232°C (450°F) at 68 psig. The remainder of the profile followed the first group's profile. The terminal blocks were energized during the steam exposure with 600 Vac and 20 A. The acceptance criterion was to maintain a leakage current less than 1 A at the 600 Vac energizing level. Monitoring of leakage currents was accomplished by a 1 A fuse. For both test groups, it was observed that the 600 Vac potential had to be reduced to approximately 150 Vac at the times when fresh, room temperature solution was sprayed into the test chamber. With potential at 150 Vac or less the leakage currents remained less than 1 A. The leakage paths appeared to heal themselves after the recirculated spray reached temperatures of approximately 93°C (200°F). IR measurements at 500 Vdc before the LOCA simulation varied between 1×10^{8} and 1.5×10^{10} ohms; after the LOCA simulation they varied between 4×10^{7} and 3.5×10^{8} ohms. Two of these terminal block assemblies were subjected to further seismic qualification tests in a subsequent test program.

3.2.5 Wyle Laboratory's Test of Weidmuller Terminal Blocks for Washington Public Power Supply System [18]

This test program tested the same five terminal block assemblies subjected to the LOCA simulation discussed in paragraph 3.2.4. These assemblies had been stored by Weidmuller at normal office temperatures and humidities in the intervening two years. The test was a post-LOCA soak of the terminal blocks with intermittent periods of demineralized water spray. The terminal block assemblies were protected with the same NEMA-4 enclosures used in the Franklin test. New cabling was installed to power the terminal blocks. The test environment did not introduce steam; rather, the chamber was filled with demineralized water to within one foot of the specimens and submersion heaters were used to bring the test chamber and specimens to 110°C (230°F). Pressure was maintained at 20 psig which means that the system was approximately 17 C° (29 F°) below boiling temperature. The relative humidity in the chamber was 100

percent. Spray was on one out of every three hours. The terminal blocks were energized with 600 Vac and 20 A. The acceptance criterion was 1 A leakage current, monitored by a fuse. In addition, leakage currents were monitored throughout the test by a digital voltmeter and computer setup which sampled each of ten channels (two per terminal block assembly) continuously throughout the test. The sampling rate was not reported, but approximately once every eight minutes a printout of the maximum, minimum and average leakage currents that occurred in the preceding eight minutes was made. The leakage currents for four of the five terminal block assemblies remained less than 0.2 mA throughout the test and for most of the time were less than 0.1 mA. One terminal block assembly failed the 1 A fuse but post-test inspection of the assembly indicated that the failure occurred at the test chamber penetration and not the terminal block. Pre-test IR values were approximately 4×10^9 to 5×10^9 ohms at 500 Vdc and post-test IR values were 1×10^5 to 1×10^7 ohms. Forty-eight hours after the test, the IR values had recovered to 5×10^8 to 5×10^9 ohms. This recovery is similar to the recovery experienced in the Sandia tests.[1]

3.2.6 Reports on Nuclear Qualification Tests of Selected Phonix Terminal Blocks [19]

These reports summarize qualification tests conducted on terminal blocks of European origin. One ceramic type block, one thermosetting insulation type block, and two types of thermoplastic insulation type blocks were tested. A total of twenty-nine blocks were tested in the LOCA/HELB simulation. Precise identification of the blocks is given in the reports but detailed specification of the materials was not provided.

The test sequence was as follows:

a. Pre-test dimensional checks, insulation resistance (at 500 Vdc), voltage strength (3 kV rms (50 Hz) for 1 minute), and contact (i.e., conductor) resistance measurements.

b. Thermal aging at 140°C (284°F) for 30 days. (Thermal aging parameters based on 10°C rule and assumed ambient operating temperature of 50°C (122°F)).

c. Damp heat of 55°C (131°F) and 80 percent relative humidity for 48 hours.

d. Gamma irradiation with Co-60 to 50 Mrad (air) Total Integrated Dose (TID) at a maximum dose rate of 0.442 Mrad/hr (air).

e. Vibration test. Terminals energized with current loads of 20 mA.

f. Seismic test. Terminals energized with current loads of 20 mA.

g. Second gamma irradiation with Co-60 to 150 Mrad (200 Mrad cumulative TID) at a maximum dose rate of 0.43 Mrad/hr (air).

h. HELB test. The test profile selected for HELB simulation reflects both LOCA and HELB and lasted 30 hours.

Two initial high temperature steam phases consisted of a 2-minute ramp to 256°C (493°F), 2 minutes at 256°C (493°F) followed by a 2-minute ramp to 185°C (365°F), 8 minutes at 185°C (365°F) followed by a 2-minute ramp to 174°C (345°F) and 2 hours, 46 minutes at 174°C (345°F). The two high temperature steam phases were separated by a 2-hour ramp to 50°C (122°F). Subsequent to the second high temperature steam phase, ramps to a 9-hour 164°C (327°F) plateau and an 18-hour 156°C (313°F) plateau completed the test. Chemical spray was initiated at the beginning of each of the 174°C (345°F) plateaus and continued until the beginning of the ramp to 50°C (122°F) ending the first high temperature phase and to the end of the 30-hour test for the second high temperature phase. The terminal blocks were energized with one of four schemes: (1) 420 Vac and 20 A; (2) 420 Vac, no current; (3) 48 Vdc, unspecified current; and (4) 24 Vdc, unspecified current. It was not clear from the reports whether or not leakage currents were monitored throughout the HELB simulation.

i. Second thermal aging (post-LOCA aging) at 135°C (275°F) for 100 hours. (Parameters based on 10°C rule and assumed ambient temperature of 70°C (158°F)).

j. Voltage strength test at 3 kV rms (50 Hz).

The main results of the tests are as follows:

a. The mean insulation resistance of all samples in the pre-test condition was 10^{13} ohms.

b. No pre-test breakdowns at 3 kV were experienced.

c. Contact resistance was on the order of 0.1 to 0.3 mohms.

d. The first thermal aging and damp heat environments did not affect the physical characteristics of the material. Insulation resistance measurements at the conclusion of each environmental exposure was about a factor of ten greater than the pre-test measurements.

e. No adverse effects occurred during vibration and seismic testing. During these tests, the terminal blocks were loaded with a 20 mA current. Circuit continuity was maintained throughout the test.

f. No adverse effects were noted other than slight material discoloration after either gamma irradiation.

g. Insulation resistance decreased by an order of magnitude to 10^{12} ohms subsequent to the HELB environment. Of the 29 terminal block assemblies tested in the HELB simulation, only one experienced an irreversible short circuit. This block was made from thermoplastic type insulation and energized with

420 Vac, but no current. A second thermoplastic insulation terminal block assembly energized to 420 Vac and 20 A experienced a leakage current of greater than 5 A at the beginning of the second chemical spray period. After replacement of circuit fuses, this assembly successfully completed the test. Five of the thermoplastic insulation blocks and one of the thermosetting insulation blocks were badly deformed by the HELB test environment. Four of them were so badly deformed that they fell off of their mounting rail due to their own weight.

h. Three kV rms (50 Hz) voltage strength tests were conducted after the post-HELB thermal aging. All ceramic terminal blocks passed the voltage withstand tests. The six plastic insulation block assemblies that were badly deformed by the HELB simulation were not subjected to this test. One of the eight thermosetting insulation blocks tested failed the terminal-to-terminal test. Of the seven thermoplastic insulation blocks tested, three failed the terminal-to-terminal tests and one failed the terminal-to-ground test.

No definition of failure or acceptance criteria was provided in the test report. The conclusion drawn from these tests was that only ceramic terminal blocks should be used for in-containment applications.

3.2.7 Wyle Laboratory's Test of Eight Marathon Terminal Blocks for Commonwealth Edison Company [20]

This report documents testing performed on Series 6000 and 1600 Marathon fixed barrier terminal blocks. Two assemblies of terminal blocks were tested, each consisting of three Series 6000 terminal blocks and one Series 1600 terminal block. They were housed in an electrical enclosure manufactured to Commonwealth Edison specifications and connected in the usual alternating terminal, serpentine type wiring scheme used in other industry qualification tests of terminal blocks. Okonite 10 AWG Hypalon insulated cable was used to make the connections. The test sequence was as follows:

a) Baseline Functional Tests

b) Irradiation to 206 Mrad gamma (Co-60)

c) Functional Test

d) Thermal Aging - one assembly at 120°C (248°F) for 466 hours (20-year equivalent life) and one assembly at 120°C (248°F) for 932 hours (40-year equivalent life)

e) Functional Test

f) Seismic Test

g) Functional Test

b) Accident Exposure Simulation

i) Functional Test

The acceptance criteria for the baseline functional test were to possess an insulation resistance of at least 10^9 ohms and a resistance through the terminal block/cable conducting path of less than 10 ohms. For all of the post-test functionals, the acceptance criteria were to maintain IR greater than 10^6 ohms and resistance through the conducting path less than 10 ohms. During the LOCA simulation, the original acceptance criterion was to maintain leakage currents less than 2 A, but this criterion was changed by Commonwealth Edison to 10 A. In the report, the figure showing the schematic of the electrical circuit shows ammeters set up to measure leakage current along with fuses to limit leakage current. However, no leakage currents are reported in the test documentation.

The accident exposure was originally planned for 34 hours which was based on an Arrhenius calculation to compress a one year accident exposure. The original profile called for two 10 second ramps from initial conditions of 57°C (135°F) and 0 psig to 196°C (384°F) and 50 psig, then retreating after 100 seconds to 174°C (345°F) and 50 psig for 3 hours. During the 3 hour exposure for margin and during the first 3 hours of the accident exposure portion of the profile, chemical spray was to be sprayed at 0.5 gal/min/ft^2. After the first 3 hours of the accident exposure portion of the profile, the following conditions were to prevail: 163°C (325°F), 45 psig (28 C° (50 F°) superheat) for 3 hours, 163°C (325°F), 25 psig (47 C° (85F°) superheat) for 18 hours, and finally 163°C (325°F), 20 psig (54 C° (97 F°) superheat) for 10 hours. Due to the inability of the test facility to maintain superheat conditions for such high spray rates, the spray rate was modified to 0.04 gal/min/ft^2 for the 3 hour margin peak and the first 3 hours of the accident exposure. To make up for this deficiency from planned spray rates, at the end of the 163°C (325°F), 45 psig period, a 3 hour period was added at 127 °C (260°F), 45 psig (8 C° (15 F°) subcooled) with spray at 0.5 gal/min/ft^2. The spray was terminated at the end of this period (the 9 hour point of the accident exposure). From the 9 hour point the remainder of the planned profile was run except an extra 2.5 hours was added at the end to account for the 3 hours at 127°C (260°F).

The data in the report indicates that the first transient (for margin) had one thermocouple (TC) reading a maximum of 163°C (325°F) 24 seconds after introduction of the steam, while the second and third thermocouples had reached 141°C (285°F) and 93°C (200°F) respectively at this time. By 52 seconds, the first TC was reading 141°C (285°F) and the second TC began tracking it. At the 3 minute point, the readings of these TCs diverged from a common value of 121°C (250°F). The third thermocouple was reading 82°C (180°F) at the 3 minute point. All data ceases at the 3.9 minute point and no further data are presented until the second ramp begins.

Notice of Anomaly 14 in the Wyle test report explains that during the first transient (for margin), the chamber rupture disc burst at 20 psig. At Wyle's suggestion additional time was to be added to each temperature plateau of the main exposure rather than repeating the initial transient. Looking at the temperature profiles achieved, apparently 30 minutes was added to the 174°C (345°F) plateau. The profile actually achieved during the main exposure was 182°C (360°F) to 210°C (410°F) (depending on thermocouple), 50 psig at approximately 40 seconds elapsed time, 177°C (350°F), 50 psig from approximately 2 minutes to 3.5 hours elapsed time, 163°C (325°F), 45 psig from 3.5 hours to 6 hours elapsed time, 127°C (260°F), 45 psig from 6 hours to 9 hours elapsed time, 163°C (325°F), 25 psig from 9 hours to 25 hours elapsed time and finally 163°C (325°F), 21 psig from 25 hours to 36.5 hours elapsed time.

At approximately 1 hour and 50 minutes into the test (during the 174°C (345°F), 50 psig, 0.04 gal/min/ft^2 period), Notice of Anomaly 17 reports that a 6000 Series terminal block exceeded 10 amperes leakage current. Inspection showed that it was shorted to ground and so it was removed from the test circuit and the test continued. During the remainder of the test the leakage currents of the other terminal blocks remained below 10 amperes. In the post-LOCA functional tests, the circuit-to-circuit insulation resistance of the terminal block removed from the test was 3.6 ohms. The post-test inspection notes that the area where the failure occurred could be seen. The post-LOCA IRs of the other terminal block were between 10^6 and 10^{12} ohms.

3.2.8 Westinghouse Electric Corporation's Test of Terminal Block Performance in LOCA Environment [21]

This report documents testing performed on Curtis BT, Cinch Jones 541, Westinghouse 542247 and Marathon 1500 Series terminal blocks. No thermal or vibrational aging was conducted and no seismic simulations or radiation exposures were reported. The test was an exposure to an unspecified LOCA steam profile of approximately 5 hours, 30 minutes duration. Chemical spray was sprayed for one hour at 0.32 gal/min. It is unclear from the report whether the terminal blocks were mounted in a NEMA-4 enclosure. During the test the blocks were energized with 600 Vac. No acceptance criteria are stated in the report. IR measurements were taken before, at various times during, and after the steam exposure. Before and after the exposure the IR values were 10^{10} to 10^{12} ohms. During the test IR values varied from 8×10^3 to 2.6×10^5 ohms. The concluding statement says that " Although the insulation resistance decreased more than six orders of magnitude, the terminal blocks...were able to function at 600 Vac throughout LOCA."

4.0 SANDIA TESTS OF TERMINAL BLOCKS IN A SIMULATED LOCA ENVIRONMENT

4.1 Terminal Blocks Tested

Earlier work at Sandia [2] consisted of testing terminal blocks under TMI conditions. This test raised questions regarding terminal block performance but was not conclusive in that there were several areas where test conditions deviated from actually installation conditions. Therefore, to quantify the performance of realistically installed and protected terminal blocks in a LOCA environment and to investigate terminal block failure and degradation modes, we tested 24 terminal blocks (5 models from 4 manufacturers*) in a simulated LOCA environment.[1] Based on our reviews of the qualification documents, we determined that neither the accelerated aging process nor the seismic testing significantly affected terminal block performance. Thus, we tested terminal blocks in the "as received" condition. To simulate normal handling during installation, no special care was taken during test preparation to prevent the deposit of fingerprints or other normal contaminants on the terminal block surfaces; however, we did not simulate deposits of construction dirt or other sediments which tend to accumulate over time. As such, the terminal blocks were probably in the best initial condition that might possibly exist for terminal blocks installed in the field. The terminal blocks were protected by NEMA-4 electrical enclosures with 1/4" diameter weep holes in the bottom. Cables entered the boxes from the side through nuclear grade, liquid-tight conduit. To simulate cables entering a conduit from a cable tray system, the conduit was terminated inside the test chamber and was unsealed at both ends.

4.2 Test Configuration

The test was divided into two phases. Phase I exposed 12 terminal blocks (three each of four designs) to an 11-day steam-only environment. Phase II exposed 12 terminal blocks (six each of one design and three each of two other designs) to approximately one day of simultaneous steam and chemical spray followed by five days of a steam-only environment. Both temperature profiles closely followed the PWR temperature profile recommended by IEEE-323-1974, Appendix A.[37] Saturated steam conditions were maintained throughout both test phases. In Phase I, the terminal blocks were connected in an alternating terminal serpentine, similar to the wiring scheme used in industry qualification tests (Figure 4-1). In Phase II, the terminal blocks were connected in a configuration more representative of actual plant connections with one terminal powered and the two adjacent terminals and base plate monitored for leakage currents (Figure 4-2). One terminal block in the Phase II test was connected to a pressure transmitter in a circuit configuration representative of a plant transmitter circuit. This transmitter circuit was included to validate the results obtained from the other circuits and to confirm the analysis of the effects of terminal block degradation on low power circuits. Figure 4-3 shows the transmitter circuit wiring.

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* Table 1 in Reference 1 identifies the manufacturers I through IV and the Models A through E. That nomenclature is continued in this report, and is extended in Table 5-1 to Manufacturer V, Model F.

The terminal blocks were powered at voltages typical of in-plant applications: 4 Vdc typical of RTD circuits (Phase I test only), 45 Vdc typical of instrumentation circuits, and 125 Vdc typical of control circuits. The terminal-to-terminal leakage currents were monitored in both Phase I and Phase II tests, and the terminal-to-ground (base plate) leakage currents were monitored in the Phase II tests. The data were acquired at discrete time steps by data loggers. The time interval between successive measurements varied depending on the experimental activity being conducted. For example, during steam ramps or other transients, monitoring was accomplished as rapidly as possible (about every 6 seconds); during long periods of steady state conditions, the monitoring interval was lengthened to 30 minutes. Based on these data, insulation resistances were calculated for each leakage path on each terminal block. Four channels of leakage current data were monitored continuously by strip chart recorders throughout the test.

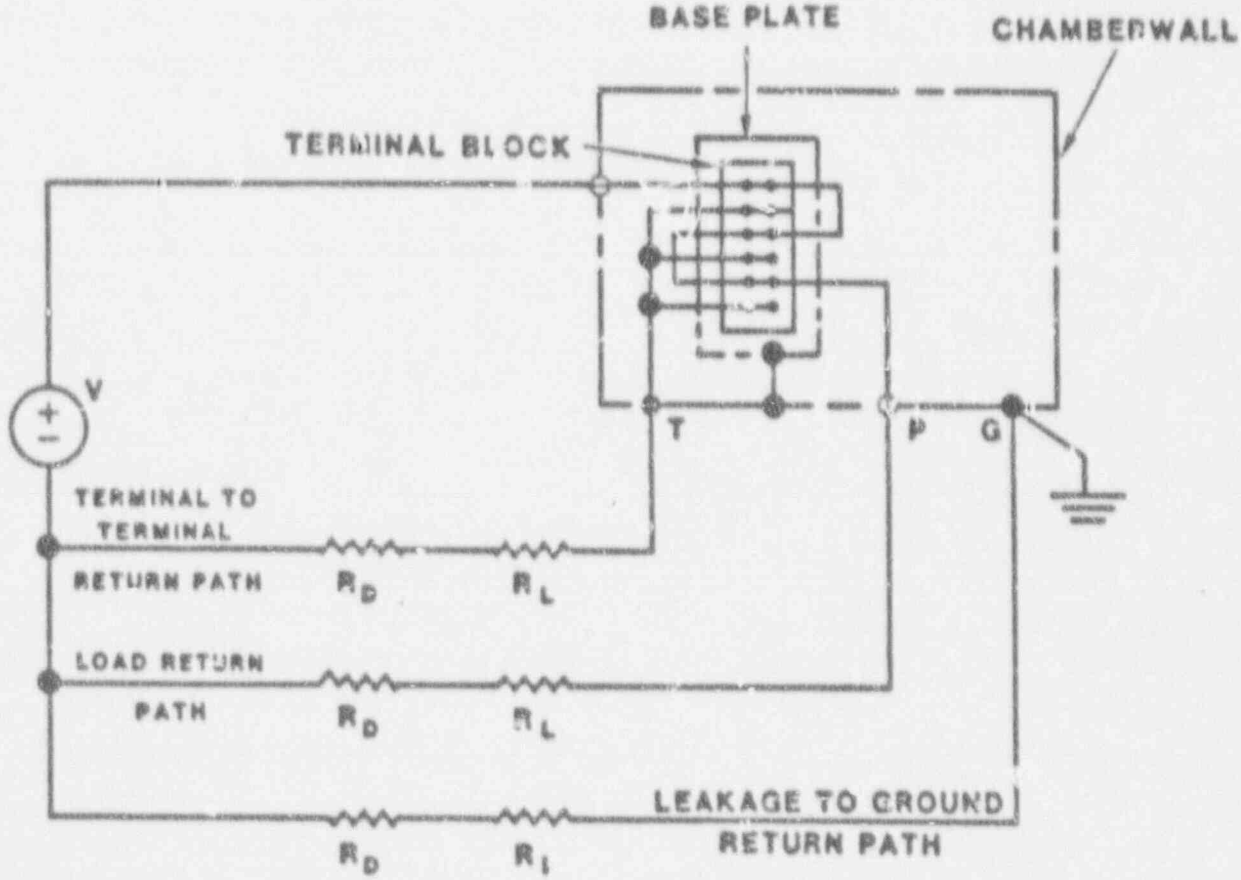

Figure 4-1: Wiring Schematic for the Sandia Phase I Terminal Block Test

(Note the serpentine connection on the terminal block)

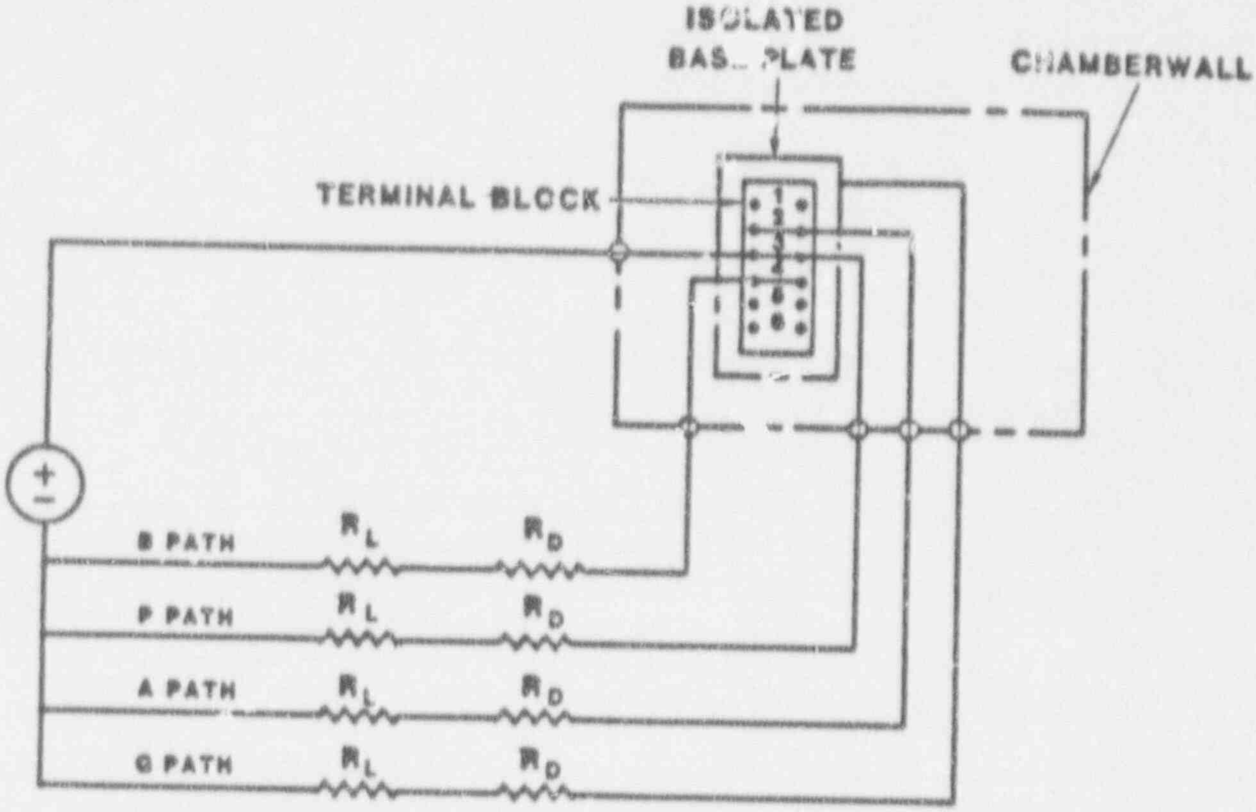

Figure 4-2: Wiring Schematic for the Sandia Phase II Terminal Block Test

(Note the once through connection on the terminal block)

4.3 Major Results

Surface leakage currents through conducting surface moisture films are the primary mechanism by which terminal blocks contribute to instrumentation and control circuit degradation. During our tests, the formation of surface films reduced insulation resistance to 10^2 to 10^5 ohms from initial values of 10^8 to 10^{10} ohms. Figures 4-4 and 4-5 illustrate these changes in insulation resistance for both Phase I and II at various LOCA temperature conditions. At 45 Vdc, leakage currents were on the order of 0.1 to 10 mA. These values are sufficiently large to affect 4 to 20 mA instrumentation circuits by 0.3 to 185 percent with a nominal effect of 0.5 to 45 percent at the mid-range of instrument output. At 4 Vdc, insulation resistance was varied from 5×10^3 to 7×10^4 ohms, values which are sufficiently low to affect RTD measurements by 0.3 to 9 percent. At 125 Vdc, the IR values were comparable to the 45 Vdc values and were at times slightly (approximately 1/2 to 1 order of magnitude) higher. Reference 2 reports slightly lower but comparable results for TMI-2 conditions; leakage currents between 0.08 and 0.3 mA are reported therein for terminal blocks protected by an electrical enclosure.

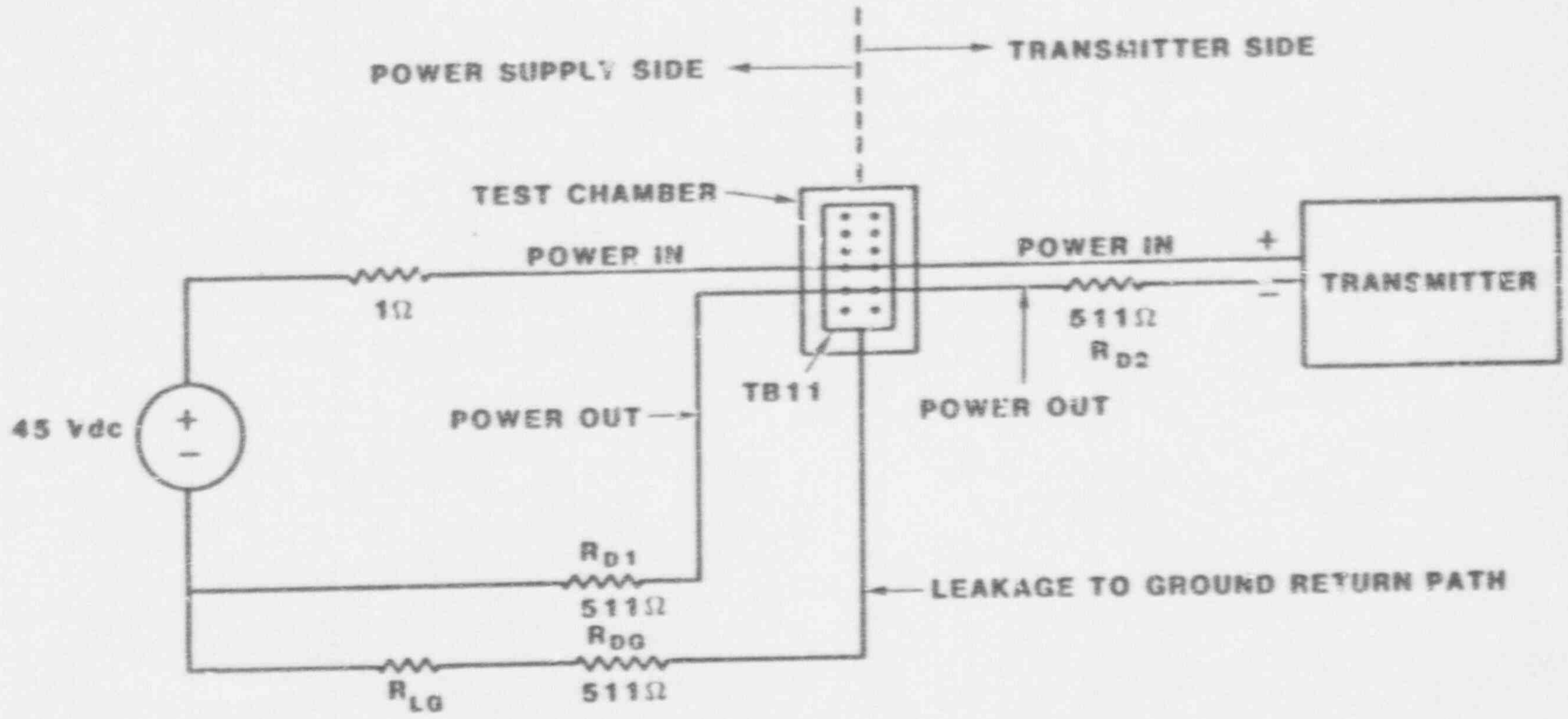

Figure 4-3: Wiring Schematic for the Transmitter Circuit Tested in the Sandia Phase II Terminal Block Test

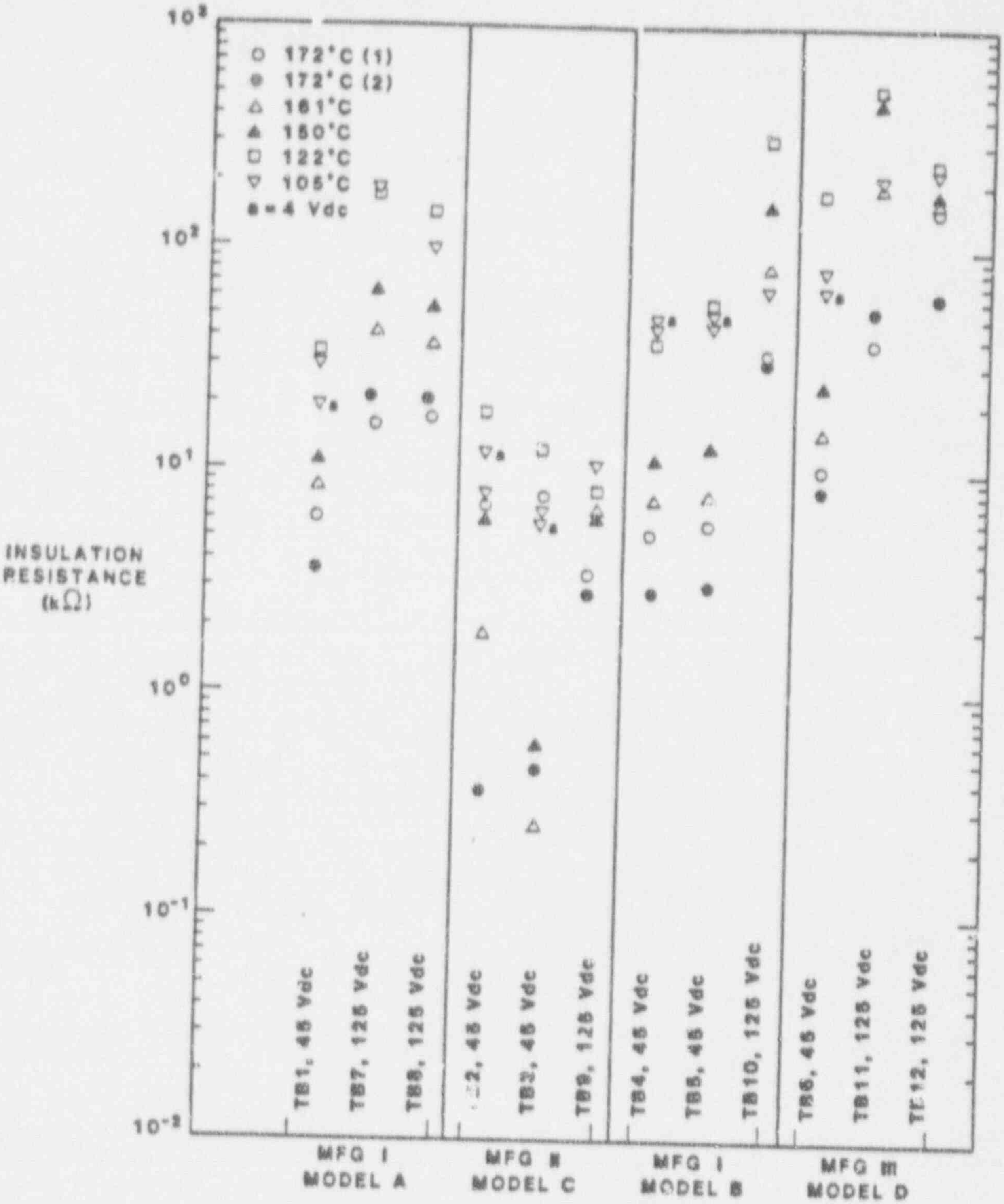

Figure 8 Terminal-to-Terminal Insulation Resistance for Sandia Phase I Terminal Blocks

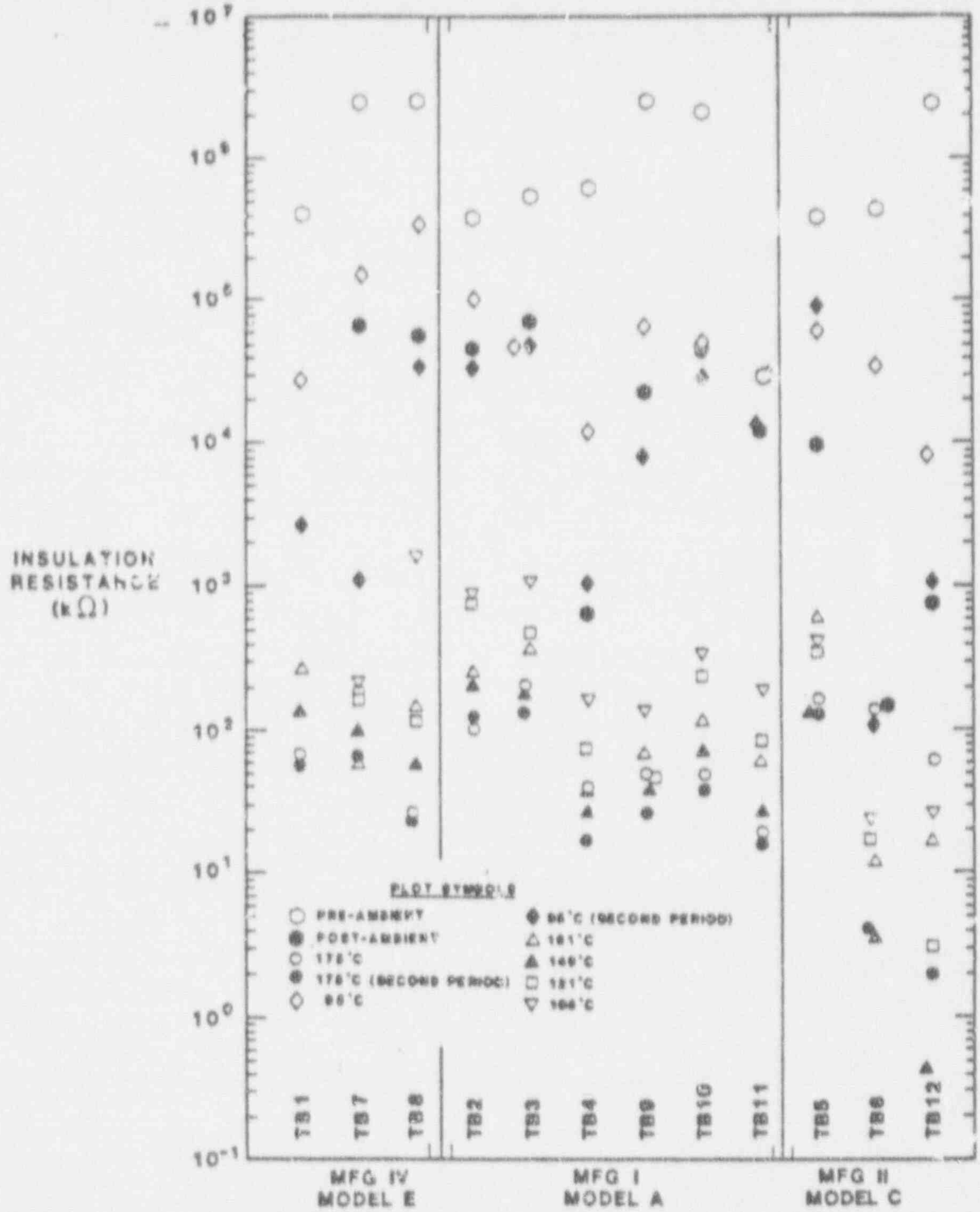

Figure 4-5: Insulation Resistance A for Sandia Phase II Terminal Blocks

Insulation resistance A is the IR calculated for the A path (see Figure 4-2). Terminal Blocks 1-6 powered at 125 Vdc, 1 A and Terminal Blocks 7-12 powered at 45 Vdc, 20 mA.

We experienced one open failure where the leakage currents increased over a 90-minute period to values which contributed to the separation of the 12 AWG wire supplying power to the terminal block. The separation occurred close to the terminal block-wire junction and was primarily caused by test induced tensile stresses.[1]

During the periods of cooldown to 95°C (203°F) and the post-test ambient temperature period, the insulation resistance values increased to 10^6 to 10^8 ohms but not to the pre-test values of 10^8 to 10^{10} ohms. This behavior illustrates three points: first, the similarity between cooldown and post-test IR values indicates that the same conduction mechanism is probably occurring during these periods; second, IR recovery to higher values after exposure indicates that a transient phenomenon is responsible for the low IR values during the steam exposure; and third, that some permanent degradation of the terminal block insulation resistance occurs. A conductive moisture film is the most probable explanation for the transient phenomenon. During cooldown periods, the residual heat of the terminal block will keep its temperature higher than the surrounding atmospheric temperature. Since the surface film will be close to the terminal block temperature, its vapor pressure will exceed the surrounding atmosphere's pressure, causing the film to vaporize. In the post-test case, the same phenomenon occurs until the terminal blocks cool to ambient temperature. Then the normal relative humidity regime takes over. The permanent degradation of the terminal block IR may have been caused by either carbonization of the terminal block surface or other organic materials in the vicinity or by residues of potentially semiconducting mediums such as cadmium sulfide. Post-test chemical analysis of three Phase II terminal blocks showed the presence of both cadmium sulfide deposits and carbonaceous residues in a graphite-like structure.

There was a noticeable dependence of IR on temperature. The IRs at temperatures less than 110°C (230°F) tended to be 1/2 to 1-1/2 orders of magnitude greater than IRs at temperatures greater than 110°C (230°F). All of the terminal blocks tested exhibited similar temperature related performance trends, though there were block-related differences in absolute performance. This result is in agreement with the findings of Reference 2 and the theory of electrolytic conduction [38] which indicates increased conductivity with increased temperature.

Since saturated steam conditions were maintained throughout the test, the temperature dependence could also have been interpreted as a pressure dependence. Pressure per se, though, is not the governing factor in film conduction, but it is important in determining the conditions necessary for film formation. Exclusive of contamination effects, if a system is superheated and at equilibrium, films will not form and the performance of the terminal block will be relatively good. Similarly, if the terminal block temperature is above the dew point in an air environment, the same condition will exist. Alternately, if the terminal block temperature is below the dew point in an air environment, or if films have formed due to a coo terminal block being surrounded with steam and the system remains at saturation, films will form and remain on the surface of the terminal bloc.

During the chemical spray periods of the Sandia Phase II tests, no effect of the chemical spray was observed. This finding was somewhat surprising since we expected the chemical spray to enter the conduit, penetrate down through the conduit-cable interstitial space, and drip onto the terminal blocks. We hypothesized that the introduction of Na^+ and OH^- ions to the surface film would enhance the conductivity of the film. The lack of any observed change in leakage currents initially indicated to us that the NEMA-4 enclosures with unsealed conduit entrances provided adequate protection against the intrusion of chemical spray. To check this result, at the conclusion of the Phase II environmental exposure we conducted a submergence experiment to observe the performance of blocks positively known to be spray contaminated. In this test three blocks were submerged in a chemical spray and steam condensate solution and three blocks were left unsubmerged. IRs in a steam environment after the submergence were compared. They indicated that there was only slight difference between submerged and unsubmerged blocks, with the unsubmerged blocks being slightly better. This data coupled with the observation that the Sandia Phase I test results were compatible with the Sandia Phase II results shows that even if spray had penetrated the enclosures little difference in leakage currents may have been observed. Apparently, the additional conducting ions from the spray may not significantly alter the conductivity of the film. It also precludes a definite conclusion about the effectiveness of the NEMA-4 enclosure in preventing chemical spray from penetrating to the terminal blocks. However, we believe the NEMA-4 enclosures as they were installed in the Sandia tests are reasonably effective in preventing such penetrations. This result correlates well with the results reported in Reference 18.

Figure 4-6 shows the insulation resistance measured during Phase I of the Sandia tests for one Manufacturer I, Model A terminal block. The data begin with the second transient and continues to the end of the test. One of the first things to note is that IR does not remain constant. There are periods when the IR improves dramatically (e.g., just after temperature reduces from 160°C (320°F) to 150°C (302°F) there is an increase in IR from 10 kohms to 63 kohms) and then deteriorates just as dramatically (e.g., following the spike to 63 kohms the IR drops back to the 10 kohm region). The introduction of steam is one parameter which causes the IR to drop and as already discussed, changes in temperature caused observable changes in IR. Another important factor is voltage gradients. Whenever power is applied or the voltage increased suddenly to an otherwise quiescent terminal block the IRs were always observed to decrease by large amounts, often to values below the range settings on the recording instruments. Two illustrations of this effect are apparent in Figure 4-6: the first is at hour 121 where power was reapplied after 25 hours without power and the second is at hour 238 where a transition from 4 Vdc to 45 Vdc occurred. In both cases an immediate decrease in IR is apparent, and then over a period of hours, an increase in IR is observed. In the first instance the IR increased eventually to the 65 kohm region. In the second case the recovery was back to the 60 kohm region at which point the test was terminated. In both cases a period of some 10-20 hours was required to make the recovery. Also note that at the same environmental temperature, the mean IR level at 4 Vdc is less than at 45 Vdc by about a factor of three.

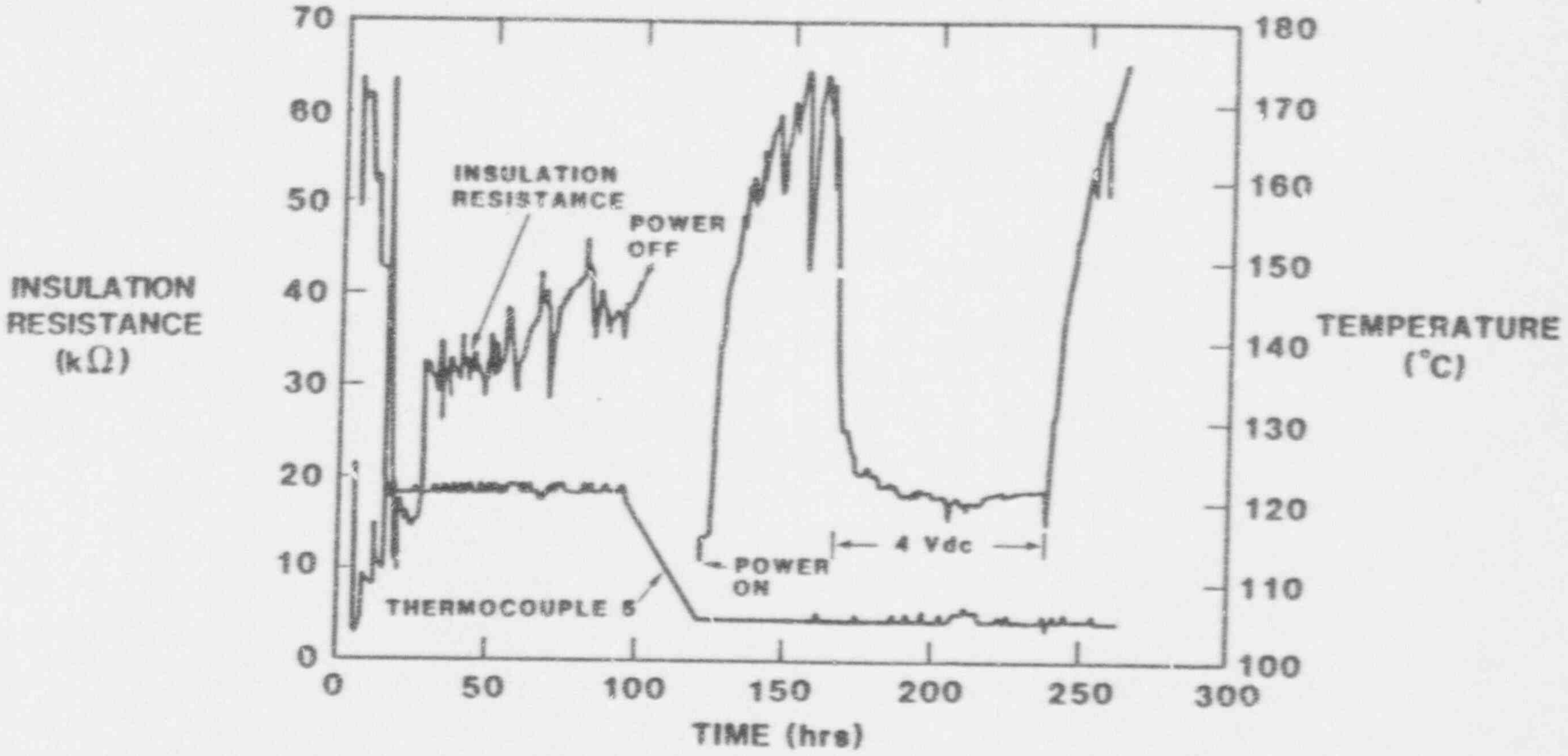

Figure 4-6: Insulation Resistance for One Manufacturer I, Model A Terminal Block From the Second Steam Ramp to the End of the Test

Temperature trace is for a thermocouple located in the NEMA enclosure with the terminal block. Except for the 4 Vdc period noted, the applied voltage was 45 Vdc.

The model in Section 6 predicts a nearly constant value of steady state IR as long as the number of conducting ions in the film remains constant. The transient application of potential increases the current through the leakage paths more than would be expected if the IR was a constant value. At the higher current values, more Joule heating exists and the film temperature increases. More convective and conductive heat transfer occurs, but during the transient period the primary energy loss mechanism is vaporization (and hence thinning) of the film. As the film thins, the IR slowly increases towards an equilibrium value. Joule heating decreases to a point where it is in balance with convective and conductive heat losses. At this point, net vaporization of the film ceases and a new equilibrium film thickness is established. The approach to equilibrium is a slow process, as evidenced by the rather long time constants observed for recovery of the IRs to higher values after application of an increasing voltage gradient.

5.0 TESTS OF TERMINAL BLOCK PERFORMANCE AT TEMPLE UNIVERSITY

To provide independent tests of terminal block performance, Temple University was contracted to perform laboratory bench tests of terminal blocks. The tests were designed and directed by Dr. Robert Salomon of the Temple University Chemistry Department. The tests at Temple were conducted in two phases. Phase I tested terminal blocks in 100 percent relative humidity and at the TMI accident temperature of 86°C (187°F). Phase II tested terminal blocks at somewhat lower temperatures, and used steam as a heat source. Phase II also introduced chemical spray into some of the test environments during selected periods of the test.

5.1 Phase I Tests of Terminal Blocks in a Quiescent Temperature and Humidity Environment

The Phase I experiments tested three* models of terminal blocks in 100 percent relative humidity and 86°C (187°F) with little chance for temperature gradients. The basic premise here was that if temperature gradients were eliminated, then leakage currents would be small since no special preference for initiating moisture condensation would exist. Test voltages were 480 Vac, 400 Vac, 300 Vac, 200 Vac, and 100 Vac. The experimental setup used is illustrated in Figure 5-1. A battery jar was used as the environmental chamber. The terminal blocks were suspended from a polycarbonate lid above a water or HCl solution via the electrical leads. The leads were connected to adjacent terminals of the terminal block and if a metal base plate was part of the terminal block design, it was connected to one of these terminals. Thus, the leakage paths were from one terminal to an adjacent terminal or from one terminal to an adjacent terminal and the base plate. The solution in the battery jar was four inches deep and was either deionized water or a 10 percent by volume solution of HCl. The solution was stirred vigorously throughout the test by a high speed magnetic stirring device. The motion of the solution also stirred the atmosphere in the battery jar above the solution. Heat was supplied to the system via heating wire wrapped around the outside of the battery jar from the bottom, to a level just below the level of stationary solution in the jar. The exterior of the battery jar was insulated with fiberglass insulation to reduce any thermal gradients within the jar. In addition, for some of the experiments run in Phase I, an infrared lamp was used to prevent condensation of moisture on the terminal block. The lamp was positioned such that its rays penetrated the polycarbonate lid and impinged on the terminal block. Without this light, visible droplets of moisture would condense on the polycarbonate lid; however, at no time, either with or without the infrared lamp, was moisture observed on the terminal blocks.

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* Two of the three models tested were also tested in the Sandia tests.[1] These were Manufacturer I, Model A, and Manufacturer II, Model C.

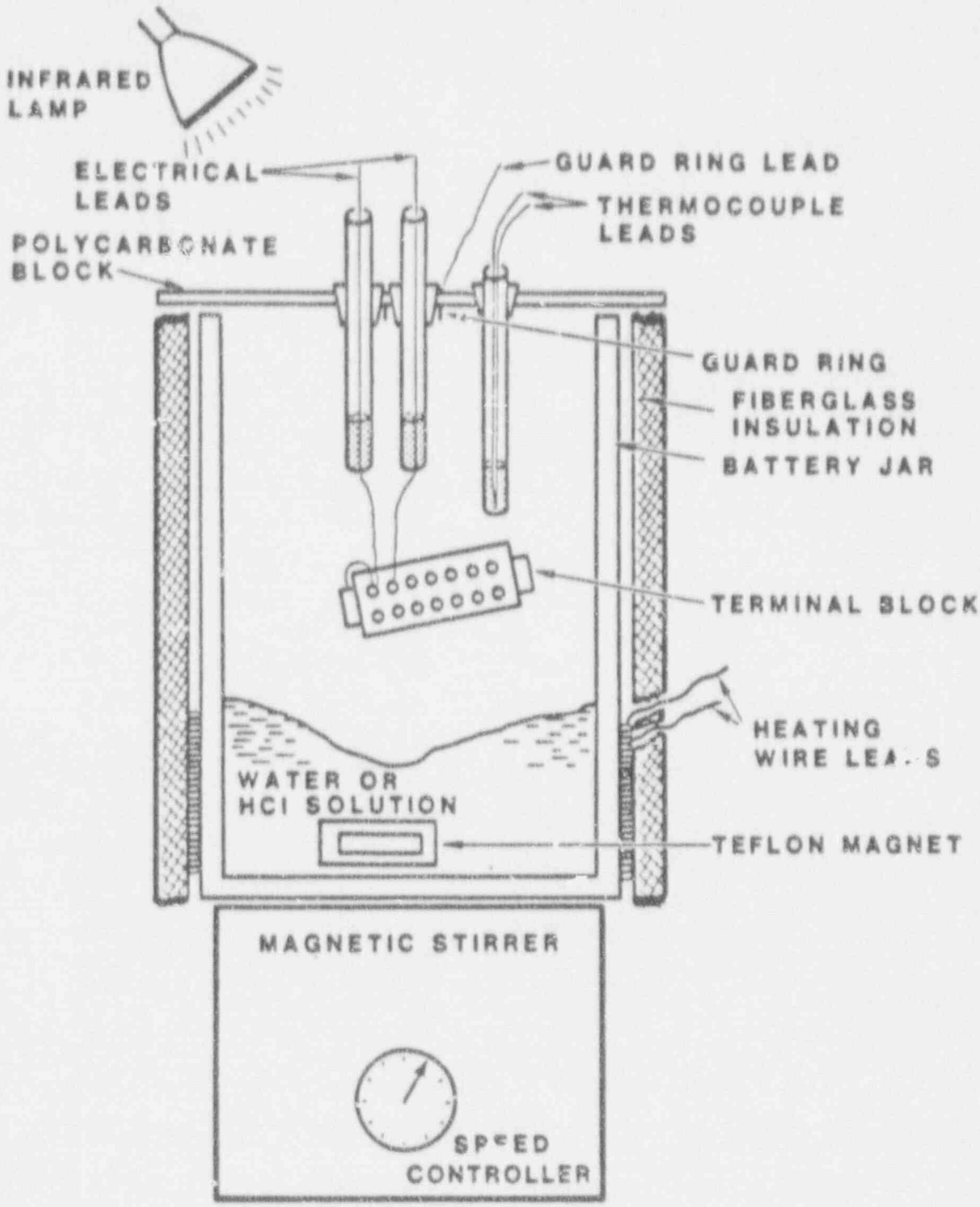

Figure 5-1: Experimental Setup for Salomon's Phase I Tests

Figure 5-2 shows the electrical circuit used in Salomon's Phase I tests. Initially a Princeton Applied Research lock-in amplifier was used to measure the leakage current, but this instrument failed and the resistor-diode-electrometer* circuit shown in Figure 5-2 replaced it.

The system was calibrated against known resistances, and to protect against giant current surges, the Variac supplying power to the primary side of the transformer was underfused. The guard ring was tightly pressed against the polycarbonate lid and completely encircled one electrode feeding through the lid. It was always at a potential slightly less than the guarded electrode. Any possible leakage currents along the surface of the polycarbonate lid were thus returned to the power supply without affecting the measurements of terminal block leakage current.

Initially the blocks were tested in the "as-received" condition and no special care was taken to clean them. These blocks therefore were contaminated with fingerprints. The leakage currents were measured as a function of time and temperature as the system moved toward the final system temperature of 86°C (187°F). The experiments lasted from one to three hours. Generally, leakage currents with the deionized water solution in the jar were in the micro-ampere region or lower if the infrared lamp was turned on. The leakage currents with the HCl solution in the jar were sometimes slightly higher, but not significantly so since HCl has a high vapor pressure at 86°C (187°F).

After testing the blocks in the "as-received" condition, they were soaked briefly (a few minutes) in 1%, 10% (0.26% and 2.6% by weight) and saturated NaCl solutions, oven dried at 90°C (194°F) and then reinstalled in the experimental setup. The experimental procedure was then repeated. The leakage currents generally increase monotonically with the NaCl concentration of the soaking solution. For those blocks soaked in the saturated salt solution, the leakage currents reached the milliampere region before the final system temperature of 86°C (187°F) was reached. In some case, the heavily contaminated blocks experienced a decrease in the leakage current as applied voltage increased. We attribute this phenomenon to Joule heating of the conducting film which caused drying and precipitation of salt and therefore reduced conductivity. There also may be some formation of drybands which would reduced path continuity. One actual breakdown was experienced at approximately 400 Vac for a terminal block soaked in saturated NaCl solution. The breakdown path is illustrated in Figure 5-3 and was evidenced by severe blistering of the phenolic material. A summary of some of Salomon's Phase I results is given in Table 5-1.

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* The electrometer was a Keithley Model 610C.

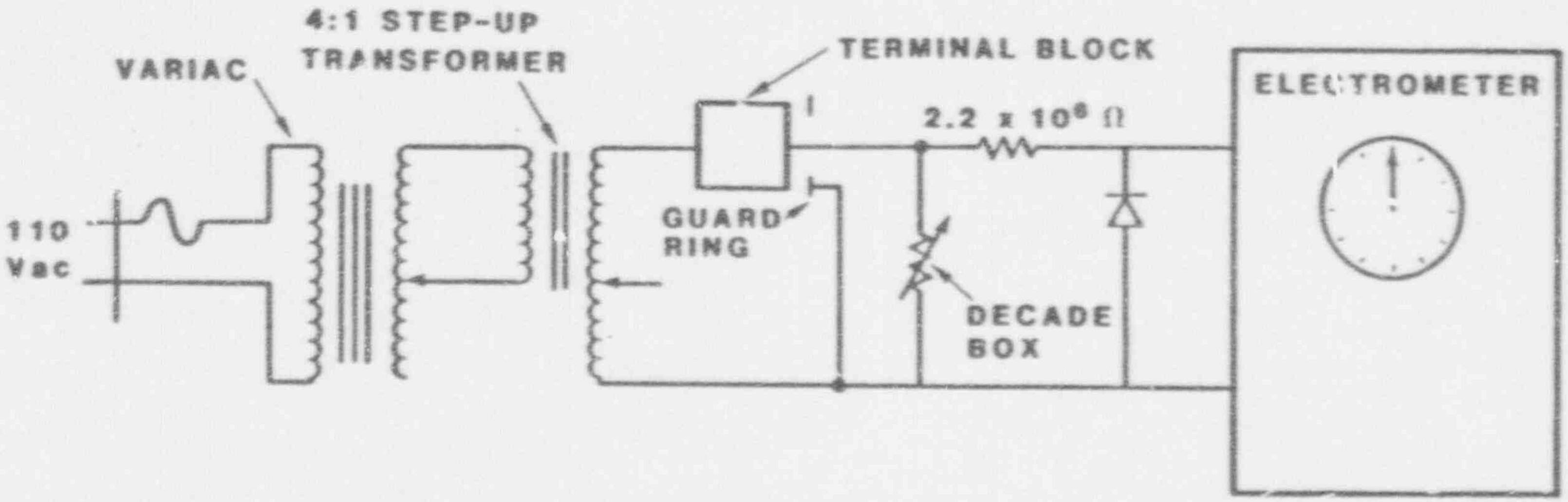


Figure 5-2: Electrical Circuit for Salomon's Phase I Tests

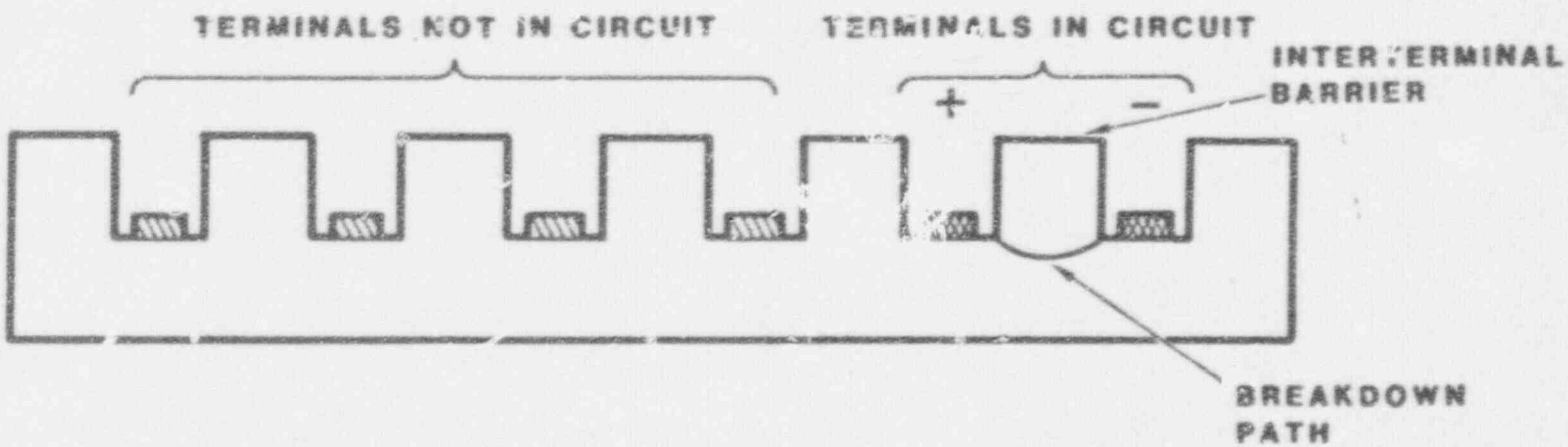


Figure 5-3: Sketch of Terminal Block Show[illegible]cation of Breakdown Path

Table 5-1

Representative Data For Salcmon's Quiescent Environment
Bench Tests of Terminal Block Performance

Applied Voltage (Vac)	Mfg I Model A Leakage Current (mA)	Mfg I Model A Temp (°C)	Mfg II Model C Leakage Current (mA)	Mfg II Model C Temp (°C)	Mfg V** Model F Leakage Current (mA)	Mfg V** Model F Temp (°C)	Contamination
100	0.024	86	0.60	86	0.0084	86	"as-received"
200	0.038	86	0.16	86	0.0071	86	+
300	0.068	86			0.0069	86	100% RH
400	0.095	86	0.30	86	0.0077	86	
[illegible]	0.075	86					
480	0.032	83					
480	0.022	81	0.38	86	0.011	86	
100	0.040	86	No Msmts Made		0.080	86	1% NaCl solution
200	[illegible]	86			0.15	86	+
300	0.030	86			0.070	86	100% RH
400	0.040	86			0.080	86	
480	0.070	86			0.060	86	
480	0.060	86			0.060	86	
480	0.060	85			0.080	82	
480	0.040	84			0.070	78	
480	0.030	83			0.080	76	
100	[illegible]	86	No Msmts Made		0.10	86	10% NaCl solution
200	0.110	86			0.060	86	&
[illegible]	0.180	86			0.070	86	100% RH
400	0.240	86			0.070	86	
480	0.250	86			0.080	86	
480	0.250	85			0.10	80	
480	0.175	80			0.070	70	
480	0.070	69			0.060	60	
480	0.050	60			0.023	45	
480	0.0090	45			0.021	35	
480	0.010	35					
20	9.0	86	No Msmts Made				Saturated NaCl
40	20.	86					&
100	60.	86			19.2	86	100% RH
140	20.	86					
160	30.	86					
200					0.70	86	
300	200.	86			0.20	86	
400	Breakdown*				0.17	86	
480					0.20	86	

* Breakdown occurred before reaching 400 Vac.

** The nomenclature for terminal block manufacturer and model number established in Reference 1 is extended here.

5.2 Phase II Tests of Terminal Blocks in an Active Steam, Chemical Spray, and Temperature Environment

In Phase II, seven different models of terminal blocks from four manufacturers were tested. The test arrangement was similar to the one used in Phase I except for the modifications in the lid for steam and chemical spray entrance ports and the use of a commercial temperature controlling bath apparatus instead of a battery jar as the environmental chamber. No infrared lamp was used in the Phase II tests. Figure 5-4 illustrates the experimental arrangement for Phase II tests. The steam was produced from a commercial vaporizer modified with an asbestos wrapped tube leading to the bath controller lid. Deionized water was used in the vaporizer together with a small amount of sodium sulfate as a nonvolatile conductor. Deionized water was used to avoid the potential for volatile impurities being introduced into the terminal block environment. The steam made in this manner was condensed, and the conductivity of the condensate measured. It measured 3×10^{-4} $ohm^{-1}cm^{-1}$. Steam was delivered to the system at low pressure and at a rate equal to approximately 20 ml of condensate per minute. Temperature in the chamber was controlled by an auxiliary heater in the bath which supplemented the energy introduced via the steam. The temperature of the system never exceeded 90°C (194°F) in any of the experiments.

The composition of the chemical spray was that specified by IEEE 323-1974 Appendix A.[37] It was introduced into the system by forcing a stream through a small glass nozzle at approximately 20 psig. This stream was intersected with a jet of nitrogen at the same 20 psig. The result was a finely atomized spray in the chamber. The point of intersection for the chemical spray stream and the nitrogen jet was approximately 9 cm from the terminal block, and thus the chemical spray stream did not directly impinge on the terminal block. A polycarbonate lid sealed the bath controller opening. The terminal block was suspended from this lid by the electrical leads just as the Phase I terminal blocks were installed in the battery jar. The electrical wires used glass enclosed leads to penetrate the polycarbonate lid. One of these leads was electrically guarded to prevent leakage currents along the interior surfaces of the chamber from entering into the measurements. The leads were connected to adjacent terminals on the terminal blocks. For those terminal blocks which had a base plate as an integral part of the design, this plate was connected to one of these terminals. Thus, either terminal-to-terminal or terminal-to-terminal and base plate leakage currents were measured. Figure 5-5 shows a schematic of the electrical connections.

Twenty-four experimental runs were made using various combinations of terminal block model, spray, and no-spray. When spray was introduced, it was always after the steam had been on for at least 30 minutes. Table 5-2 summarizes the data obtained from one run with one Model I, Manufacturer A terminal block. Figures 5-6 through 5-11 give the results of all runs made with this model of terminal block. These plots show three pieces of information: leakage currents as a function of time, leakage currents as a function of temperature and temperature as a function of time.

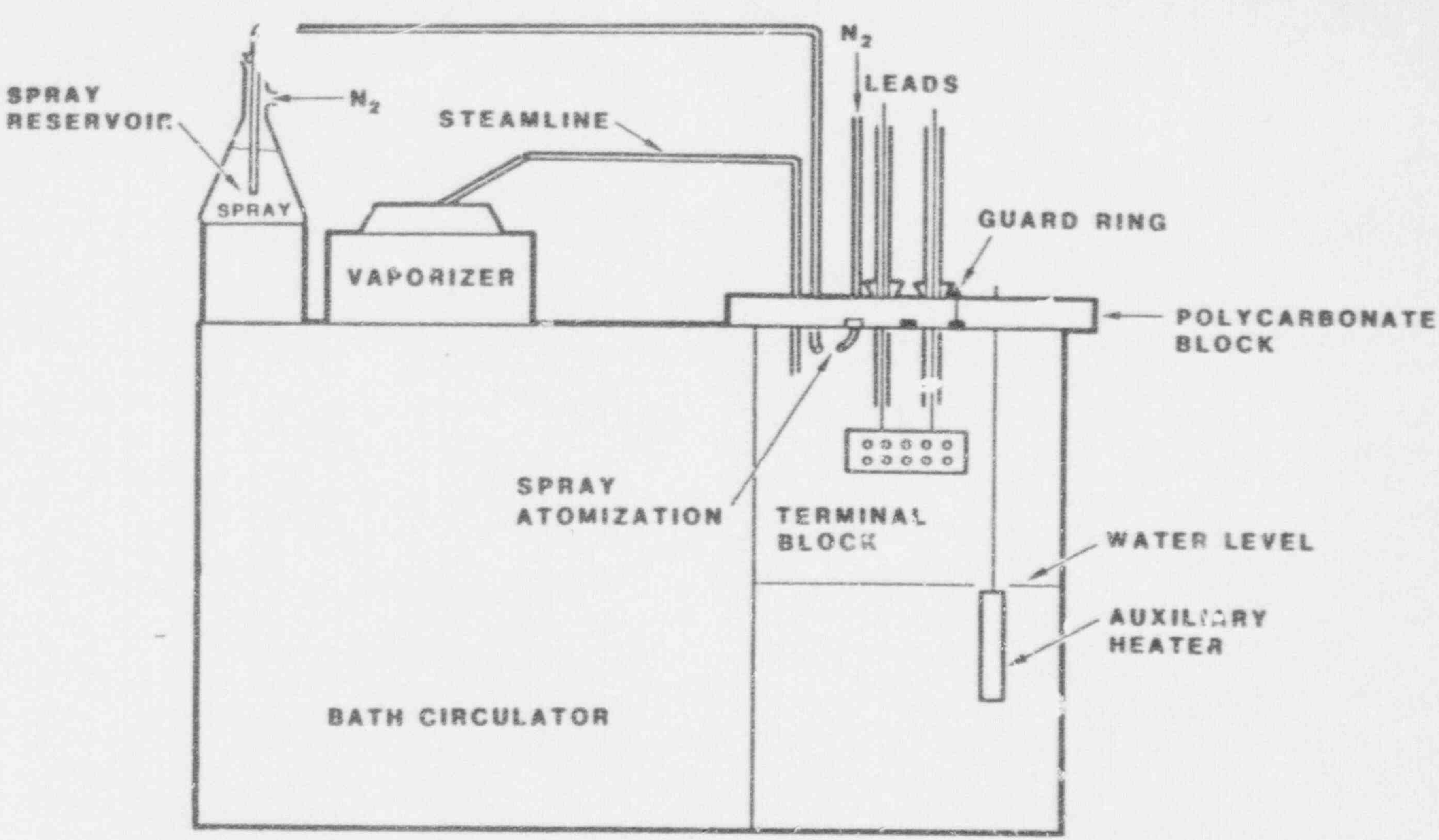


Figure 5-4: Experimental Setup for Salomon's Phase II Tests

The environment included clean steam and controlled additions of atomized chemical spray at selected times.

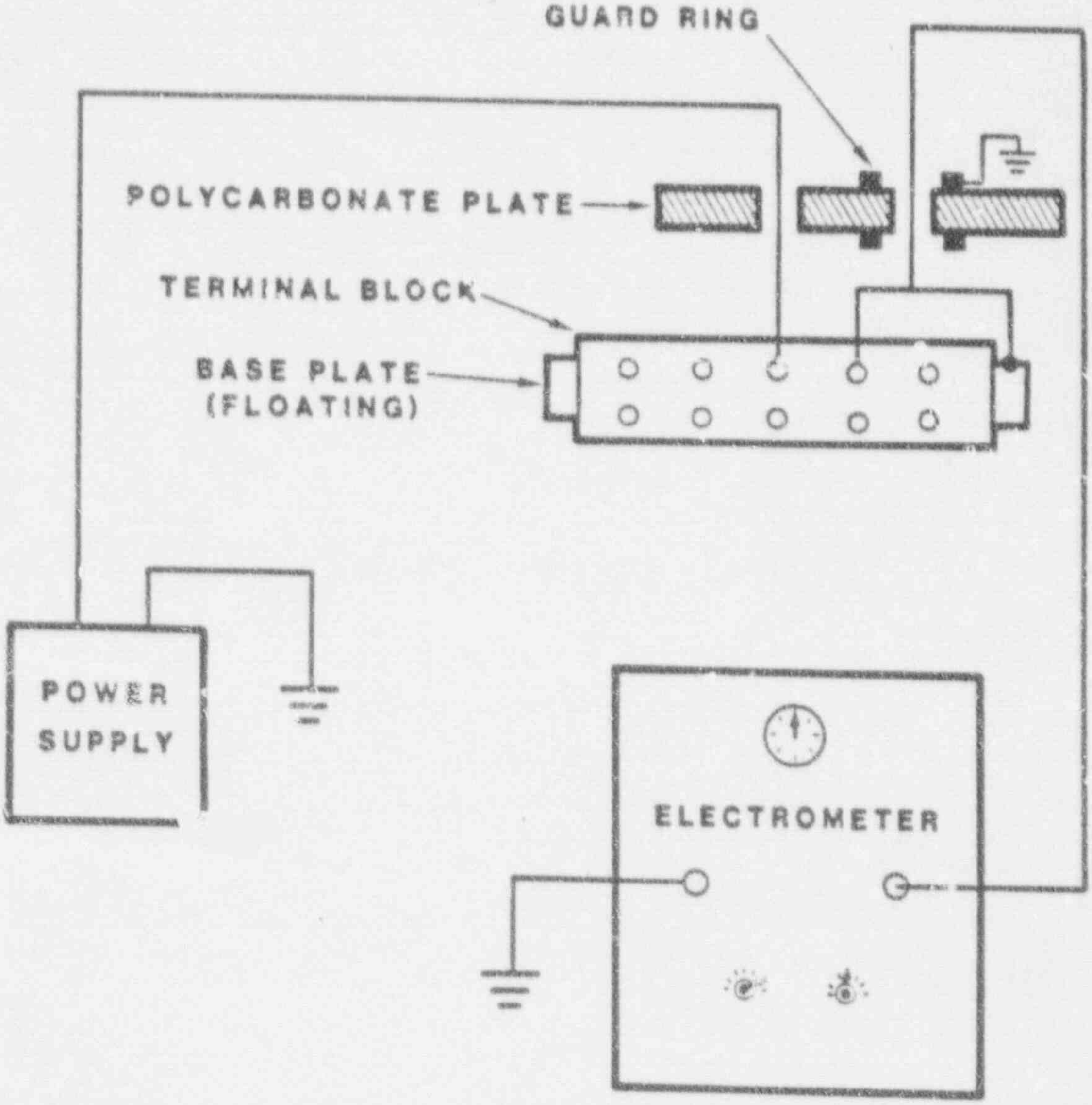


Figure 5-5: Electrical Circuit for Salomon's Phase II Tests

Table 5-2

Typical Leakage Current Data From Salomon for One Manufacturer I, Model A Terminal Block Powered at 45 Vdc in an Clean Steam Environment

Measurement No.	Time (min)	Temperature (°C)	Leakage Current (mA)
1	0	22	0
2	1	70	0
3	2	75	0.1×10^{-3}
4	3	77	0.4×10^{-3}
5	4	77.5	1.2×10^{-3}
6	8	80	3.7×10^{-3}
7	10	81	5.6×10^{-3}
8	15	83	8.0×10^{-3}
9	22	85	11.0×10^{-3}
10	25	86	12.4×10^{-3}
11	30	86	15.0×10^{-3}
12	55	86	21.4×10^{-3}
13	60	86	29.0×10^{-3}

Salomon's data, not all of which are presented herein, show several things. First, the data show a great deal of variability in the magnitude of the leakage currents. Variations between 10^{-7} A to 10^{-3} A were noted, with the latter value being rare. Although, the example in Figure 5-10 does not clearly show the effect, when containment spray was present the currents were frequently enhanced and often reached the milliampere region. One was as high as 6 mA. The greatest variety of tests were run on the Manufacturer I, Model A terminal block. Table 5-3 tabulates the leakage currents observed at the end of the test for these blocks. The environment temperature for these observations war between 80°C (176°F) and 90°C (194°F).

Except for the block dipped in saturated NaCl solution and dried, the final leakage currents are the highest values observed during the test. For similar block conditions, these endpoint leakage current values compare reasonably well with data reported for the Phase I quiescent tests by Salomon. The "as-received" condition in the Phase I test had values varying from 0.024 mA at 100 Vac to 0.095 mA at 400 Vac, while the Phase II value was 0.029 mA at 45 Vdc. During the Phase I tests, the terminal block which had been dipped in saturated NaCl solution and dried experienced leakage currents of 9 mA at 10 Vac to 200 mA and breakdown at 400 Vac. For this same block condition, a maximum of only 0.33 mA was observed in the Phase II test. This difference may possibly be attributed to the polarization of the electrolytic solution [61] that occurs in conductive solutions when a dc potential is applied.

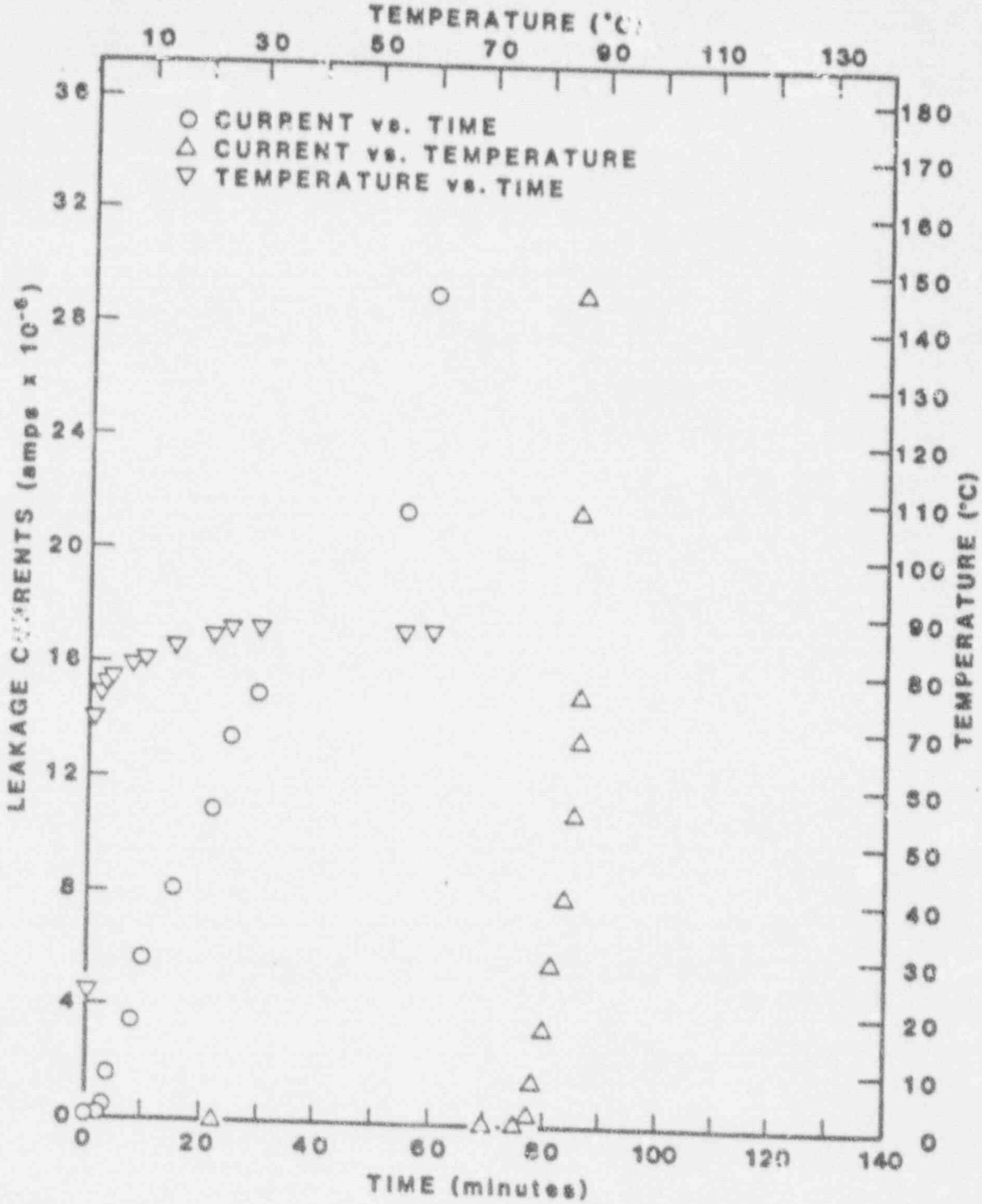


Figure 5-6: Leakage Currents at 45 Vdc as a Function of Time and Temperature for a Manufacturer I, Model A Terminal Block in the "As-Received" Condition

Environmental temperature as a function of time is is also shown.

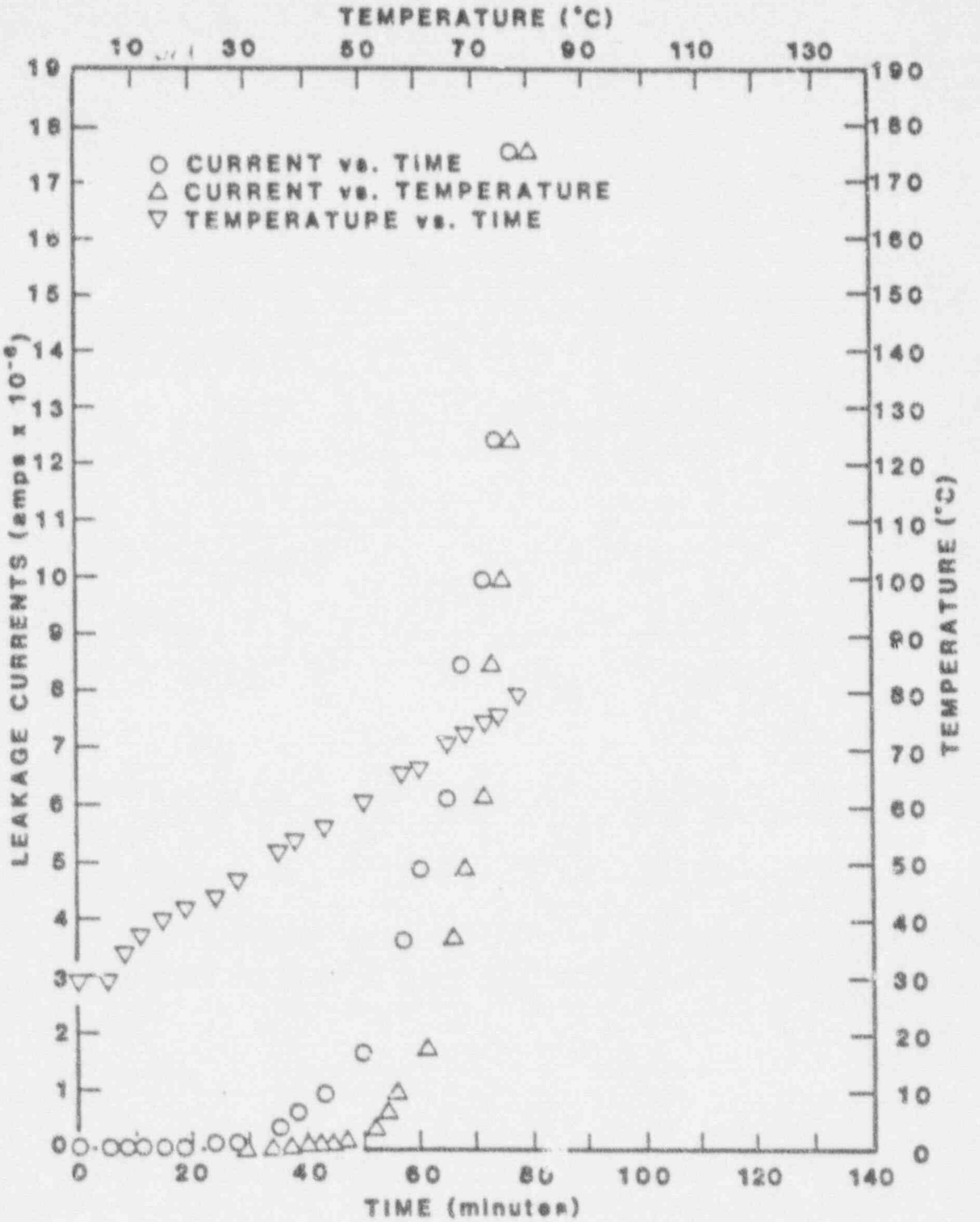


Figure 5-7: Leakage Currents at 125 Vdc as a Function of Time and Temperature for a Manufacturer I, Model A Terminal Block in the "As-Received" Condition

Environmental temperature as a function of time is also shown.

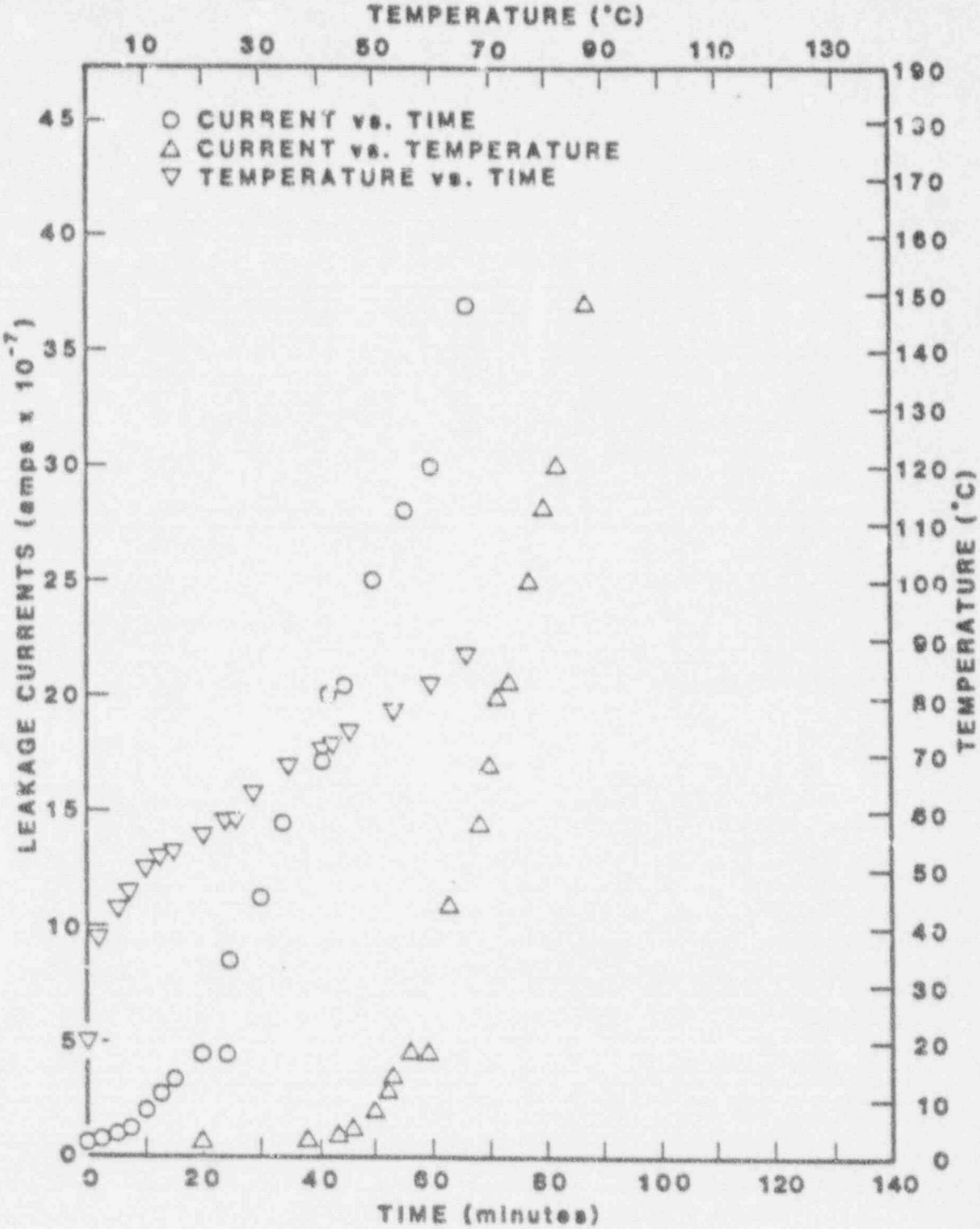


Figure 5-8: Leakage currents at 45 Vdc as a Function of Time and Temperature for a Manufacturer I, Model A Terminal Block After Being Washed and Soaked in Distilled Water

Environmental temperature as a function of time is also shown.

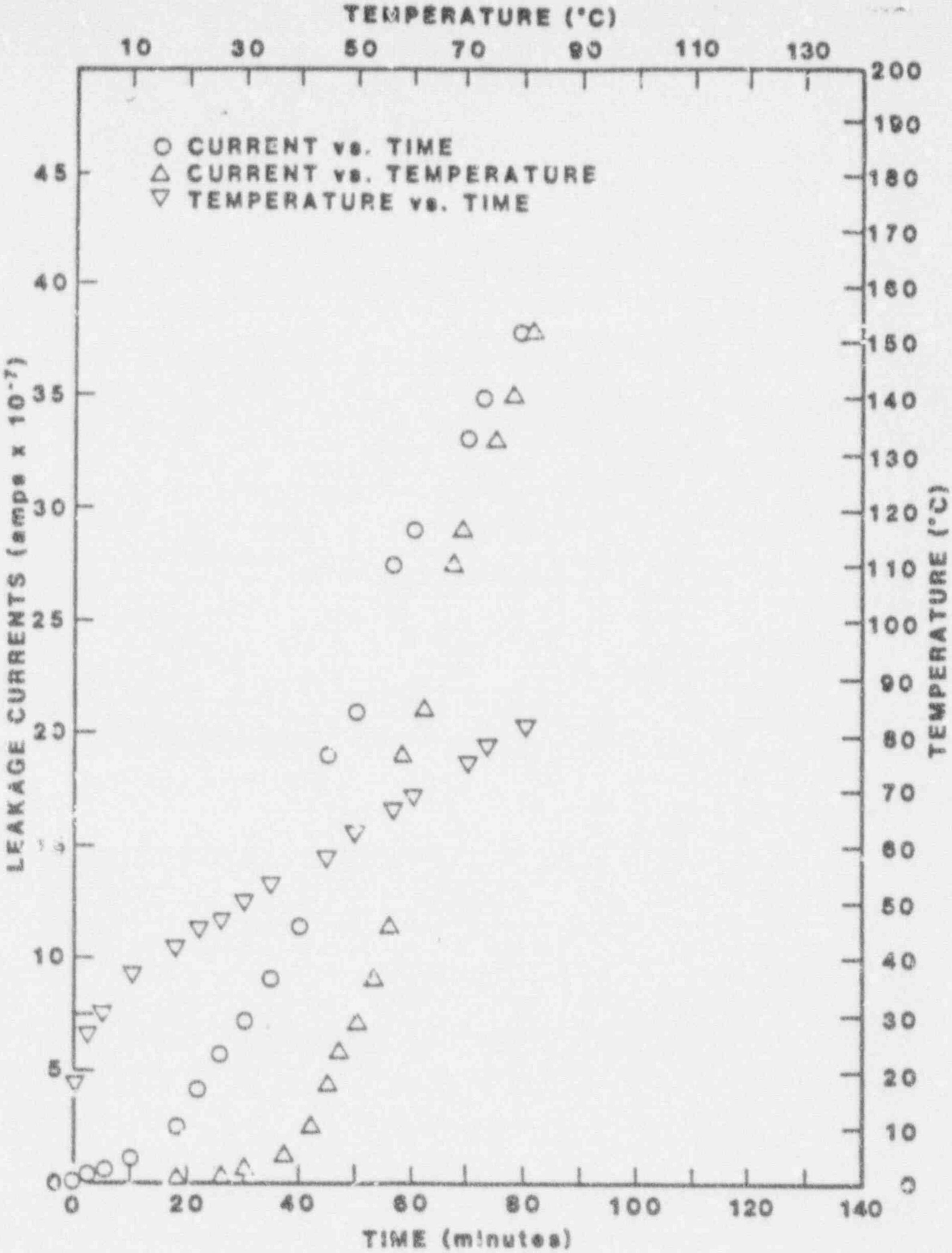


Figure 5-9: Leakage Currents at 45 Vdc as a Function of Time and Temperature for a Manufacturer I, Model A Terminal Block After Being Washed With Distilled Water and Then Handled

Environmental temperature as a function of time is also shown.

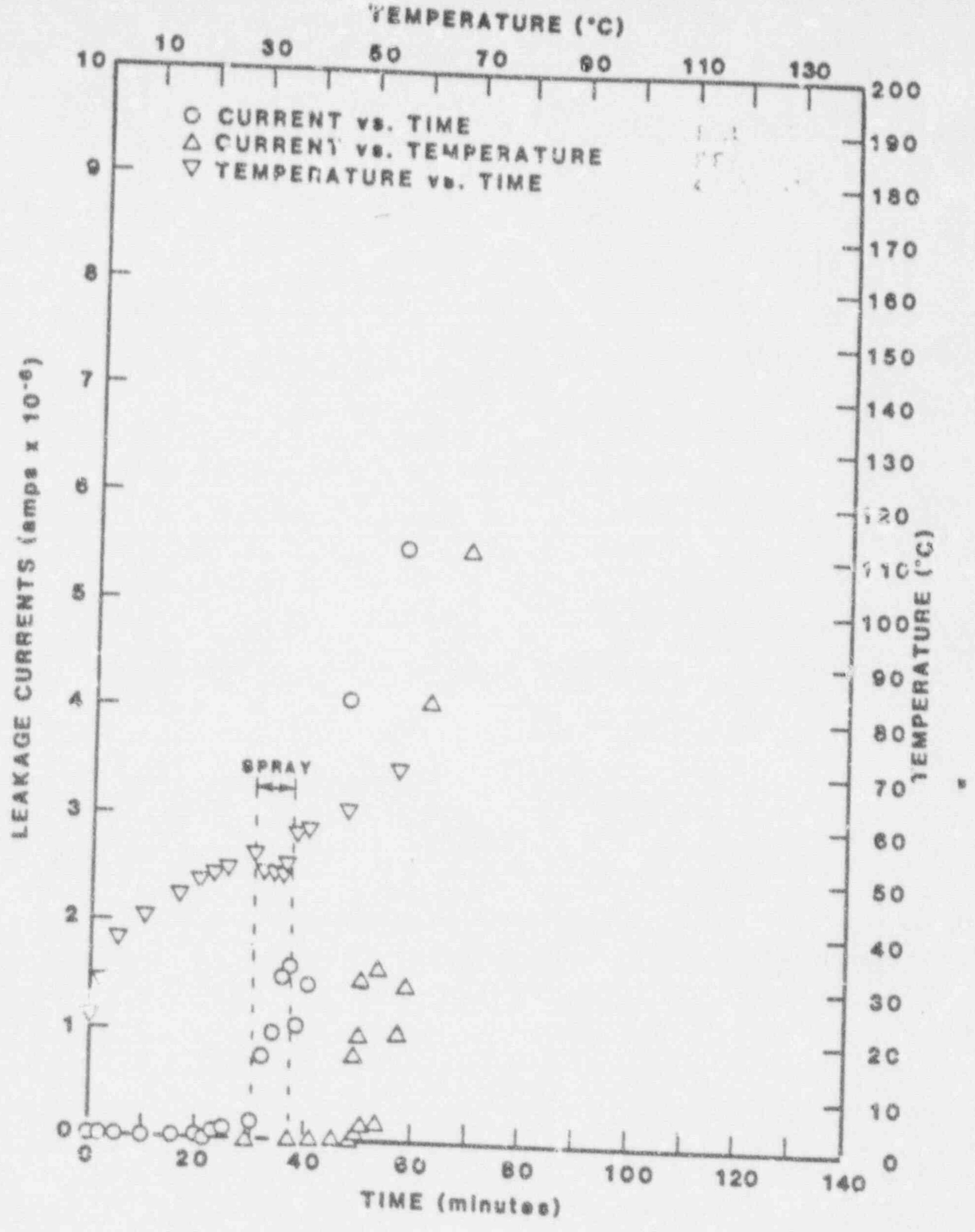


Figure 5-10: Leakage Currents at 45 Vdc as a Function of Time and and Temperature for a Manufacturer I, Model A Terminal Block in the "As-Received" Condition and Subjected to 7 Minutes of Finely Atomized Chemical Spray

Environmental temperature as a function of time is also shown.

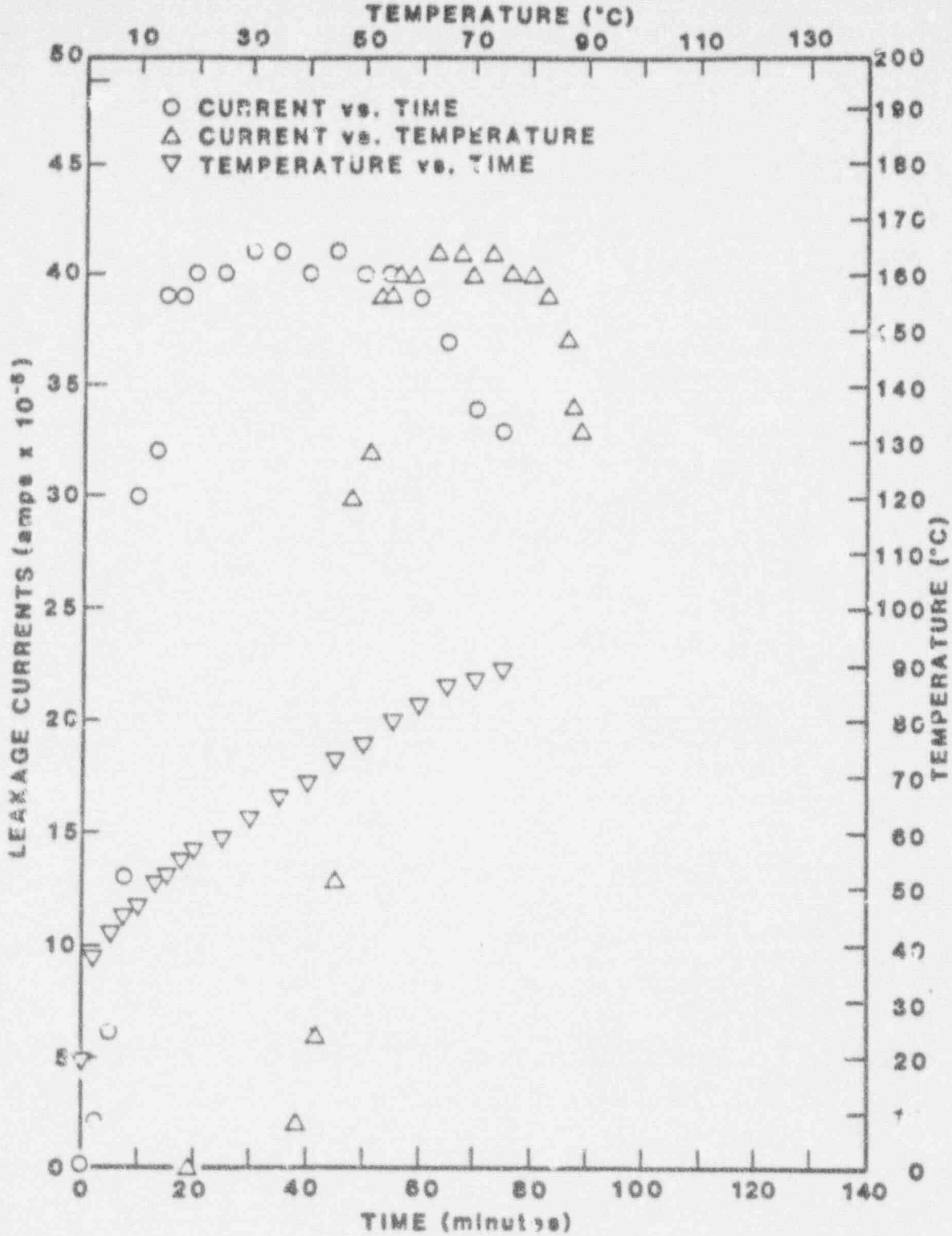


Figure 5-11: Leakage Currents at 45 Vdc as a Function of Time and Temperature for a Manufacturer I, Model A Terminal Block Dipped in Saturated NaCl Solution and Dried

Environmental temperature as a function of time is also shown.

Table 5-3

Final Values of Leakage Current and the Ratio of Final to Initial Values of Leakage Current for Manufacturer I, Model A Terminal Blocks

	-----45 Vdc-----		-----125 Vdc-----	
	I_f (mA)	I_f/I_i *	I_f (mA)	I_f/I_i *
As Received	0.029	290	0.0175	175
Washed & Soaked in Distilled Water	0.0037	60	-	-
Washed & Soaked in Distilled Water, Handled	0.0038	76	-	-
As Shipped, With Chemical Spray	0.0055	183	-	-
Dipped in Saturated NaCl Solution and Dried	0.33	330	-	-

* I_f = Final value of leakage current
I_i = Initial value of leakage current

Also included in Table 5-3 are the ratios of final leakage current, I_f, to beginning leakage current, I_i. These ratios give an idea of the relative change observed during the test. For the most part, this change occurred between 35°C (95°F) and 80°C (176°F) and for some terminal blocks it occurred over a much narrower range--nominally 55°C (131°F) to 70°C (158°F). The temperature behavior is readily apparent in Figures 5-6 through 5-11 and may contribute to the lower leakage currents observed in these tests versus those observed in the Sandia tests. Electrolytic conductivity is known to follow an Arrhenius relationship.[38] However, the overall behavior results from the influence of the many other factors, especially changes in concentration which affect the conductivity of the film solution.

5.3 Characterization of the Amount of Salt Deposited by Fingerprints

In order for a moisture film to be conductive, it must contain dissociated ions. There are potentially many sources for these ions on the surface of a terminal block. These included surface dust contamination, residue from manufacture and salt from fingerprints. Of

these, the most likely source is the salt deposited from the fingerprints of those who handle the terminal block during its life. On this premise, a brief experimental determination of the salt deposited by fingerprints was undertaken.

All measurements were made with six Westinghouse #542247 terminal blocks. This terminal block is made from a cellulose-filled phenolic insulation material. The experiment consisted of cleansing the surface to be tested, then masking off a square area 1 cm on a side and touching this area with the tip of the index finger. The pressure of the contact was not measured, but was assumed to be typical of an average man picking up a terminal block. Three subjects, A, B, and C participated in the test, which helped average both the amount of salt deposited and the contact pressure between the fingertip and the terminal block.

To measure the amount of salt deposited, the area was flooded with between 0.3 cc and 0.5 cc of deionized water. This drop was held on the contact area by surface tension. After 30 seconds of contact, the water was removed with a syringe and a portion was added to a micro conductivity cell. This cell was calibrated against solutions of accurately known NaCl concentrations. By measuring the sample's conductivity, the concentration of salt was determined, and knowing the sample volume the moles of salt were calculated. A test of the rinse solution's ability to remove the salt was made by making a second rinse and measuring the residual salt in the second solution. It was found that the primary rinse removed virtually all the available salt.

Two sets of measurements were made, the first being with dry fingers, the second with wet fingers. A sample of the results is included in Table 5-4. The greatest contamination occurred for wet fingers (5×10^{-6} moles $NaCl/cm^2$), while the dry fingers left contaminations approximately two orders of magnitude less (5×10^{-8} moles $NaCl/cm^2$).

A measure of the NaCl contamination on a 1 cm^2 area of several blocks in the "as-received" condition was made. These measurements varied widely, but were within the range of the dry finger contamination level. The results from these measurements give an order of magnitude feel for the amount of ions available on "clean" terminal blocks for dissolution in a moisture film. We use the term "clean" to imply the contamination level that may be present after installation and assuming loose dust and other contaminants have been removed. We see in the next section that 10^{-7} moles of salt is sufficient to provide approximately 1.0 mA of leakage current depending on the applied voltage.

Table 5-4

Sample of Data for Measured Residual Salt (NaCl) From One Fingerprint on a 1 cm^2 Area of a Phenolic Terminal Block

Subject	Wet (W) or Dry (D)	Moles of NaCl (10^{-7})
A	D	1.1
B	D	1.04
A	D	0.8
A	D	2.0
A	D	1.0
A	D	1.5
A	D	0.56
C	D	0.30
C	D	0.22
C	D	0.25
C	D	0.32
C	D	0.26
A	W	25
A	W	40
A	W	34
A	W	52
A	W	33
A	W	28
A	W	53
A	W	20
A	W	50
A	W	63

6.0 THEORETICAL CONSIDERATIONS GOVERNING FILM FORMATION AND CONDUCTION ON TERMINAL BLOCK SURFACES

The model presented in this section is based on the work of Dr. Robert Salomon of Temple University and Mark Jacobus of Sandia. The objective of this work was to provide a basic understanding of the mechanisms of film formation and to predict, if possible, the conditions where dryband formation and tracking breakdown will occur. There were two motivations to develop these theoretical considerations. First, the data from the Sandia tests indicated that film formation was the most probable explanation for the transient phenomena and it was therefore desirable to explain the mechanisms which governed this behavior. Second, the formations of drybands due to Joule heating of the moisture film has been proposed by others [39] as a possible mechanism leading to tracking breakdown and it was desirable to estimate the potential for this mechanism to be operable at the voltage and current levels of instrumentation and control applications.

The model assumes that the terminal block is initially contaminated with salt from fingerprints and there is 100 percent relative humidity in the environment surrounding it. The basic premise is that at steady state the vapor pressure of the film will equal the partial pressure of the water vapor in the atmosphere. At 100 percent relative humidity, this partial pressure is equal to the saturation pressure of water at the ambient temperature. The model employs a basic relationship for the vapor pressure of a liquid at two different temperatures which is derivable from the well known Clausius Clapeyron equation. An additional factor is incorporated into this basic equation to account for the vapor pressure lowering resulting from the presence of a solute (dissolved impurity) in the film. The derivation makes some reasonable assumptions such as the applicability of the ideal gas equation of state, a large molar volume of vapor compared to the molar volume of liquid, and a temperature independent heat of vaporization. The model also uses data from the International Critical Tables [40] to predict the conductivity of sodium chloride in water as a function of temperature.

6.1 Qualitative Discussion of Phenomena

Moisture will initially condense on a terminal block surrounded by a steam environment because it will be at a temperature below the saturation temperature of the steam. In the absence of any contamination or imposed voltage between the terminals, the film on the block will reach a temperature equilibrium with the surrounding environment. As long as the surrounding environment is at 100 percent relative humidity, the film will remain on the surface and not evaporate.

If the surface of the terminal block is contaminated with salt (e.g., from fingerprints), then the film's vapor pressure will be lowered relative to the vapor pressure of pure water at the same temperature. Thus, the film vapor pressure will be below that of the surrounding water vapor's partial pressure, and water will condense into the film. The addition of water dilutes the film, resulting in less film vapor pressure lowering. The condensation process raises the film temperature because

the latent heat of vaporization is deposited in the film, while heat transfer back to the surroundings tends to return the film temperature to the ambient temperature. The process of condensing vapor, diluting the film solution, and transferring heat away from the film continues until an infinite dilution is reached. At this point, there is no longer any film vapor pressure lowering.

When an electric potential is applied, a current flows in the film electrolyte. This current is an additional source of energy to the film, heating it through Joule heating. The film temperature rises accordingly, and the vapor pressure equilibrium point is reached before infinite dilution is achieved. Thus, the additional energy from Joule heating is the balancing factor which compensates for the vapor pressure lowering due to the salt. Disregarding the physical dimensions for the moment, the equilibrium point is a result of the interaction of three parameters: the amount of salt present, the applied voltage, and the external environment's temperature. The amount of salt governs the solution concentration and hence the amount of vapor pressure lowering that occurs. It is also the primary contributor to the film conductivity since it is the source of ions in the solution. The applied voltage determines the amount of current which will flow for a specific solution conductivity and hence is a factor in determining the amount of Joule heating that occurs. The external environment's temperature affects the heat transfer from the film surface slightly by changing the associated convective heat transfer properties. With some geometric assumptions concerning conductive film dimensions and the heat transfer areas, and by specifying the three parameters just discussed, the equilibrium salt concentration, film temperature, and film thickness can be calculated. Also, as an integral part of the calculation, a leakage current can be determined.

The film thickness is expecially interesting since it provides insight to the onset of dryband formation. As stated at the beginning of this section, dryband formation is believed to be the initial step in tracking breakdown of a moist surface which leads to the permanent degradation of surface resistance even after the film is dried.[39, 41]

6.2 Explanation of the Model

A very appropriate and useful model of the phenomena is a steady-state model which calculates the conditions that exist in the film for a given set of parameters. We begin by considering the vapor pressure of the film given by:

$$P_v = P_o \exp\left[\frac{\Delta H}{R}\left(\frac{1}{T_e} - \frac{1}{T}\right)\right]\left(1 - \frac{2n_2}{n_1}\right) \qquad \text{Eq. 6-1}$$

where
- P_v = vapor pressure of film at temperature T (atmospheres)
- P_o = vapor pressure of pure water at temperature T_e (atmospheres)
- T_e = ambient temperature of external environment (Kelvin)
- T = film temperature (Kelvin)
- ΔH = heat of vaporization of water (calories/mole)
- R = ideal gas constant (1.987 calories/(mole Kelvin))
- n_2 = moles of salt dissolved in film
- n_1 = moles of water in film

Except for the $(1 - 2n_2/n_1)$ factor, this equation is derivable from the Clausius Clapeyron equation which describes the relationship between saturation (vapor) pressures and temperatures. The $(1 - 2n_2/n_1)$ factor modifies the expression to account for the vapor pressure lowering which results from the salt dissolved in the film. It is based on the knowledge that the vapor pressure of solutions is lowered to a factor of 1 - X of the initial value where X is the mole fraction of solute. The "2" arises from the dissociation of the NaCl into Na^+ and Cl^- ions. Hence, for every mole of salt, two moles of ions are generated in the dissolution process. To apply Equation 6-1 to the film model we first express n_2, the moles of salt, as:

$$n_2 = C \cdot V$$

where C is the concentration of salt in the solution in moles/cc of solution and V is the volume of the film in cc. P_o is the saturation pressure of pure water at temperature T_e and hence, for 100 percent relative humidity, it is the partial pressure of water vapor in the atmosphere at temperature T_e.* Thus, the condition of equilibrium between the partial pressure of water vapor in the atmosphere and the film vapor pressure can be expressed as:

$$P_v/P_o = 1$$

---

* Note that in the test set up used at Sandia the entire pressure in the chamber was due to steam and hence the water vapor partial pressure was the entire measured pressure. The test set up of Salomon closely achieved 100 percent relative humidity.

Applying this condition to the film and substituting for n_2, Equation 6-1 can be rearranged to express salt concentration, C, in terms of temperature:

$$C = \frac{\rho}{2MW}\left[1 - \exp\left[\frac{\Delta H}{R}\left(\frac{1}{T} - \frac{1}{T_e}\right)\right]\right] \qquad \text{Eq. 6-2}$$

In this equation, the leading coefficient, $n_1/2V$, has been expressed as $\rho/2MW$ where ρ is the density of water and MW is the molecular weight of water. Making this change in coefficient assumes that the volume of the solution does not change when the salt is dissolved in the water.

Equation 6-2 provides us with a relationship between the salt concentration in the film, the temperature of the film, and the external temperature. In order to apply Equation 6-2, it is necessary to know two of these three parameters. Before the solubility limit of salt is reached, the obvious parameters to determine from other means are the two temperatures. T_e is normally specified as an environmental condition either in a test or an accident specification. T, the film temperature, can be determined by balancing the energy sources and sinks for the film. To achieve this balancing, consider a simplified geometric model of a film on a phenolic surface pictured in Figure 6-1.

A phenolic substrate material of width, w, and length, ℓ, and depth, d, is covered on one surface with a film of thickness h. The film is at temperature T and the surrounding environment is at temperature T_e. To simplify the calculations the back boundary of the phenolic block is assumed to be at temperature T_e, an assumption that is not entirely correct, but which seems to work fairly well for the order of magnitude calculations being conducted. q_{cv} is the convective heat lost from the film to the surrounding environment; q_{cd} is the conductive heat lost from the film to the phenolic block. The power, P, input to the film arises from the leakage current I. Thus:

$$P = EI = E^2/Z$$

where E is the potential across the film and Z is the resistance of the film. At steady state the temperature of the film will be determined by the balancing of heat loss and heat input. Thus:

$$E^2/Z - q_{cv} - q_{cd} = 0 \qquad \text{Eq. 6-3}$$

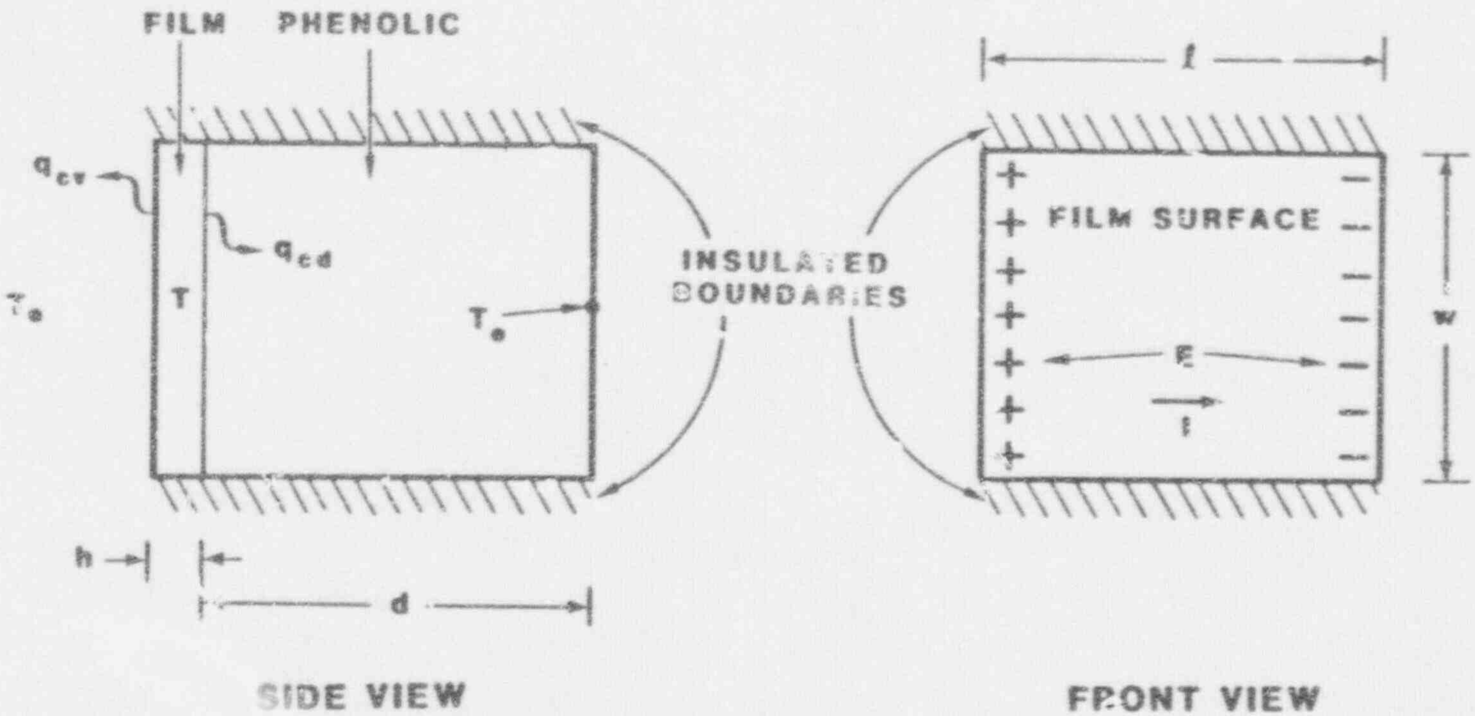


Figure 6-1: Side and Frontal Views of Simplified Geometric Model for Film Conduction on a Phenolic Substrate Material

Each of these terms are evaluated in turn below.

First, consider the power input term, E^2/Z. E is the applied potential, in volts, across the phenolic block. In the case of a terminal block, it is the potential between the poles. Z is the resistance of the film in ohms. In the model, the film is considered to be a NaCl salt solution. To obtain the relationship between Z and film temperature, data from the International Critical Tables [40] was used. This date is reported as equivalent conductivity values in $cm^3/[(ohm*cm)mole]$. By definition, equivalent conductivity Λ, is the conductivity, s, divided by the concentration. That is:

$$\Lambda = s/C$$

It is known that Λ follows an Arrhenius relationship of the form:

$$\Lambda = u*\exp\left[-\frac{E_A}{RT}\right]$$

where u is the temperature independent part of the ion mobility and E_A is the activation energy for conduction. Using the International Critical Table Data [40] to evaluate u and E_A, we find that u = 17800 $cm^3/[(ohm*cm)mole]$ and E_A = 3160 calories/mole. R is the ideal gas constant and T is the solution temperature. Combining the two above equations yields the film conductivity, s:

$$s = uC*\exp\left[-\frac{E_A}{RT}\right]$$

and since s = 1/Z, the power input to the film is:

$$P = E^2uC*\exp\left[-\frac{E_A}{RT}\right] \qquad \text{Eq. 6-4}$$

Equation 6-4 is the desired expression for the first term in Equation 6-3, the power input to the film as a result of Joule heating. Noting the value of E_A, it is clear that though s varies with T, large changes in T are required to change s significantly. This fact, combined with the knowledge that T will be close to T_e, is used in the computer implementation of this model to obtain the initial guess of the power input to the film.

The second term in Equation 6-3 is the convective heat loss, q_{cv}, given by:

$$q_{cv} = h'A(T-T_e) \qquad \text{Eq. 6-5}$$

where q_{cv} is the heat lost per unit time in watts, h' is the average convective heat transfer coefficient, in watts/(cm^2•Kelvin), A is the heat transfer surface area in cm^2, and $T - T_e$ is the difference between the film and ambient temperatures in Kelvin. From the dimensions in Figure 6-1, we see that:

$$A = \ell w$$

Evaluating h', however, is not nearly as straightforward as evaluating A. First, the expression for h' depends on the orientation of the heat transfer area. Since terminal blocks are typically mounted on walls, the heat transfer area is assumed to be vertical and hence:

$$h' = \frac{Nu \bullet k}{w}$$

where Nu is the average Nusselt number, k is the thermal conductivity of the gaseous medium surrounding the heat transfer area in watts/(cm•Kelvin), and w is the vertical dimension of the heat transfer area in cm. The average Nusselt number for a vertical flat plate is:

$$Nu = 0.68 + \frac{0.670\,(Ra)^{1/4}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{4/9}}$$

where Ra is the Rayleigh number and Pr is the Prandtl number. The Prandtl number is the dimensionless ratio of the molecular momentum to the thermal diffusivity of the medium surrounding the heat transfer area, and is a measure of how rapidly momentum is dissipated compared to the rate of diffusion of heat through a fluid. The Rayleigh number is the product of the Grashof number and the Prandtl number. The Grashof number is used in natural convection and may be interpreted as the ratio of the buoyancy forces to the viscous forces. Thus, the Rayleigh number is a measure of relative convective forces on a body compared to the rate of heat diffusion. The Rayleigh number is given by the relation:

$$Ra = \frac{g\beta\, T - T_e\, w^3}{\nu\alpha}$$

where g is the acceleration of gravity in cm/sec^2, β is $2/(T + T_e)$ in $Kelvin^{-1}$, ν is the kinematic viscosity in cm^2/sec, and α is the thermal diffusivity in cm^2/sec. Combining these equations, we find that the expression for h' is:

$$h' = \frac{k}{w}\, 0.68 + \frac{0.670\left(\frac{g\beta\ T - T_e\ w^3}{\nu\alpha}\right)^{1/4}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{4/9}} \qquad \text{Eq. 6-6}$$

Equation 6-6 coupled with Equation 6-5 gives the convective heat loss.

The third term in Equation 6-3 is the conductive heat transfer per unit time, q_{cd}, in watts. q_{cd} is given by:

$$q_{cd} = kA\,\frac{T - T_e}{d} \qquad \text{Eq. 6-7}$$

where k is the thermal conductivity of the phenolic in watts/(cm•Kelvin), A is the cross sectional area through which the heat is conducting, and d is the conduction distance. Here T is the film temperature, and T_e is the temperature of the opposite side of the phenolic. As mentioned above, for simplicity we assume that this T_e is the same as the temperature of the surrounding ambient environment. This assumption tends to overestimate q_{cd}; however, for the accuracies of this model, further refinement is not warranted. Using Equations 6-4, 6-5, 6-6, and 6-7, all of the terms in Equation 6-3 are defined in terms of known or assumed values and the film temperature, T. Assuming an applied potential E, and using appropriate values for the constants, T can be easily found. The solution for T is arrived at using a binary iteration algorithm in the computer implementation of this model. Knowing T, it is now possible to return to Equation 6-2 and solve for the concentration of the salt in the film. This process is a straightforward substitution for T and T_e in Equation 6-2. Then, having determined the salt concentration and knowing the width and length of the film, the film thickness, h, can be found as follows:

$$C = n_2/V$$

$$= n_2/\ell wh$$

or rearranging

$$h = n_2/\ell wC$$

n_2 is the number of moles of salt initially assumed to be on the surface, C was just calculated from Equation 6-2, and ℓ and w are the assumed dimensions of the conductive film. Though not explicitly given above, the leakage current in the film can be easily obtained from the computation of power since voltage and resistance are both available. It should be emphasized that the output obtained from the model is at steady state. The transient process of vaporization resulting in the thinning of the film is not modeled; we look at the film after this transient process has occurred.

Table 6-1 gives a sample output from the computer simulation implementing the above model for an assumed ambient temperature of 450 K (177°C (351°F)), an initial salt contamination level of 10^{-7} moles (approximately one fingerprint), an electrical conduction length of 2 cm, a film width of 0.75 cm, and a thermal conduction length through the block of 1.25 cm. Figure 6-2 shows the predicted leakage currents as a function of voltages for this set of conditions but with varying film widths. The change in film widths increases the peak leakage currents predicted as well as the voltage at which it occurs. In all cases, the peak leakage current occurs at the point where the solution is saturated. Thereafter, higher voltages cause additional heating and hence additional vaporization of the film. Since the film is saturated, precipitation of the salt occurs, reducing the number of ions available for conduction and hence lowering the leakage current. At each voltage the balance between Joule heating and convective and conductive heat losses determines the equilibrium value of leakage current. The wider film widths increase the film volume and the heat loss mechanisms, and hence the amount of heat input necessary to achieve equilibrium is increased both when saturation is approached and subsequently when salt precipitates.

A potentially important implication of these results is that qualification testing which incorporates increased voltage for margin may actually be nonconservative; after a threshold is reached, the model predicts that the leakage currents will decrease with increasing voltage. Some experimental support for this type of behavior was observed in the Phase I results of the Sandia tests.[1]

Table 6-1

Sample Equilibrium Film Parameters Predicted by Film Conduction Model*

Applied Potential (Vdc)	Leakage Current (mA)	Salt Concentration (moles/cc)	Film Temperature (K)	Film Thickness (cm)
5	0.064	0.000044	450.074	1.51E-03
15	0.19	0.00034	450.578	1.94E-04
25	0.32	0.00088	451.496	7.59E-05
35	0.46	0.0016	452.78[illegible]	4.15E-05
45	0.60	0.0025	454.442	2.66E-05
55	0.74	0.0035	456.461	1.88E-05
65	0.89	0.0047	458.854	1.42E-05
75	1.1	0.0059	461.636	1.12E-05
85	1.0	0.0065**	462.932	8.89E-06
95	0.93	0.0065	462.932	7.12E-06
105	0.84	0.0065	462.932	5.83E-06
115	0.77	0.0065	462.932	4.86E-06
125	0.71	0.0065	462.932	4.11E-06
135	0.66	0.0065	462.932	3.52E-06
145	0.61	0.0065	462.932	3.06E-06

* Parameters assumed are an initial salt contamination of 1.0E-07 moles, ambient environment temperature of 450 K, electrical conduction length of 2 cm, electrical conduction width of 0.75 cm, and a thermal conduction length of 1.25 cm. The thermal conductivity of steam at 450 K is 2.99E-04 watts/(cm•Kelvin).

** Solubility limit of NaCl is ~0.0065 moles/cc.

If the salt concentration calculated by the above method exceeds C_s, the solubility limit of salt (~0.0065 moles/cc), a different computation procedure is used*. First the salt concentration is set equal to the solubility limit; then using Equation 6-2, a film temperature is calculated. Note that once the solubility limit is reached, the film temperature becomes a constant. Such a condition is entirely reasonable since for a saturated solution the maximum vapor pressure lowering has occurred, and thus the film has reached its maximum temperature.

* Note that the solubility limit of salt is only weakly dependent upon temperature, and hence the model does not incorporate this minor effect.

1

IMAGE EVALUATION TEST TARGET (MT-3)

1

IMAGE EVALUATION
TEST TARGET (MT-3)

150mm

6"

1

IMAGE EVALUATION TEST TARGET (MT-3)

150mm

6"

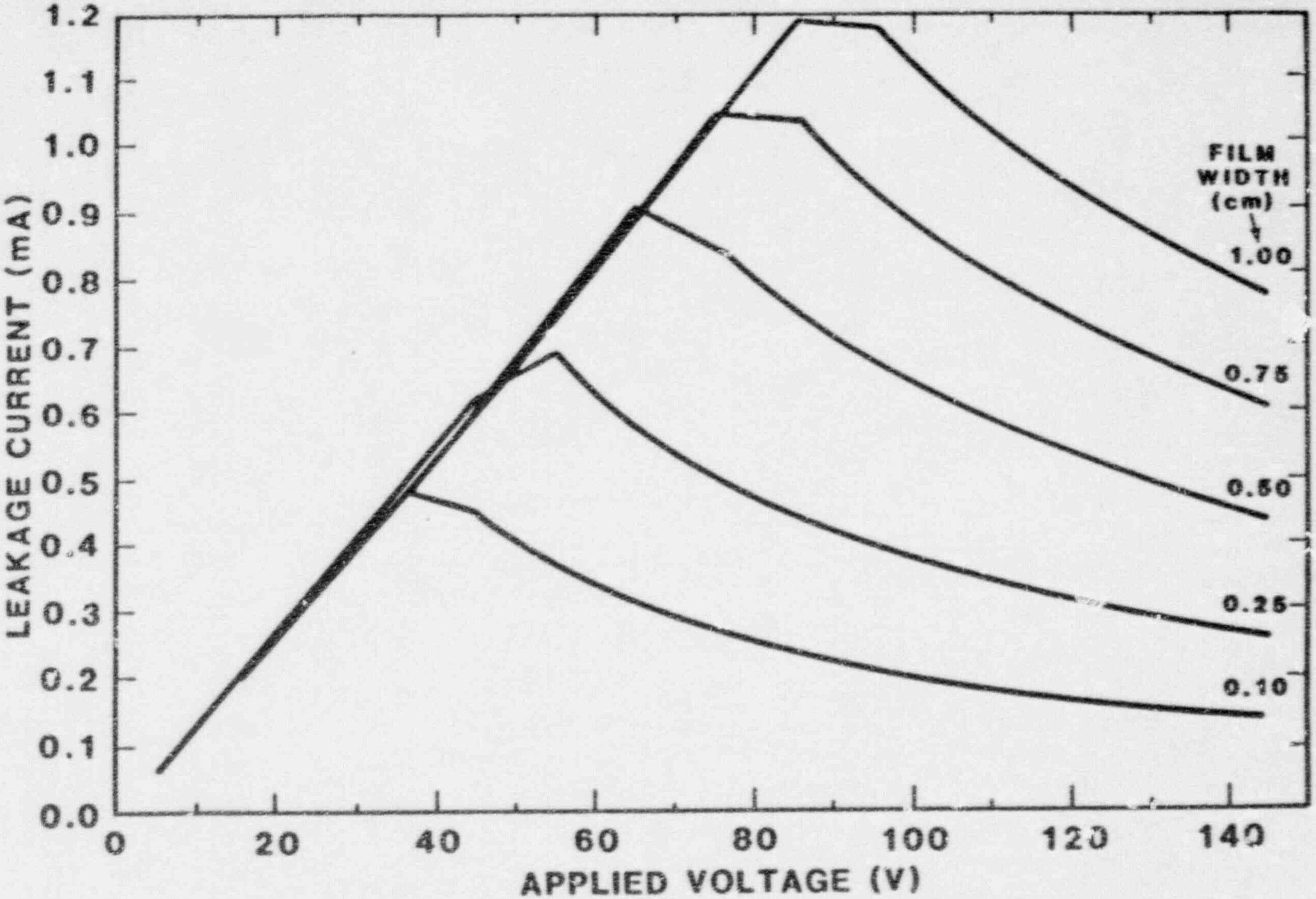


Figure 6-2: Predicted Leakage Current Versus Applied Voltage for Selected Film Widths and Other Parameters as Specified in Table 6-1

By fixing the film temperature, the convective and conductive heat losses become constant and any additional Joule heating causes further vaporization of water and begins precipitating salt. The film thickness continues to drop and the potential for dryband formation increases. In the model, a reduction in the number of salt ions available for conduction occurs due to precipitation of the salt. This effect reduces the rate of Joule heating (leakage current) until it equals the rate of convective and conductive heat loss to the environment. However, in this model the saturation limit may be artificially reached too soon because the film dimensions are fixed. In the real case, we hypothesize that at the lower potential, the salt remains in solution with different film dimensions. At the higher potentials, dry areas may be formed rapidly and a localized voltage gradient may be large enough to support arcing. In this case surface breakdown, rather than film leakage currents, may be experienced. These latter phenomena have not been modeled directly, but by extrapolating the film conduction model to higher voltages, we see that the film thickness reaches the 10^{-6} to 10^{-7} cm range at about 300 volts. These thicknesses are on the order of 1 to 10 molecules which probably means dry bands have formed somewhere in the conduction path. Thus we might reasonably expect drybands to become an important surface mechanism at or above 300 volts. This conclusion, though not proved by data, is supported by it since the only confirmed breakdown was observed by Salomon at 400 Vac.

6.3 Strengths and Weaknesses of the Model

The primary strength of this model is that it offers a plausible explanation for the observed phenomena based on first principles. It only assumes ideal gas behavior and temperature independence of two parameters: the heat of vaporization of water and the solubility limit of salt. With reasonable assumptions for the dimensions of the conduction path, the model predicts leakage current values within the range observed by both Sandia and Salomon. The dimensional dependence of leakage currents (as illustrated by Figure 6-2) may reflect reality since the observed variations in leakage current may be a result of fluctuations in the size of the conducting path. The model works for a saturated steam or a 100 percent relative humidity environment. In fact, it will work with minor modifications as long as the percent relative humidity exceeds the adjustment factor for the vapor pressure caused by the presence of a solute in the moisture film. The model also provides a framework that allows an estimation of the relative importance of the various parameters and phenomena involved. For example, the film temperature will not be dramatically different from the environment's temperature, and film conduction is not strongly dependent on temperature. Of more importance is the amount of salt (ions) present and the conducting geometry.

The primary weakness of the model is its inability to simultaneously predict both high and low temperature data using fixed film dimensions. This effect may be a result of a change in mechanism or a change in film dimensions at lower temperatures which is not accounted for in the model. Further, the model assumes that a film will always be present whereas this may not always be the case. Salomon's data are about an

order of magnitude below the values predicted by the model; however, almost all of his data ends with a strong upward trend in leakage current. Since his experiments proceeded only to a specified temperature and were of relatively short duration, his data may represent only transient behavior. The true steady-state values predicted in the model were perhaps never achieved in his experiments. As already noted, dimensional sensitivity exists and it is, therefore, incumbent upon the analyst to choose reasonable dimensions. The fixed dimensions do not allow for parallel conducting paths that would change leakage currents and effective IRs for a given set of conditions. Finally, the uniform film thickness assumed by the model does not recognize that the film undoubtedly undergoes localized heating and cooling which leads to localized thinning and reforming of the film.

7.0 FAILURE MODES OF TERMINAL BLOCKS

Table 7-1 provides a summary of terminal block failure modes. The three broad categories of failure modes presented therein are gross electrical breakdown, leakage currents, and open circuits. Gross electrical breakdown is one end of the spectrum of leakage currents and is defined as that leakage current which makes the circuit inoperable. It may be either permanent as in the case where carbonized tracks form on the insulator surface or it may be temporary as in the case where voltage is applied rapidly in the presence of a moisture film and the IR momentarily decreases to virtually zero. Leakage currents imply any level of leakage which does not render the circuit totally inoperable, but does affect the operation in some manner. Leakage currents are the usual precursor to gross electrical breakdown. The dividing line between leakage currents and gross electrical breakdown is not precise and is application dependent. For example, milliampere leakage currents in an instrumentation circuit may make that circuit inoperable, but milliampere leakage currents in a power circuit are probably acceptable. An open circuit is the final terminal block failure mode. It is simply the breaking of the desired electrical conduction path. Gross electrical breakdown precipitated by leakage currents is one possible mechanism which could lead to an open circuit. A momentary surge of current, or a sustained high level of leakage current in conjunction with stress, corrosion, or other factors may cause the cable or the terminal block or their interface to separate. As reported in Reference 1, we observed one such failure in the Sandia tests of terminal blocks. Another example of an open circuit failure mode is the embrittlement of the metal forming the "U" clip in a sliding link terminal block and subsequent torquing of the screw in the sliding link. This failure mode has previously been studied.[42,43]

Table 7-1 shows the three basic failure modes and then correlates some relevant mechanisms by which these modes may occur. The term "causes" refers to those conditions which enable the mechanism to proceed. "Causes" may be independent of one another, but more likely they will work synergistically. "Contributing factors" are those items which aid and abet, or in some way affect a "cause" or "causes", but are probably not sufficient by themselves to cause the failure mechanism to proceed. "Effects and/or symptoms" summarize the consequences that the failure mode has on the circuit or the terminal block. Normally, these effects would be observable or at least detectable by the operator.

Table 7-1

Summary of Failure Modes for Terminal Blocks

Failure Mode	Mechanism	Potential Causes	Contributing Factors	Effect/ Symptom	Comments
Gross Electrical Breakdown (e.g., low resistance path terminal-to-terminal or terminal-to-base plate)	Low Voltage Surface Breakdown*	Environmental Conditions High Temperature Humidity/Moisture Contaminants	Voltage Exposure Time Insulation Type	Loss of Circuit Operability	Temporary
		Volatile/Soluble Surface Contamination	Contaminant Deposition Rate		Temporary
		Radiation	Aging Normal Accelerated		
		High Leakage Currents and Surface Tracking			
		Non-Volatile Surface Contamination	Corrosion Products Conductive Residue		Permanent
	Conducting Path	Thermal and/or Pryolytic Decomposition of Insulation	High Temperature Exposure to Burning Environment	Loss of Circuit Operability	Permanent
		Structural Failure	Excessive Temperature Excessive Thermal Shock Vibration	Cracking of Insulation	Permanent

* High voltage breakdown not included due to lack of HV circuits in nuclear applications

Table 7-1 (continued)

Summary of Failure Modes for Terminal Blocks

Failure Mode	Mechanism	Potential Causes	Contributing Factors	Effect/ Symptom	Comments
Gross Electrical Breakdown (continued)	Conducting Path (continued)	Structural Failure (continued)	Improper Maintenance		
			Improper Installation		
			Aging		
	Bulk Insulation Breakdown	Radiation			
		Moisture Absorption Cracking	Moisture Absorption	Splitting of insulation and formation of conducting paths	
Leakage Currents	Surface Conduction	Surface Contamination	Installation Practices	Low Frequency Line Noise	Some leakage will always occur. The question is a matter of degree. Leakage of a few milli-amperes may be detri-tal to an instrumen-tation circuit, but have no effect on a power circuit.
		Environmental Conditions (e.g., High Temperature Humidity/Moisture, Contaminants)	Maintenance Practices	Circuit Crosstalk	
			Voltage Level	Excessive Power Drain	
			Aging	Biased Readings on Instrument Outputs	
		Radiation	Access for beta-emitting isotopes	Gross Breakdown	

Table 7-1 (continued)

Summary of Failure Modes for Terminal Blocks

Failure Mode	Mechanism	Potential Causes	Contributing Factors	Effect/ Symptom	Comments
Leakage Currents (continued)	Surface Conduction (continued)	Structural Failure	Excessive Temperature	Cracking of Insulation	
			Excessive Thermal Shock		
			Vibration		
			Improper Maintenance		
			Improper Installation		
Open Circuit	Separation of Conductor	Loose Terminal Screws		Loss of Circuit Operability	
		Contact Corrosion	Chemical Reagents		
			Moisture/ Humidity		
		Structural Failure	Vibration	Cracking of Conductor	
			Thermal Shock		
			Improper Maintenance		
			Improper Installation		
			Differential Expansion		

Table 7-1 (continued)

Summary of Failure Modes for Terminal Blocks

Failure Mode	Mechanism	Potential Causes	Contributing Factors	Effect/ Symptom	Comments
Open Circuit (continued)	Separation of conductor (continued)	High Leakage Currents			
		Failure to Reconnect Terminals	Careless Maintenance Procedures		
			Lack of Quality Assurance		

8.0 EXAMPLES OF POSSIBLE TERMINAL BLOCK EFFECTS

8.1 Transmitter Circuits

A pressure transmitter typically operates with 4-20 mA of current in the instrument loop. At zero pressure, or the low end of the calibrated span, 4 mA is allowed to flow in the circuit, at full pressure 20 mA is allowed to flow. The key word here is "allowed." A transmitter essentially functions as a variable resistor in the circuit, limiting the amount of current flowing in its branch of the circuit to a value proportional to the input pressure; it is not a current source. This characterization is extremely simplified, but it captures the essence of circuit behavior and permits terminal block effects to be analyzed. Figure 8-1 shows how a transmitter might typically be connected in an actual plant application.

The transmitter will operate correctly as long as the voltage remains in a specified range. For example, a typical transmitter will operate to specification as long as the voltage across the transmitter terminals remains between 15 and 50 Vdc. The loop resistance external to the transmitter (from the current-to-voltage amplifiers, the cable, and the other external resistances) also may vary over a specified range depending on the voltage supplied to the transmitter. For a typical transmitter, if the power supply voltage is 45 Vdc, the external loop resistance may vary between 250 and 1,500 ohms. Note from Figure 8-1 that the potential across the transmitter, ΔV_T, is essentially the potential across the terminal block and therefore would be the driving potential for any terminal block leakage current. ΔV_T can be expressed in terms of the normally constant power supply voltage, V_s, and the voltage drop, ΔV_e, across the external loop resistance, R_e:

$$\Delta V_T = V_s - \Delta V_e$$

$$\Delta V_T = V_s - R_e I_L \qquad \text{Eq. 8-1}$$

where I_L is the total loop current. The leakage current, I_{TB}, across the terminal block is:

$$I_{TB} = \frac{\Delta V_T}{R_{TB}}$$

where R_{TB} is the insulation resistance of the terminal block. The total loop current, which will be observed in the control room as the transmitter signal, will be the sum of the transmitter output current, I_T, and the terminal block leakage current:

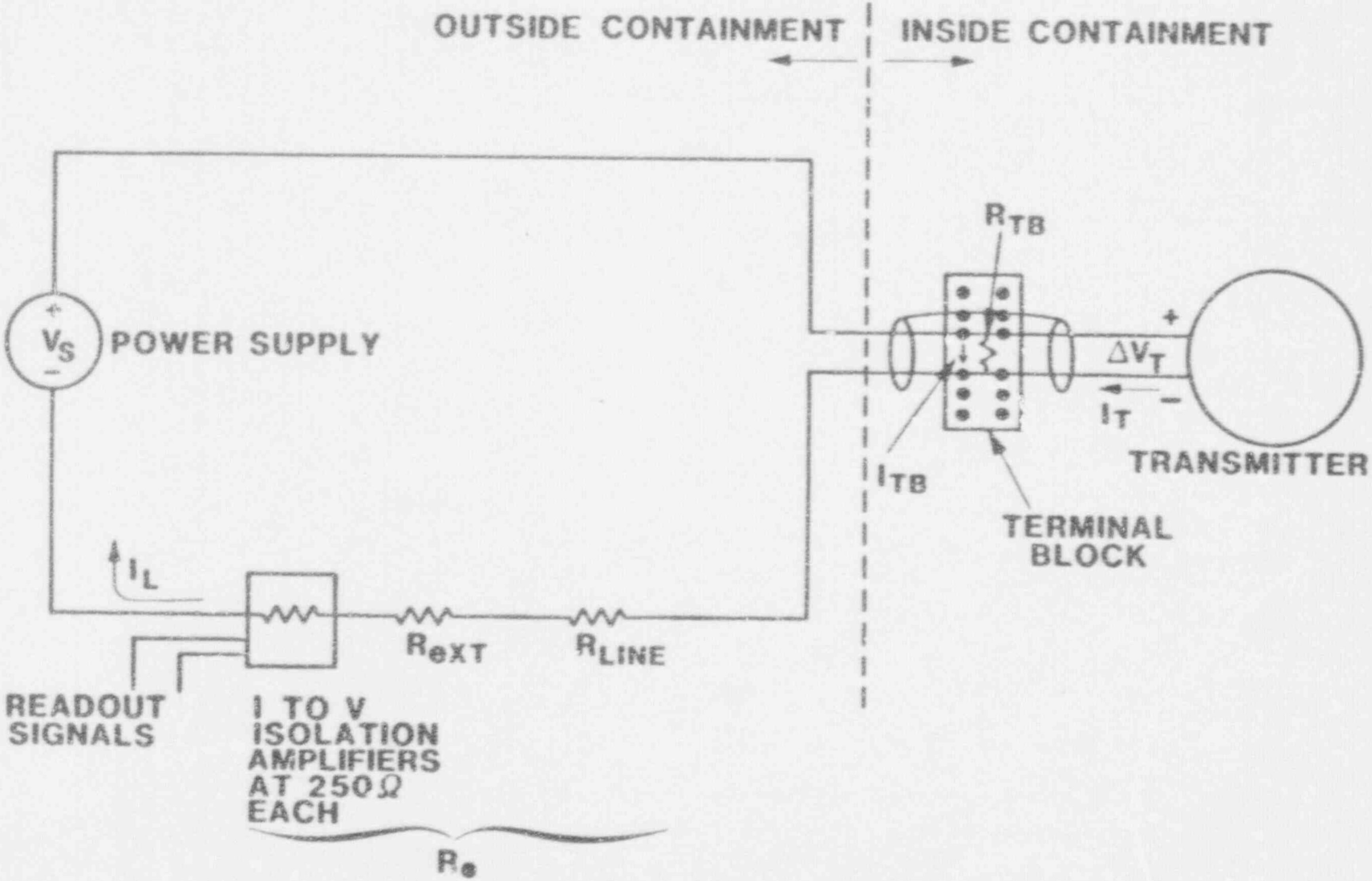


Figure 8-1: Simplified Schematic of a Typical Transmitter Circuit in a Nuclear Power Plant

$$I_L = I_{TB} + I_T \qquad \text{Eq. 8-2}$$

Under normal conditions, I_{TB} will be zero or negligibly small compared to I_T. However, under accident conditions, I_{TB} can become a sizable fraction of I_T, and therefore, becomes a sizable portion of the total loop current sensed by control room instrumentation. The error, e, in the signal will simply be the ratio of the terminal block leakage current to the transmitter signal current. That is:

$$e = \frac{I_L - I_T}{I_T} = \frac{I_{TB}}{I_T}. \qquad \text{Eq. 8-3}$$

Using the above equations, we can express e in terms of V_s, R_e, R_{TB}, and I_T:

$$e = \frac{V_s - R_e I_T}{I_T \left(R_{TB} + R_e \right)} \qquad \text{Eq. 8-4}$$

Figure 8-2 shows a plot for the signal error as a function of transmitter output for common values of V_s, R_e, and several assumed values of R_{TB}. Note that the error is expressed as a percent of output current (or reading) rather than a percent of calibrated span. This was done intentionally to illustrate the error that would actually be observed especially at the low end of the transmitter calibration.

The errors can be quite significant when the terminal block leakage current approaches the values of the transmitter signal or equivalently, when the terminal block IR approaches the values of transmitter input impedance. At 45 Vdc, the transmitter input impedance will vary from approximately 2 to 10 kohms as its output varies from 20 to 4 mA. Hence, the terminal blocks may be viewed as a resistor in parallel with the transmitter and, as such, acts as a current divider. Figure 8-3 shows the current trace of total circuit current as a function of time for the terminal block connected in the transmitter circuit during the Sandia test.[1] For the period of time covered by the plot, the transmitter was operating at ~4 mA base signal level. Clearly, the total circuit current observed is in agreement with the above analysis. During the cooldown period when the film vaporizes, the transmitter current returns to its base current level.

To illustrate the impact of these errors, suppose that the transmitter in question was a narrow range reactor coolant system (RCS) pressure monitor calibrated from 1700 to 2500 psi. Thus, each milliampere of signal corresponds to a 50 psi increment in pressure. The sensed pressure will be based on the total loop current, I_L. Assuming

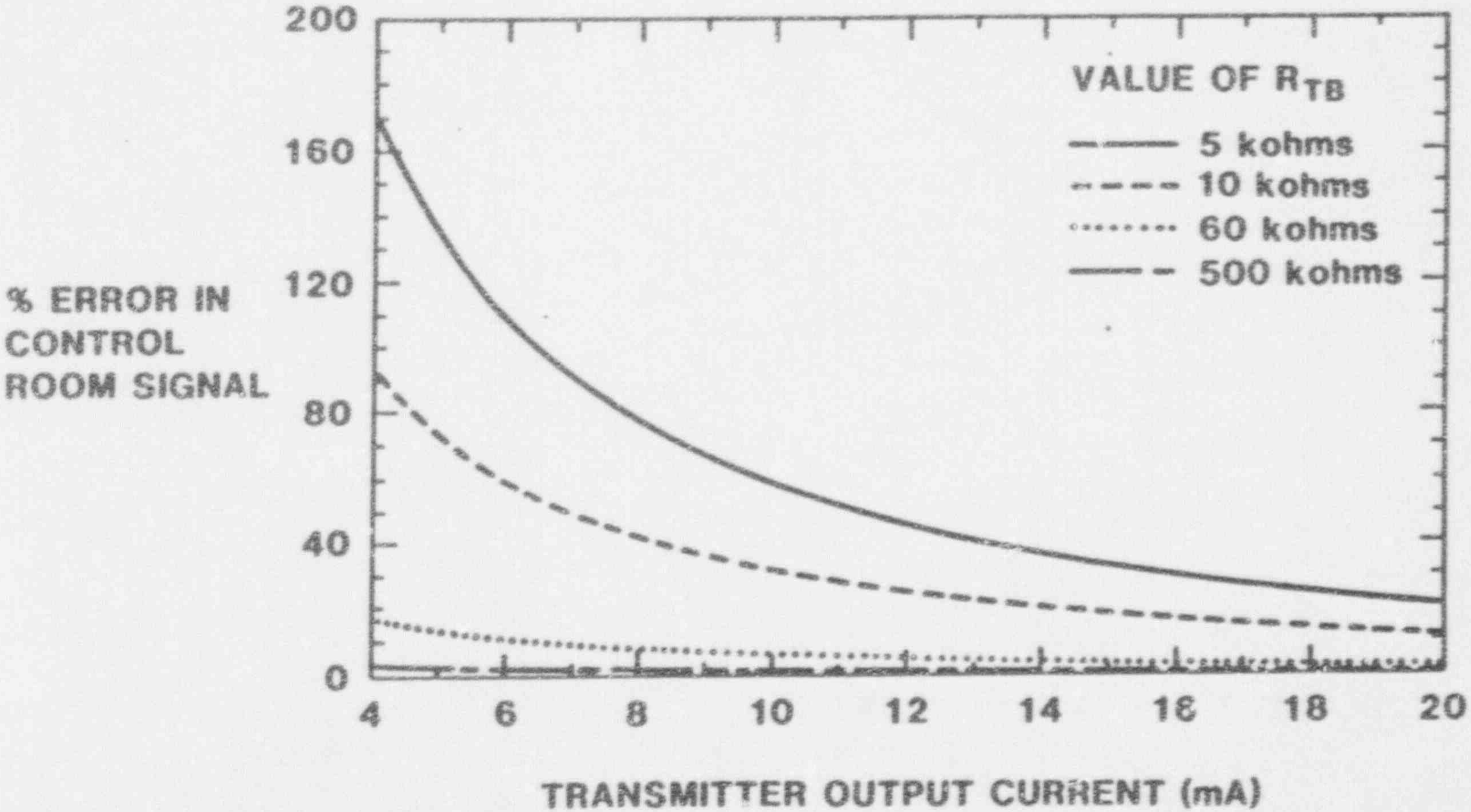


Figure 8-2: Percent Error in a Transmitter Circuit for Selected Values of Terminal Block Insulation Resistance (R_e = 1000 Ω and V_s = 45 Vdc)

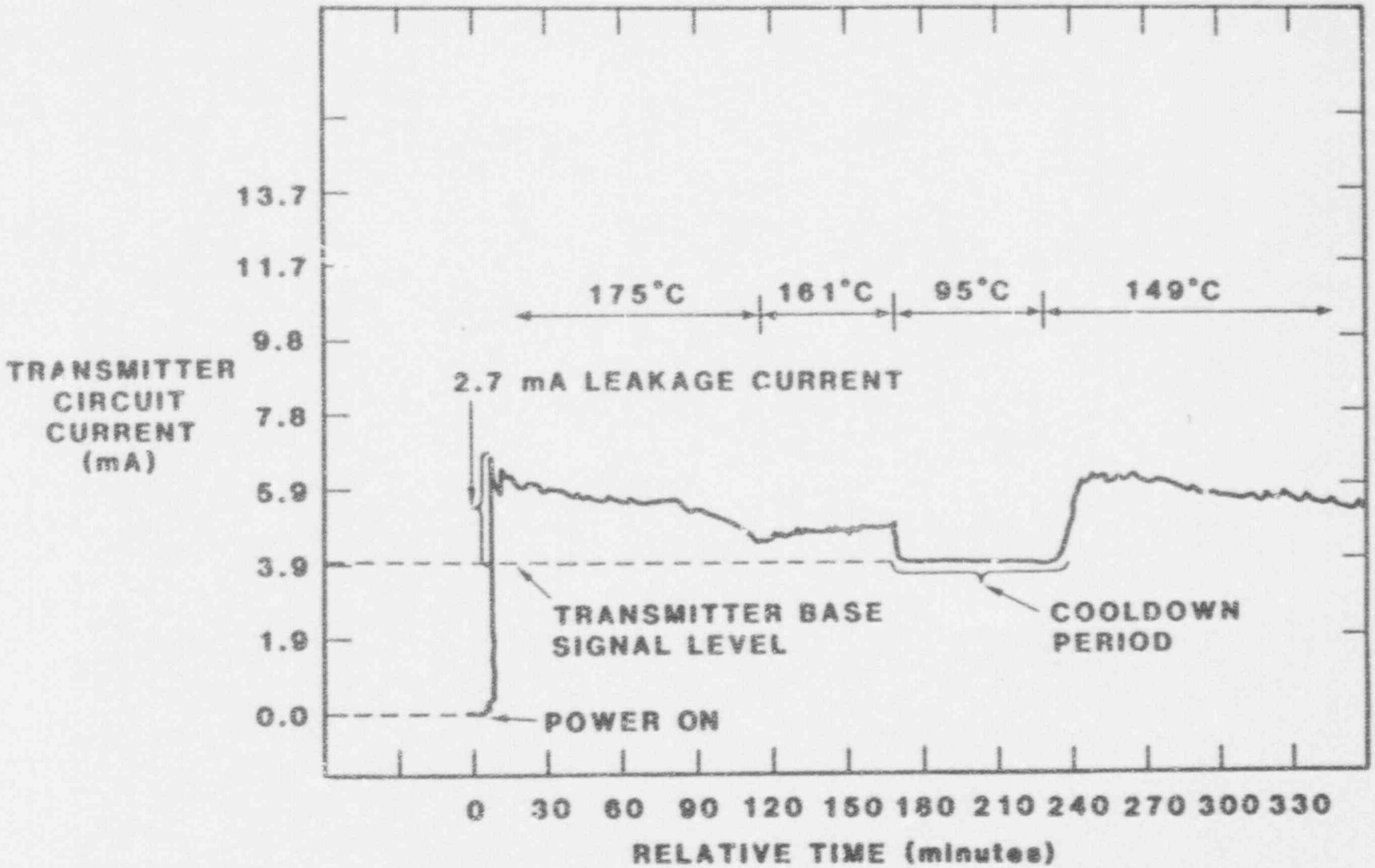


Figure 8-3: Total Current Trace of Transmitter Circuit During LOCA Simulation

everything else in the circuit works perfectly. Figure 8-4 shows the readouts that would be observed in the control room for V_s = 45 Vdc, R_e = 1000 ohms, and R_{TB} = 10,000 ohms. Note that the minimum reading is 1886 psi at the minimum transmitter current level of 4 mA.

One of the uses for a narrow range pressure monitor is to provide an actuation signal for high pressure injection (HPI). A typical set point would be 1750 psi which is less than the minimum reading of 1886 psi caused by the summing of the 4 mA base current signal of the transmitter and the terminal block leakage current. In fact, any setpoint less than 1886 psi would not be achieved. The result is that one or more of the instrumentation loops required for actuation of HPI by low RCS pressure would not reach their set points, and hence, HPI may not be automatically accomplished; in this situation another means of actuation would have to be implemented. This type of error would also affect the pressure readings observed by the operator. Not only would the readings themselves be in error, but the operator would also be faced with a discrepancy in readings between narrow and wide range gauges.

8.2 RTD Circuits

RTD circuits are low voltage, low current circuits. They are not, however, immune to the effects of terminal blocks. An RTD circuit typically operates at 4 Vdc or less with currents in the range of 1 mA or less. The resistance in a typical RTD might vary from 200 ohms to 500 ohms over the full temperature range of the RTD. Figure 8-5 shows in a very simplified block form how an RTD circuit will look using a terminal block to connect the RTD to the remainder of the circuit. The IR of the terminal block is a parallel connection with the RTD resistance. Hence, the bridge or constant current circuit used to sense the resistance of the RTD is actually sensing the effective resistance, R_{eff}, of this parallel combination. R_{eff} is:

$$R_{eff} = \frac{R_{TB} R_{RTD}}{R_{TB} + R_{RTD}}$$

and the fractional error e is:

$$e = \frac{R_{RTD} - R_{eff}}{R_{RTD}} = 1 - \frac{R_{TB}}{R_{TB} + R_{RTD}} \qquad \text{Eq. 8-5}$$

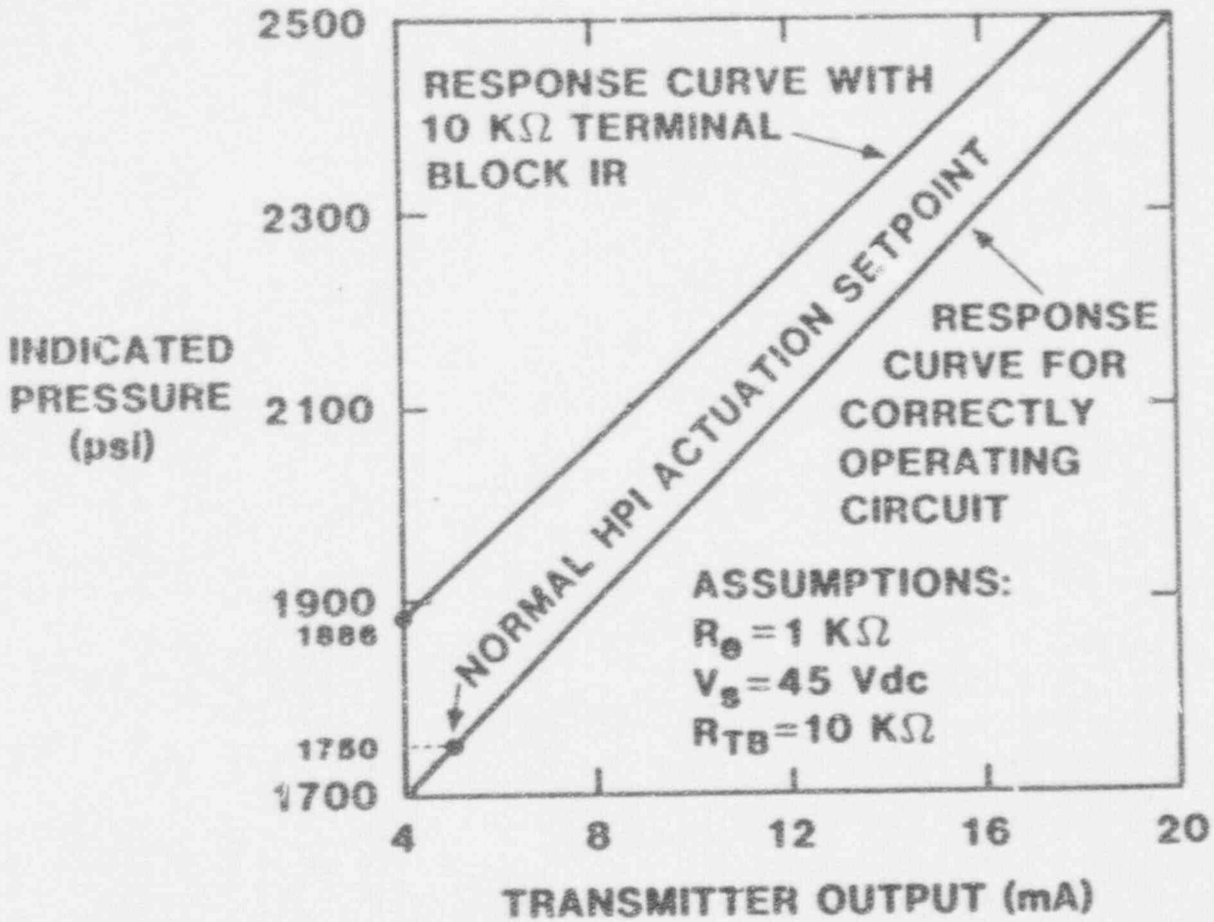


Figure 8-4: Indicated Pressure as a Function of Transmitter Output for a Correctly Operating Circuit and for a Circuit With Terminal Block Insulation Resistance Assumed to be 10 kohms

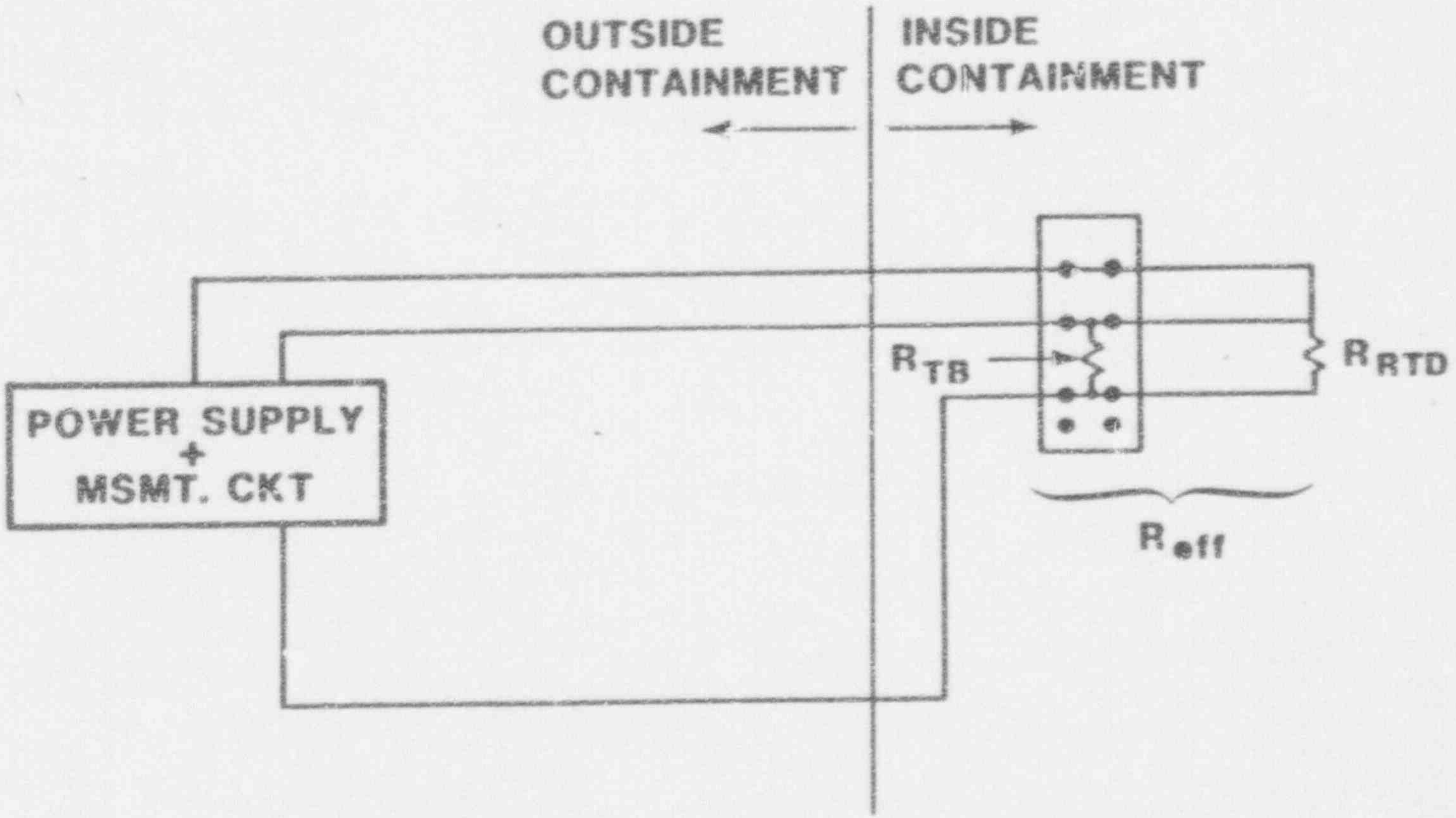


Figure 8-5: Simplified Block Diagram of a 3-Wire RTD Circuit Showing Parallel Connection Between Terminal Block Insulation Resistance and the Resistance of the RTD Sensing Element

For a typical 200-ohm RTD which varies in resistance from 200 to 480 ohms over its temperature range, a terminal block resistance of 10,000 ohms introduces an error in measured resistance of 2.0% at the low end of the calibration and an error of 4.6% at the high end. Figure 8-6 shows the two bounding curves of percent error in measured resistance for a commonly used 200-ohm RTD as a function of terminal block insulation resistance. For an RCS temperature monitor calibrated from 93°C (200°F) to 399°C (750°F) the 2.0% and 4.6% resistance errors translate to a 4°C (7°F) error at the low end and a 24°C (43°F) error at the high end. Since the parallel connection will make the measured resistance less than the actual RTD resistance, the indicated temperature will always be lower than the actual temperature.

To illustrate the effect that these errors may have, consider the hypothetical example where the RTD is measuring a temperature of 327°C (621°F) and the pressure is 1800 psia. If the RTD is calibrated as assumed above, it should have a resistance of 414 ohms at that temperature. A terminal block insulation resistance of 10,000 ohms in parallel with the RTD would give an effective resistance for the pair of 398 ohms or a temperature readout of 309°C (589°F). Thus the displayed temperature would be 18°C (32°F) less than what actually existed. Since the saturation temperature at 1800 psia is 327°C (621°F), the coolant at the RTD could be vaporizing, where as the perceived condition would be 18 C° (32 F°) subcooled. Thus, even relatively large terminal block IRs (e.g., 10,000 ohms compared to 414 ohms for the RTD) can have a significant impact on the perceived conditions. The temperature and pressure in this example are only illustrative; any set of conditions close to the saturation point could have been chosen with similar results. Also, it is important to recognize that an evaluation of accident sequences is necessary to determine the relevance of such misperceptions in coolant condition to accident management.

8.3 Thermocouple Circuits

Another important temperature measuring device that may employ terminal blocks in the circuit is a thermocouple (TC). One common TC circuit design closely approximates a null balance circuit; that is, the sensing device balances the potential across its input terminals so that no current flows through its branch of the circuit. Thus, if the TC circuit is properly designed and installed and is operating correctly the potential across the sensing circuit is the open circuit potential generated as a result of the temperature difference between the measurement and the reference junctions of the TC. The presence of moisture films on terminal blocks may cause shunt resistances to form between the TC elements or between a TC element and ground. As Moffat [44] points out, the introduction of shunt paths into a TC circuit can cause significant effects on the output of the TC circuit, that is, on the potential across the input of the sensing circuit. In order to analyze the effect of these possible shunt resistances and any associated spurious emfs, it is necessary to locate the thermoelectric sources of emf within the circuit relative to the potential shunt resistances and spurious emfs. Reed [45] has developed a

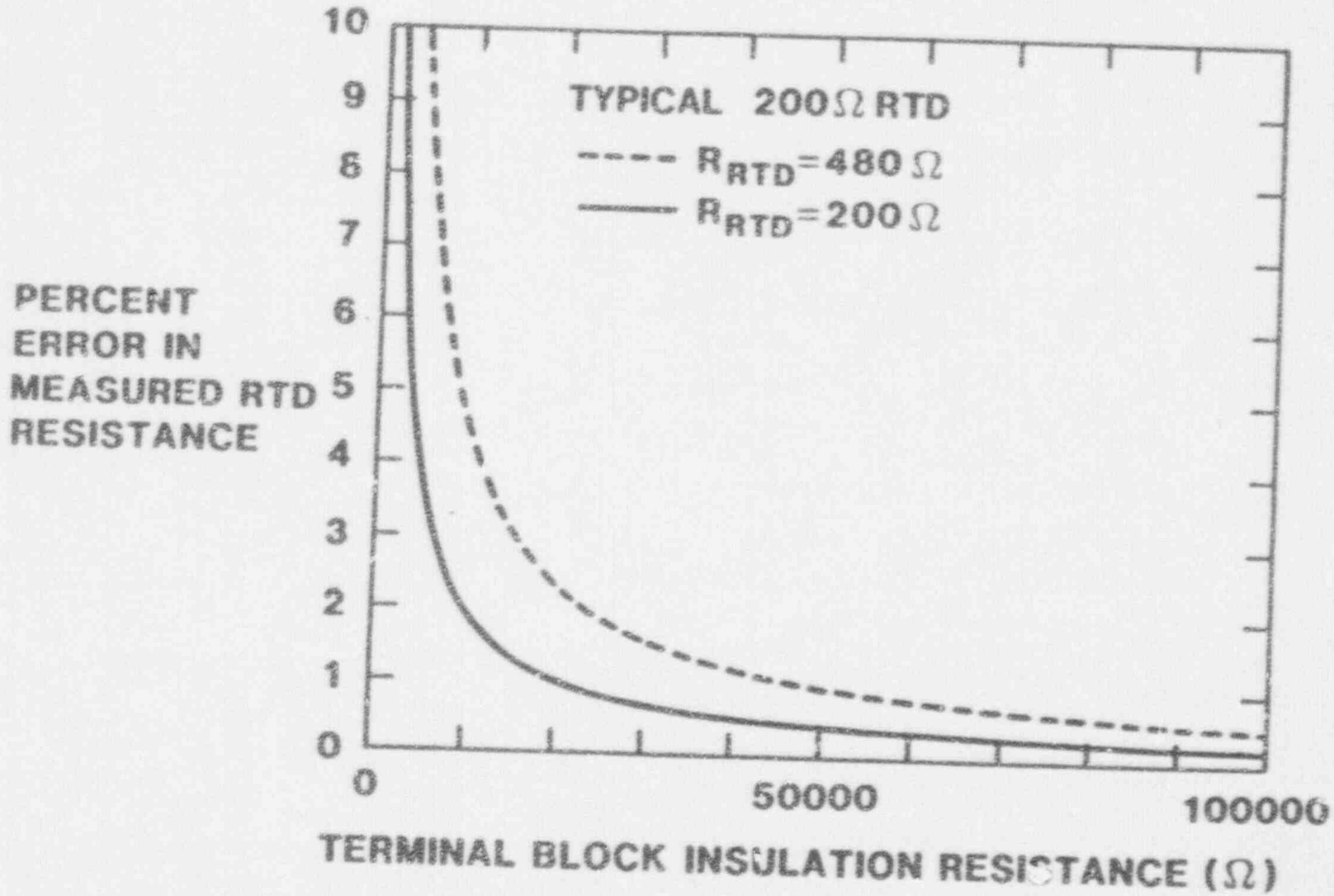
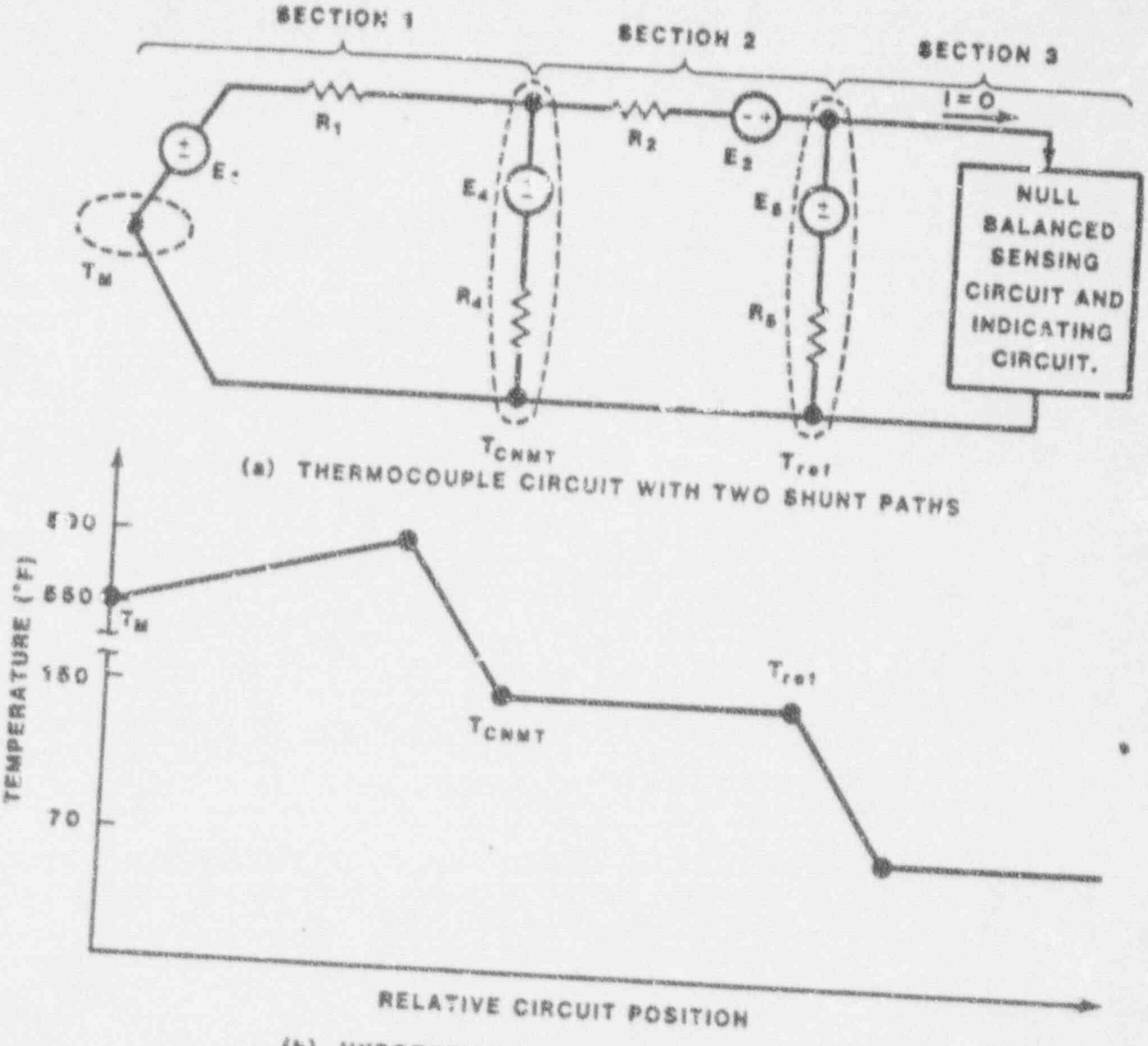


Figure 8-6: Percent Error in the Resistance Measurement of an RTD as a Function of Terminal Block Insulation Resistance

functional model of a TC circuit which clearly highlights the location of emfs in the circuit and permits one to electrically locate the relevant circuit elements for analysis. The key ingredient in Reed's model is the temperature profile for the entire TC circuit.

For illustrative purposes consider a typical in-containment thermocouple application such as core-exit thermocouples. The measurement junction of these TCs will be near the core flow exit point in the reactor vessel. From there, the TCs are typically routed down through the core and exit the reactor vessel from the bottom; shortly after the vessel exit point they may physically junction via a terminal block or other similar connecting device to TC extension wire which runs through containment to a heated reference junction. At this point, the circuit converts to a common conductor type such as copper, and proceeds via a containment penetration to the sensing circuit (device) located in the control room. Newer TC circuit designs locate the reference junction outside the containment.

Figure 8-7 illustrates one possible core-exit thermocouple circuit arrangement and shows a hypothetical, but reasonable, temperature profil for the circuit that might exist during a LOCA. The reference junction for this example is inside containment. Section 1 represents the thermocouple from the measurement junction to its junction with extension wire just outside the reactor vessel. Section 2 represents the run of extension wire from the vessel exterior to the reference junction. Section 3 represents the circuit from the reference junction through the measurement circuit in the control room. Using the method of Reed [45] and assuming homogeneous wires in each section of the circuit, lumped possible emf sources are shown in Figure 8-7. E_1 is the net emf resulting from the temperature difference between the measurement and reference junctions. For this example the temperatures of the measurement and reference junctions are assumed to be 550°F and 150°F, respectively. Thus E_1 for a Type K thermocouple is 9.036 mV. E_2 is a possible emf resulting from temperature gradients that may exist within containment along Section 2 of the circuit; for this example Section 2 of the circuit is assumed to be isothermal since an accident is in progress and the containment temperature and the reference junction temperature will most likely be the same. Thus, E_2 is zero and is not considered further in this example. E_4 and E_5 are spurious emfs which may be introduced by the terminal blocks in the shunt paths. These emfs may be of galvanic or other origin as discussed in Reference 1. R_1 is the lumped resistance of the TC wire in Section 1 of the circuit and R_2 is the lumped resistance of the TC extension wire in Section 2 of the circuit. For this example these values are assumed to be 598 ohms and 117 ohms, respectively and were chosen as follows: R_1 = (100 feet of 0.01 inch diameter Type K TC wire)*(5.98 ohm/double foot) = 598 ohms; R_2 = (200 feet of 20 AWG Type K TC extension wire)*(0.586 ohms/double foot) = 117 ohms.[46, 47, 48] R_4 and R_5 are the ohmic resistances of the shunts caused by the terminal blocks.



(a) THERMOCOUPLE CIRCUIT WITH TWO SHUNT PATHS

(b) HYPOTHETICAL TEMPERATURE PROFILE

Figure 8-7: Simplified Schematic of a Thermocouple Circuit (Figure a) and a Temperature Profile for the Circuit That Might Exist During an Accident (Figure b)

Figure a shows the circuit with shunt paths located at cable junction points just exterior to the reactor vessel and at the thermocouple reference junction. Figure b shows a potential temperature profile for an accident situation. As a result of the accident, T_{ref} and T_{cnmt} are shown equal, and therefore, E_2 becomes zero.

The parameter of interest in Figure 8-7 is V_2, the potential across the sensing circuit input. For a properly operating, null balanced, TC circuit V_2 equals E_1. However, the presence of shunt resistances and spurious emfs changes V_2, and hence changes the indicated temperature in the control room. The error in the voltage across the sensing circuit, e, is

$$e = \frac{E_1 - V_2}{E_1}$$

By any one of several methods V_2 can be expressed in terms of the other circuit elements, E_1, E_4, E_5, R_1, R_2, R_4, and R_5. The result is:

$$V_2 = \frac{R_4R_5E_1 + R_1R_5E_4 + (R_1R_2 + R_1R_4 + R_2R_4)E_5}{R_1R_2 + R_1R_4 + R_1R_5 + R_2R_4 + R_4R_5} \qquad \text{Eq. 8-7}$$

Examining Equation 8-7, we see that V_2 varies linearly with any one of the potentials (E_1, E_4, or E_5) while the other potentials are held constant. Figures 8-8 and 8-9, respectively, show the open circuit voltage, V_2, and the voltage error, e, as a function of the spurious potential E_5. In these figures, E_4 is assumed to be zero and the shunt resistances, R_4 and R_5, are 10^3, 10^4, and 10^5 ohms as noted. An interesting point illustrated by these figures is that large shunt resistances (e.g., 10^5 ohms or more) tend to mitigate the effect of large spurious emfs in the shunt paths. For example, if both R_4 and R_5 are 10^5 ohms, then the error in the desired 9.036 mV value of V_2 for this example varies from +9.7% to -6.5% (using Equation 8-6) as the spurious emf E_5 varies from -0.1 V to +0.1 V. The reason for this mitigating effect is that the large spurious emfs generate significant currents in the shunt paths (compared to the virtually zero current in the properly operating TC circuit) which in turn cause most of the spurious emf to be dropped across the large shunt resistances. Hence, V_2 is not affected as dramatically as might be expected since 0.1 V is 11 times the desired 9.035 mV. Of course, changing the relative values of R_4 and R_5 also affects the error in V_2. To compare to the above numbers, if R_4 is 10^4 ohms and R_5 is 10^5 ohms, then V_2 varies from +13.8% to -1.2% as E_5 varies from -0.1 V to +0.1 V. And as expected, as the shunt resistances fall, the effect of the spurious emfs increases. In the limit when R_5 is zero, V_2 will equal E_5.

The effect of varying R_5 on V_2 and e is illustrated in Figures 8-10 and 8-11, respectively. In these figures the three curves represent different values of E_5 (-0.01 V, 0.0 V, and +0.01 V); R_4 is assumed to be 10^4 ohms. These figures show R_5 varying only up to 11000 ohms, but the trend is clear. As R_5 increases we see that V_2 approaches $R_4/(R_1 + R_4)*E_1$, and if R_4 is large compared to R_1, then V_2 approaches E_1. As expected, for R_5 equal to zero V_2 is exactly the

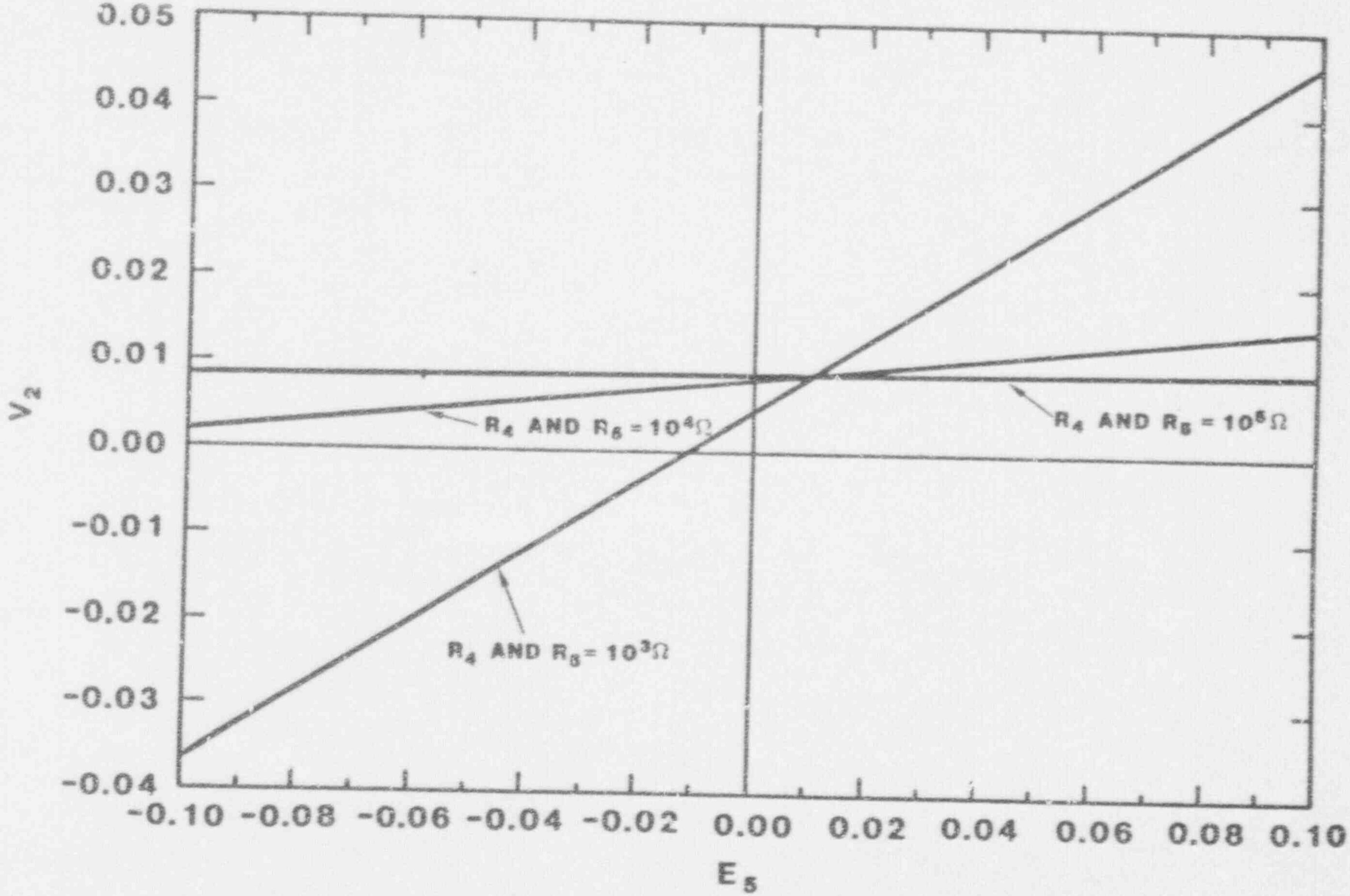


Figure 8-8: Open Circuit Voltage V_2 as a Function of the Spurious Voltage E_5 for Selected Values of Terminal Block Shunt Resistances

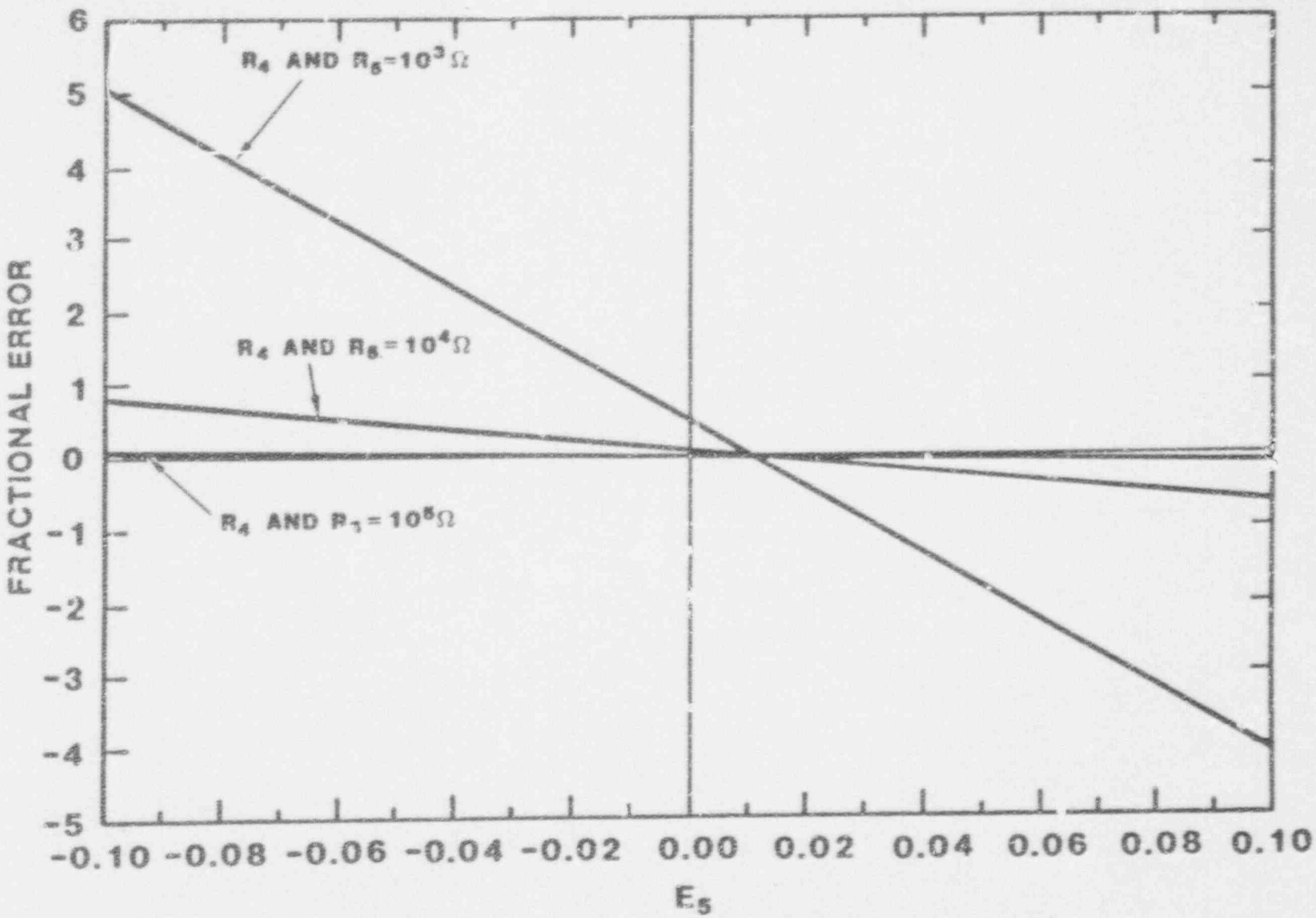


Figure 5-9: Error in the Open Circuit Voltage as a Function of the Spurious Voltage E_5 for Selected Values of Terminal Block Shunt Resistances

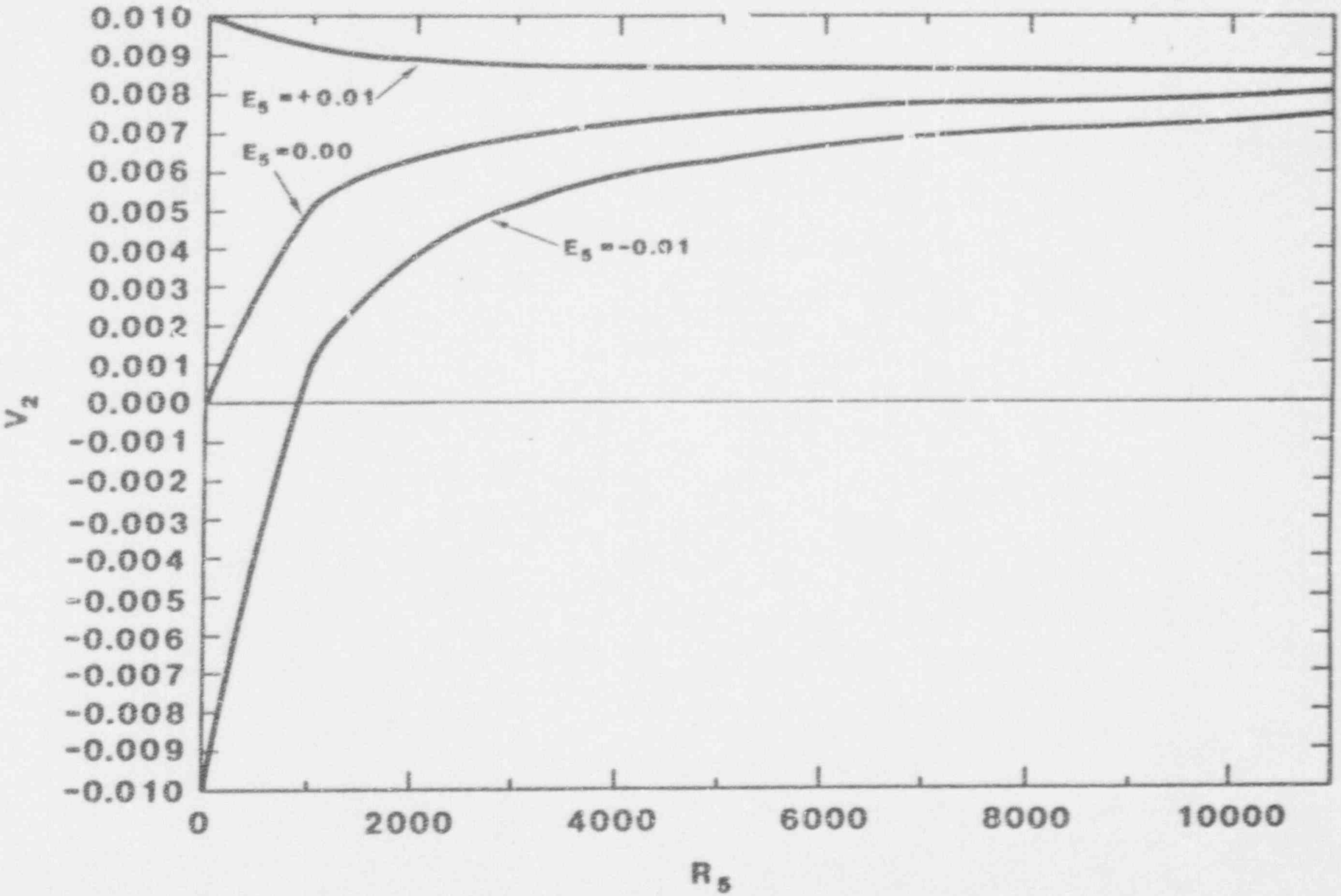


Figure 8-10: Open Circuit Voltage V_2 as a Function of the Shunt Resistance R_5 for Selected Values of Terminal Block Shunt Resistances

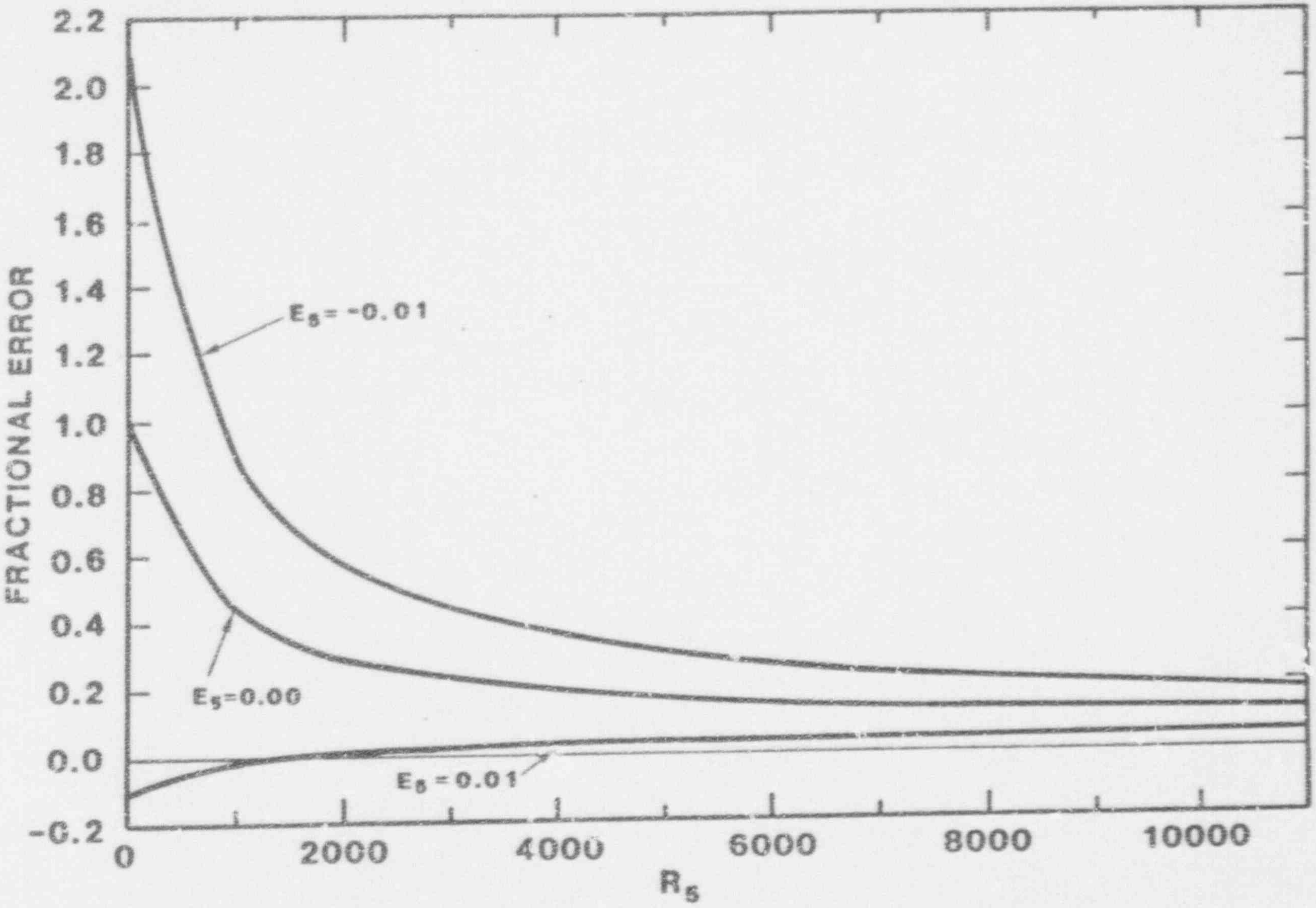


Figure 8-11: Error in the Open Circuit Voltage as a Function of the Shunt Resistance R_5 for Selected Values of Terminal Block Shunt Resistances

value of the spurious voltage, E_5. Clearly, negative spurious emfs relative to the sign convention shown in Figure 8-7 are more detrimental to circuit performance than positive spurious emfs. It is also clear that the value of the shunt resistance is a more dominant factor in determining circuit performance than the value of the spurious emfs. Since R_4, R_5, E_4, and E_5 can vary perhaps continuously over fairly large ranges, a definitive prediction of V_2 is impossible.

Finally, to illustrate precisely what these effects on V_2 mean in terms of indicated temperature, a few V_2 values predicted by the above example for selected values of R_5 and E_5 were translated into temperatures. This conversion assumed that the sensing device adds the reference junction compensating voltage to the value of V_2 before converting the indication to temperature. These temperatures are summarized in Table 8-1. The assumed values of the other parameters (keyed to Figure 8-7) are noted in the table.

Table 8-1

Selected Temperatures (°C(°F)) Indicated by the Type K Thermocouple Circuit Discussed as an Example in This Section*
(Correct temperature indication in all cases should be 288°C (550°F))

	R_5 (ohms)		
E_5	1000	5000	10000
-0.1	off scale low	off scale low	104 (220)
-0.01	90 (194)	221 (429)	247 (476)
0	190 (374)	251 (483)	253 (487)
+0.01	289 (555)	279 (535)	278 (532)
+0.1	1184 (2164)	536 (996)	415 (779)

* Values of the other circuit parameters used to derive the results in this table (see Figure 8-7):

E_1 = 9.036 mV
E_4 = 0.0 V
R_1 = 598 ohms
R_2 = 117 ohms
R_4 = 10^4 ohms

8.4 Solenoid Valve Circuits

Terminal blocks are commonly installed in 120 Vac and 125 Vdc control circuits for solenoid valves. Figure 8-12 is a simplified schematic showing one possible solenoid valve circuit. Before addressing the effects of terminal blocks, it is important to understand the normal

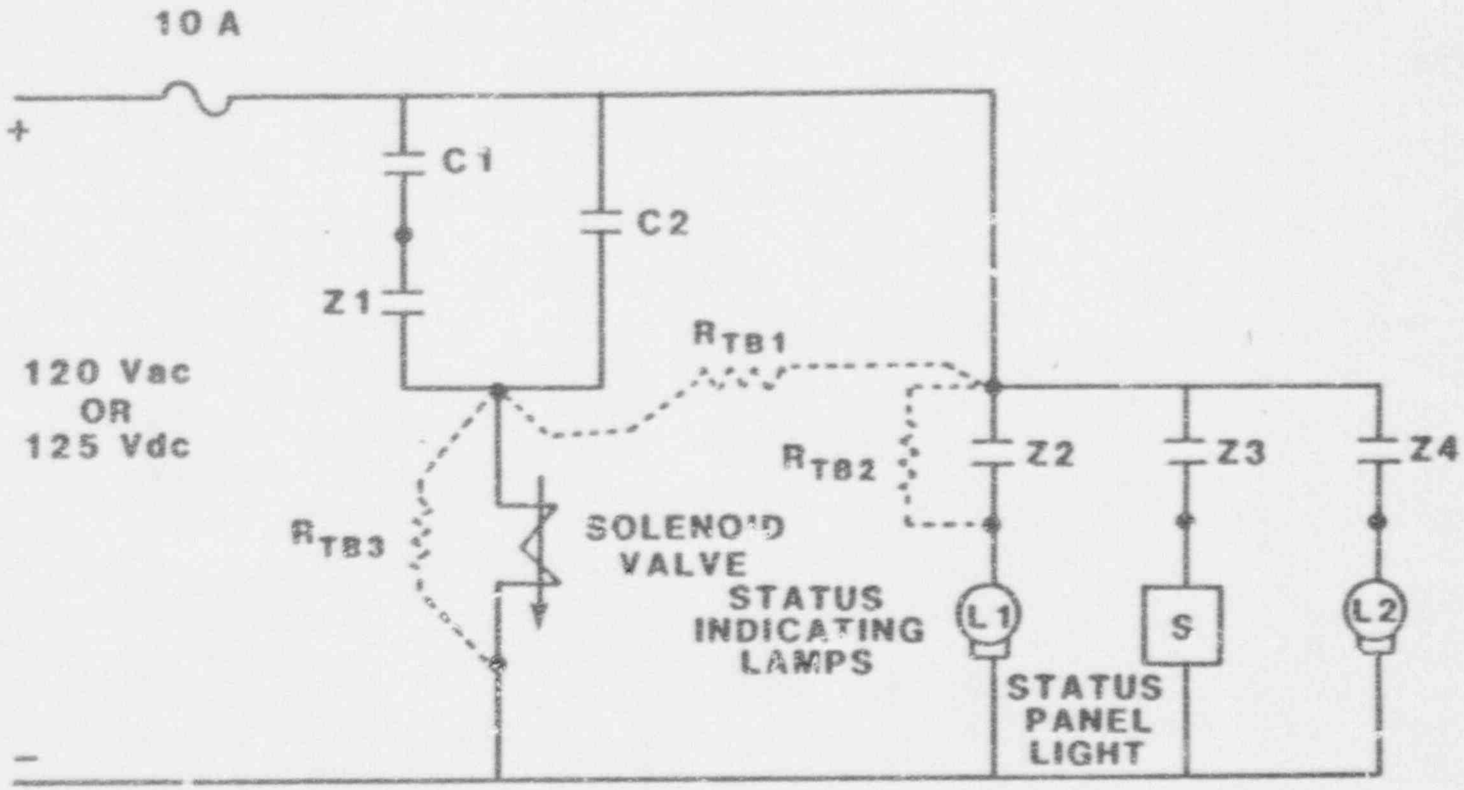


Figure 8-12: Simplified Circuit Schematic for One Possible Solenoid Valve Circuit

operation of this circuit. To begin, assume that the valve is normally open and that when energized, it closes. The desired position for operation is open.

The contacts C1 and C2 are control switches in the control room. These switches can be any one of a number of types, but a common type might be three position momentary contact switches. That is, there is a neutral position which is the rest position for the switch, and there are open and close positions which must be held by an operator in order for the switch to make contact in that position. Thus, when an operator moves the lever to open and releases it, the switches return to the neutral position. Assume that both C1 and C2 are operated by the same lever. Z1, Z2, Z3 and Z4 are two position limit switches located on the valve itself. L1 and L2 are indicator lamps in the control room and indicate that the valve is not closed and not open, respectively.* S is a status panel light which lights when the valve is in the normally desired position. Tables 8-2 and 8-3 are the contact development tables for this circuit. An "x" means that contact is made in that switch position.

Table 8-2

Contact Development Table For Control Switches C1 and C2

	---Switch and Valve Position---		
	Open	Neutral	Close
C1	-	x	x
C2	-	-	x

x = contact made
- = contact not made

* The terms "not open" and "not closed" are used rather than "closed" and "open" because that is the true meaning of the lamp. The "not open" lamp lights when the valve leaves the open position and is thus lit both while the valve is closing and when it is closed. Similarly the "not closed" lamp lights when the valve leaves the closed position and is thus lit both while the valve is opening and when it is open. If both lamps are lit simultaneously, then "not open" and "not closed" are both true which means that the valve is changing state. If only one lamp is lit, then it means that the valve is either open ("not closed") or closed ("not open").

Table 8-3

Contact Development Table for Limit Switches Z1, Z2, Z3, and Z4

	Valve Position		
	Open	Intermediate	Close
Z1	-	-	x
Z2	x	x	-
Z3	x	-	-
Z4	-	x	x

x = contact made
- = contact not made

If the valve is open, we see from Tables 8-2 and 8-3 that C1, C2, Z1, and Z4 are open. Only Z2 and Z3 are closed which means L1 and S are lit and the indication is that the valve is open (see footnote on "not open" and "not closed"). If the operator now wants to close the valve, he moves the lever for C1 and C2 to the "close" position. Both C1 and C2 make contact and, because Z1 is still open, power is applied to the valve via C2. The valve begins to close; Z3 trips open extinguishing S and Z4 trips closed lighting L2. Both L1 and L2 are now lit, and hence we know the valve is changing position. If the operator releases the lever before the valve is fully closed it will return to the full open (nonenergized) position since Z1 is not yet closed and C2 is open when in the neutral position. When the valve reaches the fully closed position, Z1 and Z2 change state. Z1 closes so that when the operator releases the switch lever, power to the valve will be applied through C1 and Z1; Z2 opens turning L1 off. The sequence happens in reverse when opening a closed valve. The operator moves the switch lever to open, thus opening C1; C2 was already open. Power to the valve is lost and it begins to open. As it does, Z1 and Z2 change state. Z1 opens to ensure that power will not be reapplied when C1 is released to the neutral position. Z2 closes, lighting L1. When the valve reaches fully open, Z3 and Z4 change state. Z3 closes, lighting S, and Z4 opens turning L2 off.

The dots in Figure 8-12 indicate circuit nodes which are physical junctions to field wiring near the valve. These may very likely be adjacent terminals on a terminal block. Three possible terminal block leakage paths have been indicated on Figure 8-12 by dotted resistors. Each may have a detrimental effect on the operation of the solenoid circuit. First, consider R_{TB1}, a leakage path between the always powered node of Z2, Z3, and Z4, and the solenoid valve. This leakage path bypasses the valve control switches C1, C2, and Z1. The effect of this leakage current could be the inadvertent energizing of the valve when a steam environment quickly envelopes the terminal block. If R_{TB1} is small enough, a leakage current sufficient to power the valve may

occur. If the valve in question is a 17.4 watt, dc service valve, then the steady state resistance of the valve is:

$$R_V = \frac{(125\ V)^2}{17.4\ W} \approx 900\ \Omega$$

In actuality, because of the finite value of R_{TB1}, the entire power supply potential will not be dropped across the solenoid valve. The minimum voltage to actuate the valve is approximately 90 Vdc [49] and hence the current necessary for this condition is:

$$I_V = \frac{90\ V}{900\ \Omega} = 0.1\ A$$

If at least 90 volts must drop across the solenoid valve, then a maximum of 35 volts can drop across R_{TB1}. Using the 0.1 A current requirement to operate the valve, we see that:

$$R_{TB1} = \frac{35\ V}{0.1\ A} = 350\ \Omega$$

Thus, a transient terminal block insulation resistance of 350 ohms would cause the valve to close when it was intended to be open. Industry qualification tests experience leakage currents sufficiently large to indicate that such low IR values are possible. Further, low values of IR would be most likely to occur under transient conditions (see Figures 4-5 and 8-3). The question here is whether or not such low values of IR would prevail for a period sufficiently long to complete the closing of the valve. Sandia test results indicate that the answer is probably yes, because solenoid actuation is fairly rapid and the low values of terminal block IR prevailed for seconds to minutes after their onset.

Next consider the leakage path designated by R_{TB2}. This path is a leakage path by limit switch Z2 and the net result could be a false lighting of indicating lamp L1. Analogous paths, not shown in Figure 8-12, would erroneously light lamps L2 or S. The current and voltage required to light L1 will undoubtedly vary from design to design, but two cases might be considered as examples. In the first case, the lamp is in a series connection as shown in Figure 8-12. A typical 125 Vdc lamp for such an application might require a minimum of 110 Vdc to operate.[50] The lamp itself might typically have a resistance of 2000 ohms and hence the current necessary would be:

$$I_{Lamp} = \frac{110\ V}{2000\ \Omega} = 0.055\ A$$

Thus, the terminal block insulation resistance would have to be:

$$R_{TB2} = \frac{15\ V}{0.055\ A} = 273\ \Omega$$

Again, this value of IR is not unreasonable for transient conditions though sustained values at this low level are unlikely.

The second lamp configuration would replace the actual lamps with a relay which would turn separately powered lamps on or off. Thus L1, L2, and S would be the pick-up coils for these relays. Such relays might typically have a pick-up voltage of 75 percent of the rated voltage and a coil resistance of 13000 ohms. The required current therefore would be:

$$I_{relay} = \frac{(0.75)(125\ V)}{13000\ \Omega} = 0.0072\ A$$

The voltage drop across the terminal block could be at most 25% of 125 Vdc or 31 Vdc and hence:

$$R_{TB2} = \frac{31\ V}{0.0072\ A} = 4300\ \Omega$$

Thus, a much larger terminal block IR would permit false operation of the indicating or status lamps if they were switched on and off by a relay. Any value of R_{TB2} less than 4300 ohms would cause the lamps to falsely illuminate for the assumed type of relay.

The final fault shown in Figure 8-12 is R_{TB3}. This path leaks by the valve itself and would cause a problem only if the leakage current became large enough to make the circuit fuse fail. For the worst case with a 17.4 watt dc valve energized and all three lamps illuminated, the current in the circuit would be:

$$I_{max} = \frac{17.4\ W}{125\ V} + 3 * \frac{125\ V}{2000\ \Omega} = 0.327\ A$$

If the circuit were fused at 10 A, then 9.673 A would have to leak around the valve to cause the fuse to fail. With the valve remaining energized at 125 V, fuse failure would occur at a terminal block IR of:

$$R_{TB3} = \frac{125\ V}{9.673\ A} = 13\ \Omega$$

This value is essentially a dead short; however, if the circuit were fused at 1 A, fuse failure would occur at a terminal block IR of 186 ohms. These low IR values are not impossible to achieve, but for any sustained period seem improbable. Momentary high leakage currents may cause the fuse to open. At these high leakage current levels, one must also be concerned with the power being dissipated by the terminal block and the effect such power dissipation may have on permanently degrading the block's surface.

In summary, the above discussion indicates that terminal blocks may interfere with the proper operation of a solenoid valve circuit when the terminal block's insulation resistance decreases to about the 4 kohm level. At this value of terminal block IR, indicating lamps may falsely light depending on how they are wired into the circuit. At a few hundred ohms of insulation resistance, the valve may falsely energize and at a few ohms of insulation resistance the leakage current may be large enough to fail circuit fuses. Being slightly conservative, we may conclude that at IR values above 5 kohms, terminal blocks probably do not affect the operation of solenoid valve circuits.

8.5 Motor Circuits

Consider the case where a terminal block is used to connect a motor to a motor control center (MCC). A typical connection might look like Figure 8-13. The terminal block leakage path is indicated as a fault resistance, R_{TB}, between lines. In this case the leakage current does not affect the motor directly, but rather would affect the thermal overload protection devices and the circuit breakers. The amount of leakage current that would be significant would depend on the settings of these devices. Figure 8-14 shows time-to-trip as a function of Percent of Motor Full Load Current [51] for one type of directly heated bimetallic overload relay. There are many manufacturers of such devices, both bimetallic type and magnetic type, and the selection of time-to-trip characteristic curves are extremely varied. Thus, the following discussion is only representative of the type of concerns that may be a problem; each application must be analyzed individually.

Probably the most sensitive case is for small 1/2 hp or 1/3 hp motors which draw ~1 A at full power. From Figure 8-14 we see that 200 percent of motor full load current requires approximately 40 seconds to trip the overload protection relay; at 500 percent the time to trip is down tc   seconds. These overload currents correspond to ~2 A and ~5 A currents for the small 480 Vac motors, or leakage currents of ~1 A and ~4 A. These values of leakage currents have been observed in industry qualification tests of terminal blocks. Sandia and industry test data suggest that it is possible to have these leakages for periods of time sufficiently long to trip the overload protection devices, and hence, the line-to-line faults caused by terminal blocks may cause them to trip. Acceptable levels of leakage current are those which do not exceed the excess current capacity of the overload protection for the time necessary to trip the device and do not dissipate damaging amounts of power on the terminal block surface. Small, low current motors are

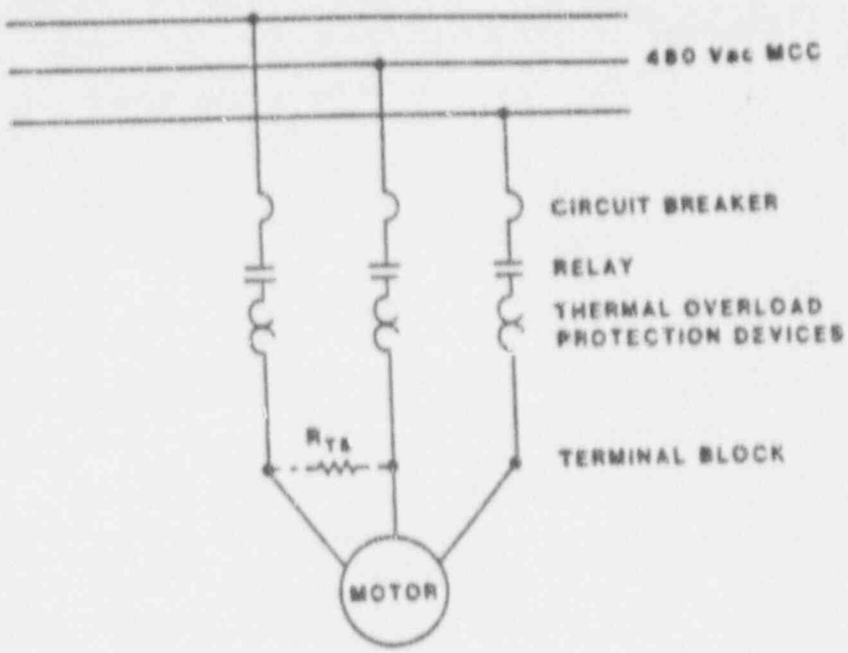


Figure 8-13: Typical Motor Circuit Connection for a 3-Phase Motor

the most susceptible motor applications because with larger sizes, the full load current is higher and larger leakage currents are required to trip the protection devices. However, industry qualification tests have reported failures of 25 A fuses used to monitor leakage currents and therefore even circuits for larger motors may be affected.

The limiting condition for a terminal block to open a circuit breaker is the set point of the circuit breaker. This value is typically well above the motor full-load current and hence the terminal block leakage currents would have to be very large to trip a breaker. Unless the terminal block was nearly shorted, such would not be the case. However, if the motor is off and then switched on, the transient application of voltage to the terminal block will cause much higher than average leakage currents. The high transient leakage current coupled with the motor starting current may reach values large enough to trip the breaker.

In summary, terminal blocks in motor circuits may be a problem, not to the motor itself, but rather to the circuit that supplies power to the motor. The most sensitive devices in the circuits are the thermal overload protection devices and the most sensitive situations are where they protect small horsepower motors. Also, the tripping of circuit breakers may be a problem on motor start-up. The effect of a tripped overload protection device or a tripped breaker would depend on the function of the motor, the ability of the operator to recognize that a protection device or breaker had tripped, and his ability to prevent the problem from recurring.

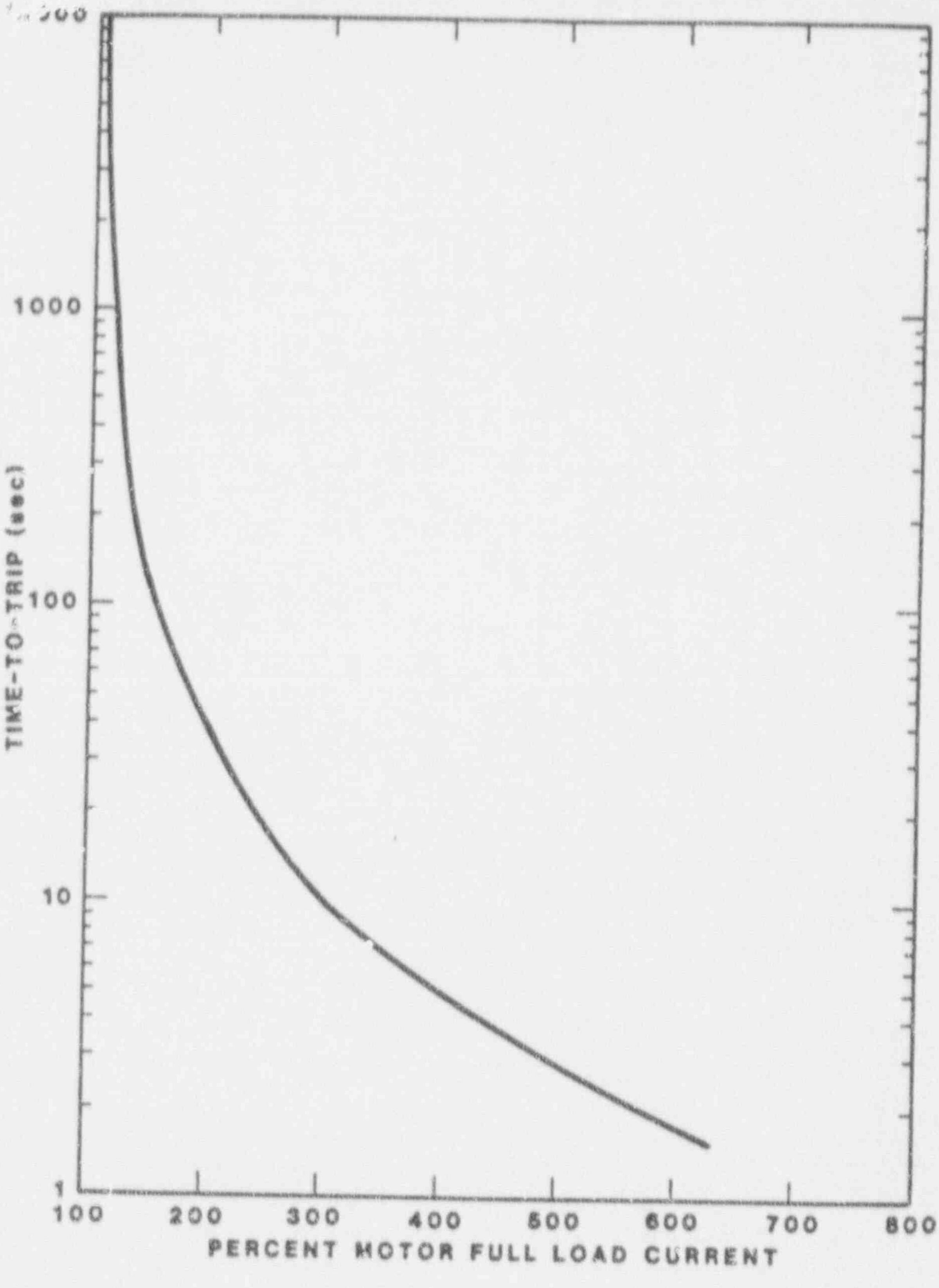


Figure 8-14: Time-to-Trip as a Function of Percent of Motor Full Load Current for One Type of Directly Heated Bimetal Overload Relay [51]

9.0 POSSIBLE METHODS OF REDUCING TERMINAL BLOCK LEAKAGE CURRENTS

Three possible methods were considered candidates for reducing surface leakage currents in moisture films: cleaning, sealing, and coating. Each is discussed in turn.

9.1 Cleaning

Cleaning of terminal blocks was a possible remedy for terminal block performance suggested by Stuetzer in his earlier work.[2] Specifically, he stated that "a very highly contaminated block, cleaned [with steam and subsequently washed with alcohol] and sealed with RTV...regenerated completely and functioned like a new block." Stuetzer reported leakage currents of approximately 0.7 mA for this cleaned block and the new blocks that he tested. These results are entirely consistent with the results reported in the later Sandia tests.[1] Reference 1 also reports that one new terminal block was cleared prior to testing by soaking sequentially in clean baths of freon, deionized water and freon. No improvement in the performance of this terminal block compared to the new, uncleaned blocks was noted. This result was somewhat surprising since we expected the cleaning to remove salts and other sources of ions for film conduction. Stuetzer's data supports this finding since his cleaned block performed essentially the same as his new blocks.

The fact that cleaning is not as effective as originally hoped for should not actually be surprising. Terminal blocks are extremely convoluted surfaces with covered cavities and many small crevices that are not easily accessed. In the sectional designs the interface between adjacent sections is not accessible without disassembly of the terminal block unit. For these reasons a thorough cleaning of a terminal block unit, even in a laboratory environment, is difficult to achieve. In a field environment it may be practically impossible to achieve and maintain cleanliness. The observed performance of a cleaned, new terminal block in Sandia tests indicates that cleaning does not reduce leakage currents to levels that will not affect instrumentation and control circuits. Note that this statement does not imply that routine cleaning should not be performed as a part of preventive maintenance.

9.2 Sealing

Terminal blocks are typically installed in NEMA-4 enclosures. An obvious question is whether these enclosures can be sealed to prevent the steam environment from surrounding the terminal blocks. As the enclosures now exist with weep holes and conventional conduit/cable entries, the practical answer is probably no. The biggest problem would be the conduit entries. To effectively seal the interstitial space between the cables and the conduit against steam intrusion would require a penetration into the NEMA-4 boxes similar to a containment penetration. Using a silicone compound such as RTV may stop condensed moisture, but achieving a reliable vapor seal in all possible conduits would be unlikely.

Given that the electrical enclosure could be sealed successfully, another set of questions arises. First is the question of structural integrity of the box. Rapid external pressurization may collapse the box around the terminal blocks. In tests of new NEMA-4 enclosures without weep holes or conduit entries, external pressurization with nitrogen gas to 20-35 psid deformed the boxes sufficiently so that they leaked and equilibrated pressure. These pressure levels are below the design basis containment pressures specified in IEEE 323-1974, Appendix A.[37]

Another question is the phenomenon of cable "piping" observed during Sandia and industry qualification tests. In these tests, a compression fitting around a cable forms a pressure barrier between the test chamber and the environment. In cable "piping", differential pressure drives moisture along the cable between the insulation and the conductor from the high pressure end to the low pressure end. If the terminal blocks are hermetically sealed in the NEMA boxes, this differential pressure condition could be set up in reverse during an accident situation. Moisture would then be driven along the cables directly onto the terminal blocks. Such a condition would be extremely undesirable.

It would be difficult, if not impossible to practically achieve total enclosure sealing. Even if it could be achieved, another set of questionable effects such as NEMA enclosure strength and cable "piping" would arise. Thus, sealing the enclosures does not appear to be a viable solution.

9.3 Coatings

Conformal coatings for terminal blocks were investigated as a means of sealing the exposed conductors. Several classes of coating materials were looked at including polyamides, silicones, polyurethanes, epoxies, and proprietary materials. The coatings were judged according to their moisture permeation, dielectric strength, heat resistance, strippability, and applicability. Based on these criteria, two materials were chosen as likely candidates for coating terminal blocks. These were Red Glypt™ insulating varnish which has been available for some time, and a new class of epoxy, cycloaliphatic epoxy, which has recently become commercially available. The advantage of both of these materials is that they are one part systems and easily applied.

Red Glypt™ dries by exposure to air and its maximum operating temperature is quoted in the manufacturer's catalog as 121°C (250°F). To test its ability to function at higher temperatures, copper substrates were coated with Red Glypt™ and then baked for 10 to 180 minutes at 160°C (320°F). The higher temperatures did not affect the resistivity of the material, however, it became quite hard and some creep was observed. In order to test the importance of film uniformity on resistance, other samples were coated by brushing Red Glypt™ on to them with no attempt being made to achieve a uniform coating. At 500 V applied potential, one sample experienced periodic breakdowns and another sample experienced corona discharge. No breakdowns were observed on samples coated uniformly. These breakdowns illustrate the importance of uniform coating since the material is too viscous to flow and provide a pinhole free film.

The cycloaliphatic epoxy is cured by exposure to ultraviolet light rather than by using an amine curing agent as is required for common epoxy materials. This makes field application reasonably easy. It also has reasonably good electrical properties measured at 150°C (302°F) and maintains these properties up to ~180°C (356°F) which envelopes the IEEE 323 design basis temperatures.

To test the effectiveness of these two materials, four terminal blocks were coated with them, two with Red Glypt™ and two with the epoxy. To achieve a good coating, the metallic conducting parts of the terminal blocks were removed from the insulating material and otherwise concealed surfaces were coated. Such a procedure probably would not be possible in a field application. Wires were attached in a serpentine configuration identical to the electrical connections reported for the Phase I Sandia test.[1] Continuity though the desired conducting paths was verified and surface coatings were applied so that no electrical continuity existed between the adjacent terminals and cable terminations. These four terminal blocks were installed in a NEMA-4 enclosure along with two uncoated terminal blocks which acted as test controls. All terminal blocks were of the same make and model. These terminal blocks were exposed to a saturated steam LOCA simulation profile which approximately followed the temperature profile recommended by IEEE-323-1974, Appendix A.[37]

Figures 9-1 and 9-2 show the leakage currents of the Red Glypt™ and epoxy coated terminal blocks, respectively, as a function of time. The control block leakage current traces are also included for comparison. Basically the coated blocks performed like the uncoated blocks. These results point to the fact that complete coatings were not achieved, and that leakage paths existed. Post-test examination and diagnostic tests showed that the primary connection point between the metallic conductors and the phenolic insulation was the screw which attached the conductors to the phenolic. In fact, the mating threads of the phenolic insulation were carbonized into a powder which appeared to enhance the connection between the metallic conductors and the insulation surface. The threaded mating surface of the screws, though originally coated, were not coated at the end of the test. Reinserting them into the phenolic probably removed the coating from the screw surface. The results of this test indicate that coatings applied under laboratory conditions do not achieve a significant improvement in terminal block performance. A field application would most likely be less perfect; hence we must conclude that conformal coatings, short of a complete potting, do not provide the desired improvement in terminal block performance.

A coating which was not investigated or tested is a spray of a silicone-based fluid. Silicones are extremely hydrophobic and may inhibit film formation for some period of time. Such a coating would not be permanent and would require routine recoating to maintain its protective quality. Further, the inrush of steam may strip the silicone from the surface and render it ineffective. It may also have detrimental effects such as enhanced agglomeration and retention of dust and dirt.

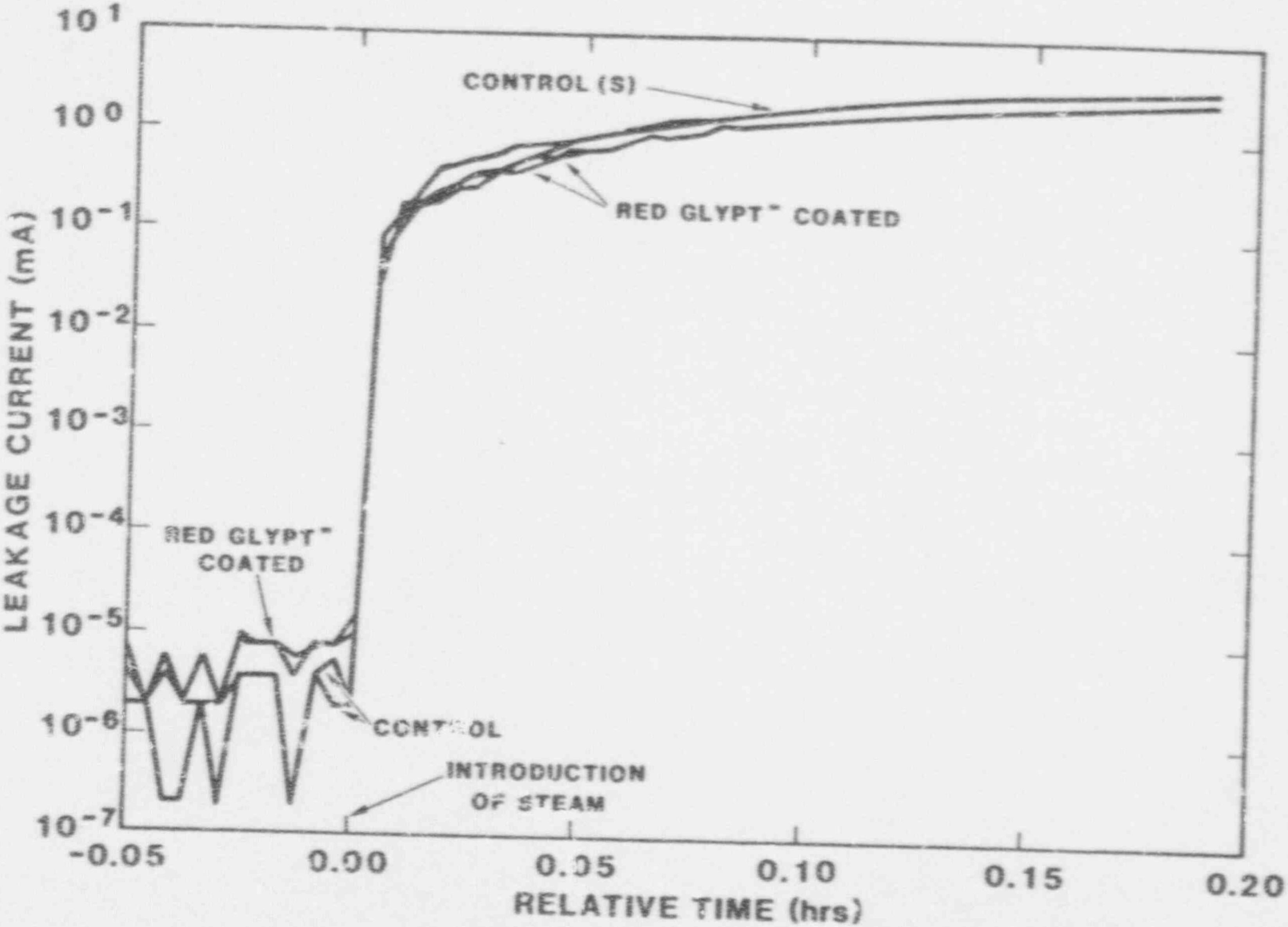


Figure 9-1: Comparison of Leakage Currents for Red Glypt™ Coated and Uncoated Terminal Blocks

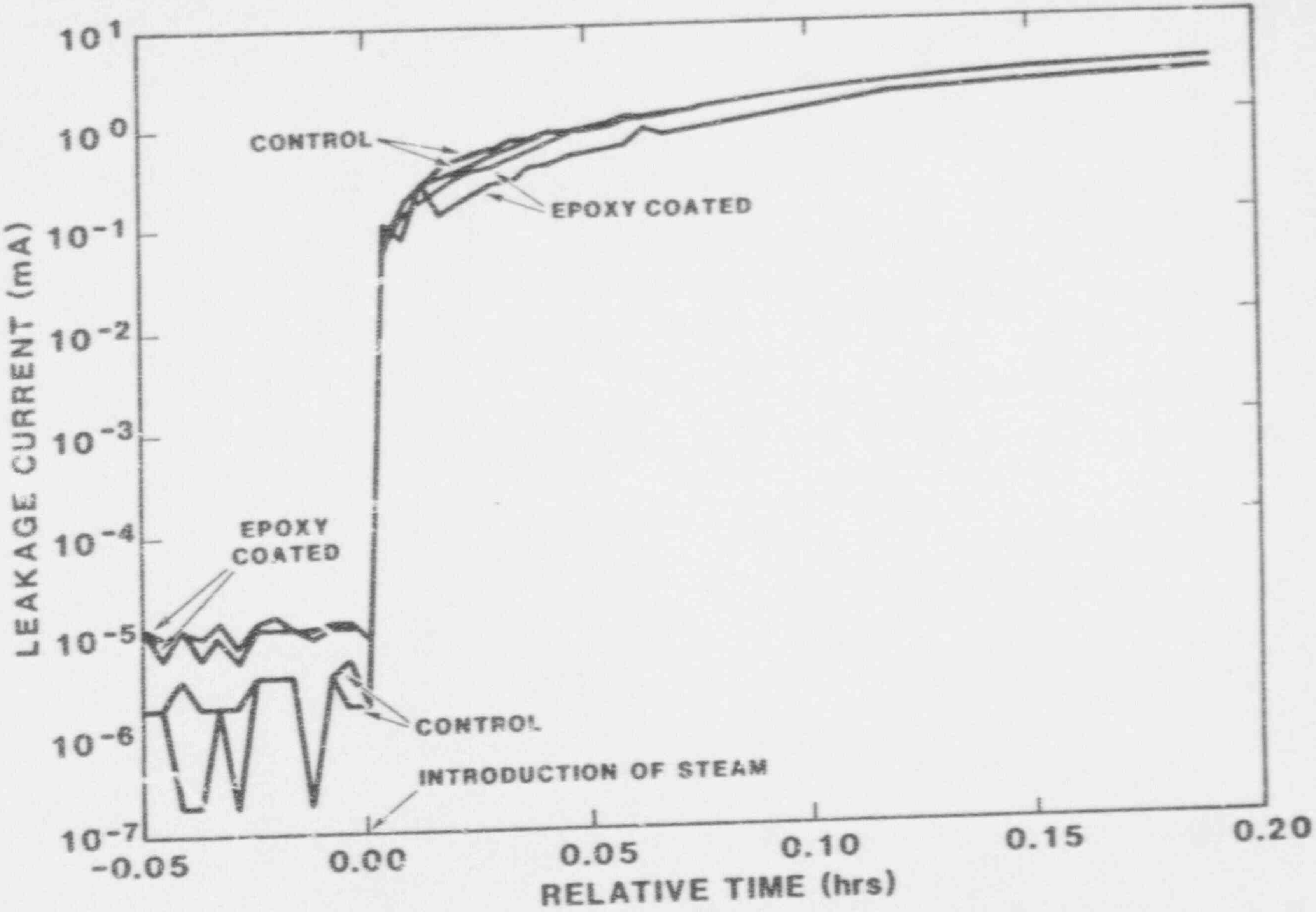


Figure 9-2: Comparison of Leakage Currents for Cycloaliphatic Epoxy Coated and Uncoated Terminal Blocks

10.0 ASSESSMENT CRITERIA

The question asked at the outset of this effort was what are the failure and degradation modes of terminal blocks and what are their effect on system performance. The answer, of course, is not simple or straightforward. It depends on many complex and interacting factors. This report and the report of the Sandia tests of terminal blocks [1] provide an insight into the performance of terminal blocks. This report also illustrates some simple analyses which can be performed to define the effect of terminal blocks in various applications. It is not the intent of this study to judge the safety significance of terminal blocks, but rather to provide the necessary technical bases to make a safety judgment. The following paragraphs summarize the conclusions about terminal blocks which we believe are supported by the data obtained and the analyses made. Engineering judgments and recommendations are clearly noted as such.

10.1 Terminal Block Design Considerations

The two basic designs of terminal blocks (sectional and one piece) do not appear to be radically different in their performance in a LOCA environment. Although some sectional blocks did perform comparably to the one-piece blocks, other sectional blocks performed noticeably worse (one or two orders of magnitude) during the LOCA simulation.[1] The materials from which terminal blocks are commonly made (phenolic and ceramic) do not appear to dramatically affect their performance during a LOCA environment. This result arises because the primary mechanism for degrading terminal block performance (film formation) is somewhat independent of the underlying insulation material of the terminal block. However, some difference in film formation and continuity may result from differences in the surface wettability characteristics of the insulating material.

Though we did not include radiation in any of the Sandia tests, evidence from industry indicates that it is good engineering practice to choose a fill material for the phenolic, such as glass or mineral, which is as radiation resistant as possible. Cellulose, a commonly used filler material, has a lower radiation resistance than glass or mineral fillers and may contribute to failure modes such as cracking or crazing or water absorption. These phenomena were not examined in the Sandia tests.

Terminal blocks are, by their very nature, convoluted surfaces with inaccessible cavities and interfaces. For example, a hole may exist below the conducting plate to accommodate the screw which attaches the lug terminating the wire to the terminal block; or, in sectional designs the interface between adjacent sections is not accessible without disassembly of the terminal block unit. For these reasons, a thorough cleaning of the terminal block surface, especially in an installed plant situation, may be difficult if not impossible to achieve. Sandia's test of a "clean," one-piece terminal block further indicates that for our cleaning method (soaking in freon and deionized water), little improvement in performance over that of new, but uncleaned blocks can be expected.

Thus, for common terminal block designs with highly convoluted surfaces, and inaccessible cavities and interfaces, cleaning may not be an effective method of reducing low level leakage currents that exist during exposure to a steam environment. Proper cleaning cannot make the situation worse, but it is doubtful that it will reduce leakage currents to a level acceptable for most instrumentation and control applications. The large, positive impact on terminal block performance that was originally believed to accrue from cleaning was not observed in the Sandia tests.

During the Sandia tests, relatively large emfs (0.01 mV to 0.5 V at ~0.1 mA) were observed to be generated within unpowered test units.* A possible explanation for these emfs is oxidation-reduction reactions between dissimilar metals at the interfaces of the terminal block terminals, the ring-lugs, and the cable conductors. The addition of high temperature, conducting moisture films provides the electrolyte necessary for these reactions to occur. Cadmium sulfide was found as a residue on the terminal blocks at the conclusion of the Sandia tests, suggesting the possibility of galvanic reactions.** Emfs may have significance to low power circuits such as thermocouples and points to a design/installation need for using metals with like oxidation potentials and system components which will not form potentially detrimental compounds under accident conditions.

10.2 Testing Considerations

The primary objective in testing components for nuclear power applications is to determine their performance in adverse accident environments. Using data obtained from these tests, analysis can determine the effect of component performance on the systems. Thus, qualification testing of components has two objectives: (1) demonstrate that the equipment will perform its function in an accident situation; and (2) provide data that characterizes the component's performance in an accident situation. Though easily stated, achieving these objectives is less than trivial. At a minimum, sufficient knowledge about the equipment's required functions must be known so that relevant data can be collected and relevant acceptance criteria formulated. Also, knowing the function of the equipment allows one to put the failure modes into perspective. Test methods must be adequate to detect failure modes if they exist and to monitor the performance of the equipment.

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* The test unit consisted of the electrical cable, crimp type ring-lugs and the terminal block.

** The cadmium source was the plating on a 1/4-20 nut used to attach the enclosure mounting plate to the NEMA-4 enclosure studs. The sulfur was hypothesized to be from the sodium thiosulfate added to the chemical spray solution or from the cable jacket material. The occurrence of CdS points to a system consideration in assembling the terminal block-NEMA-4 enclosure unit: even an innocuous nut or bolt somewhere in the unit may affect the performance of the unit in an accident environment.

The primary application of terminal blocks in the nuclear power industry is in instrumentation and control circuits. Therefore, generic testing should be geared to this application. For these applications leakage currents on the order of a fraction to a few milliamperes can become significant to the operation of a circuit. Thus, test apparatus should be designed to obtain such data; the common practice of measuring leakage current with a 1 A or larger valued fuse provides no information about leakage currents less than 1 A. Industry test reports indicate numerous failures of these fuses. It is necessary to obtain low level leakage current data if analyses of the effects of terminal blocks are to be made. If on-off power cycling is anticipated in the operation of a circuit (e.g., a motor circuit), then the ability to measure transient, high level leakage currents and their duration should be part of the test.

Because film formation followed by Joule heating of the film may lead to film vaporization, higher potentials may actually lead to higher film resistances. Thus, the testing of terminal blocks at increased potentials for margin may actually be less conservative in terms of measuring terminal block performance than testing at actual use potentials.

Test environments must be such that they include the pressure-temperature conditions expected to be present in the predominant accident sequences. This consideration is important since pressure in concert with temperature govern the conditions necessary to form and sustain a moisture film. Tests which maintain superheat throughout the test are inappropriate unless superheat is expected throughout all possible accidents. Thus, the practice of using Arrhenius techniques to compress accident exposures by elevating temperatures into superheated regimes does not test terminal blocks in saturated steam and condensing steam environments. The saturated environments are commonly accepted as a predominant long-term accident environment. Further, the use of Arrhenius techniques to accelerate aging and accident simulations is based on the time-temperature superposition phenomenon of polymer chemical degradation; it has nothing to do with the primary failure mode of terminal blocks--film formation and conduction through these films.

In general, test methods and procedures must be germane to the application, and they must provide data for analyses of the effects of component performance on system performance. To accomplish this goal, an understanding of the failure and degradation modes is required.

10.3 System Design Considerations

Terminal blocks will affect the operation of instrumentation and control circuits. Proper utilization of terminal blocks is therefore a critical question in nuclear plant applications. For high impedance circuits such as transmitters and thermocouples, terminal blocks can significantly change the sensed output of the circuit. A graphic illustration of the effect was presented in Figure 8.3. RTD circuits are also important since they are the primary temperature monitoring device for the primary coolant system and the containment building. Valve

circuits are not as susceptible as RTDs or high impedance circuits, especially from an operability point of view, but the existence of power on a terminal block close to a valve may falsely provide power to valve indication lights. The results would be erroneous valve position indications to an operator in the control room. Motor circuits are relatively immune to the effects of degraded terminal block operation, except to the extent that leakage currents may cause thermal overload protection devices or circuit breakers to trip. Unfortunately, these effects will occur at the time when operators are under pressure to respond to a plant transient and are inundated with alarms. They will most likely be performing activities of a higher priority than determining that circuit breakers have tripped or thermal overload protective devices have actuated. Thus, terminal blocks may affect motor circuit operation, though not directly.

The question of terminal block failure is one of relative magnitude of the effect. Clearly, if terminal blocks are to be used, then analyses specific to the application are required to insure that the circuit operation is not detrimentally affected.

The current method of terminal block installation appears to be as good as can be practically achieved. The NEMA-4 enclosures with a weep hole in the bottom protects the blocks from direct impingement of chemical spray and permits condensation to drain from the enclosure. Based on the results of Sandia chemical spray and submergence data, the presence of spray external to the electrical enclosure does not significantly affect terminal block performance. A logical measure to prevent condensed moisture and spray from penetrating the interstitial space between the cable and conduit and then dripping onto the terminal block would be to bring the cables into the enclosure from the side or bottom. Top entry of cables into the enclosure would not prevent moisture from dripping onto the terminal blocks.

Hermetically sealing the terminal block enclosures is probably an impractical solution. The chances of achieving good seals around all the cables where they enter the NEMA-4 enclosure or where the cables enter conduit is remote. Further, the NEMA-4 enclosures do not have good ability to withstand external pressurization for long periods. Depending on the pressurization rate, the maximum differential pressure that can be tolerated is 20 to 35 psid. Hermetically sealing the enclosures also creates a condition where, due to differential pressure, moisture can be driven along the cables between the conductor and insulation into the terminal block enclosure. Since the cable insulation continues right up to the terminal block, the moisture could be driven onto the terminal block. This "piping" phenomenon is commonly observed in both Sandia and industry tests of cables and terminal blocks where unspliced cables penetrate test chamber boundaries. Therefore, hermetic sealing of terminal block enclosures is not advised, nor is it easily achieved.

Coatings were initially believed to be a feasible solution to terminal block leakage problems. However, as with hermetic sealing, achieving a good conformal coating, especially for already installed terminal blocks, will be almost impossible. The test run at Sandia to test two possible coatings showed no observable difference or delay between leakage currents observed on coated terminal blocks and uncoated blocks. Thus, we do not believe that coatings are a viable means of limiting terminal block leakage currents.

In conclusion, leakage currents observed during LOCA testing of terminal blocks can cause erroneous indications and/or actions in low power instrumentation and control circuits. Possible solutions such as cleaning, sealing, or coating do not appear to have the desired corrective effect, and hence two possible courses of action are apparent: (1) analyze for the effects of terminal blocks in circuits and account for these effects circuit design; or (2) remove terminal blocks from instrumentation and control applications. If the first option is chosen, then qualification activities should monitor leakage currents at levels appropriate to the application.

11.0 CONCLUSIONS

1. The primary application of terminal blocks in the nuclear power industry is instrumentation and control circuits.

2. Terminal blocks receive minimal quality assurance attention in selection, installation, inspection and maintenance activities.

3. Most industry qualification tests do not continuously monitor for low level leakage currents during LOCA simulation tests of terminal blocks. Without quantitative knowledge of these leakage currents, adequate analyses of their effects on instrumentation and control circuits cannot be performed.

4. Surface moisture films are the most probable explanation for degradation in terminal block performance during exposure to a steam environment. Because the existence of moisture films is highly dependent upon environmental conditions, test environments must realistically reflect the predominantly expected accident environments. For example, superheated test conditions may not accurately represent the terminal blocks' performance.

5. The use of voltage levels above actual use conditions in qualification tests of terminal blocks may be nonconservative with respect to the measurement of low level leakage currents which are the primary degradation mode of terminal blocks.

6. Terminal block leakage currents in a steam environment may degrade performance of instrumentation and control circuits to an extent sufficient to cause erroneous indications and/or actions.

7. Cleaning will probably not reduce leakage currents to a level acceptable for most instrumentation and control applications. The large, positive impact on terminal block performance that was originally believed to accrue from cleaning was not observed. Further, terminal block leakage currents were not significantly reduced by the application of either of two coatings tested.

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The primary application of terminal blocks in the nuclear power industry is instrumentation and control (I&C) circuits. The performance of these circuits can be degraded by low level leakage currents and low insulation resistance (IR) between conductors or to ground. Analyses of these circuits show that terminal blocks, when exposed to steam environments, experience leakage currents and low surface IR levels sufficient to affect some I&C applications. Since the mechanism reducing surface IR (conductive surface moisture films) is primarily controlled by external environmental factors, the degradation of terminal block performance is mostly independent of terminal block design. Testing shows that potential methods of reducing surface leakage currents will not reduce them sufficiently to prevent terminal blocks from affecting I&C circuits. Therefore, terminal blocks can cause erroneous indications or actions of the I&C circuits in which they are a component. Most of the present qualification tests of terminal blocks do not address the issue of low level leakage currents, and hence do not demonstrate that terminal blocks will operate properly in I&C circuits.

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