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Selected Fault Testing of Electronic Isolation Devices Used in Nuclear Power Plant Operation

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ABSTRACT

Electronic isolation devices are used in nuclear power plants to provide electrical separation between safety and non-safety circuits and systems. Major fault testing in an earlier program indicated that some energy may pass through an isolation device when a fault at the maximum credible potential is applied in the transverse mode to its output terminals. During subsequent field qualification testing of isolators, concerns were raised that the worst case fault, i.e., the Maximum Credible Fault (MCF), may not occur with a fault at the maximum credible potential, but rather at some lower potential. The present test program studies whether problems can arise when fault levels up to the maximum credible potential are applied to the output terminals of an isolator. The fault energy passed through an isolation device during a fault was measured, to determine whether the levels are great enough to potentially damage or degrade performance of equipment on the input (Class 1E) side of the isolator.

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Electronic isolation devices are used in nuclear power plants to provide electrical separation between safety and non-safety circuits and systems. Nuclear plant control and protection systems that rely heavily upon electronic and computerized instrumentation and controls make extensive use of isolation devices to maintain electrical separation. As older plants upgrade and modernize their designs to incorporate more electronics, computerized displays, and digital instrumentation and control systems, the already large population of isolation devices in nuclear plants will continue to increase. Proposed control systems for the next generation of advanced reactors will also depend heavily upon the use of electronic isolators.

With a large existing population of electronic isolation devices in nuclear power plants, most of which are used in PWR reactor protection systems (Ref. 5), and more being added as plants implement the requirement for a Safety Parameter Display System (Refs. 6,7), the US NRC initiated several activities to explore various aspects of the qualification, application, and risk significance of electronic isolation devices (Refs. 4,5,10.)

Major fault qualification testing in an earlier program (Ref.4) found that some energy may pass through an isolation device when a fault at the maximum credible potential is applied in the transverse mode to its output terminals. During subsequent field qualification testing of isolators (Refs. 8,9), concerns were raised that the worst case fault, i.e., the Maximum Credible Fault (MCF), may not occur as a result of a fault at the maximum credible potential but rather at some lower potential.

The present test program determines whether problems can arise when fault levels up to the maximum credible potential are applied to the output terminals of an isolator. The fault energy passed through an isolation device during a fault was measured to find out whether the levels are great enough to potentially damage or degrade performance of equipment on the input (Class 1E) side of the isolator.

A total of twelve models of isolation devices, representative of the major types found in nuclear power plants, were subjected to incremental fault testing. A series of faults, was applied in increasing increments of 10% of the maximum credible potential, from 10% up to 110% of the maximum credible potential, directly to the signal output terminals. Some of the major findings of this testing are:

- All of the devices tested demonstrated their ability to withstand and isolate a series of incremental faults without transferring significant quantities of energy across the isolation barrier to the input side.
- Peak 1/2 cycle reach-through energy measured at the input terminals of the isolation devices during fault application testing did not always occur at the level defined as the MCF potential. However, the magnitudes of the reach-through energies measured even at their peak were very small (less than 350 microjoules) and considered insignificant.
- Ten of the twelve models of isolators that were tested failed electronically, i.e., functionally lost the capability to transmit signals from input to output (their normal operating configuration), during the incremental fault testing process.

- Three of the five multiple channel isolators tested failed electronically in all of their channels even though only one of the channels was subjected to the incremental applied fault testing process. The cause attributed to these failures was the loss of a common power supply on the output side used to power all of the isolator channels on a device.

Based on the results of this testing program, the worst case, or maximum credible, fault in regard to the reach-through energy, did not always occur when a fault at the maximum credible potential was applied. The qualification of electronic isolators for a major fault by testing only at the maximum credible potential level is therefore not adequate if the intention is to assure that the isolators are qualified for worst case, credible fault conditions. In the future, the major fault qualification test should be expanded to test at several levels up to and including the maximum credible potential to ensure that a worst case condition is not missed.

It should be noted that the reach-through energies measured during this testing program were considered insignificant, even in the worst case faults. Previous qualification tests for the twelve isolator models in this test program were adequate to demonstrate their acceptability as isolators even though all mechanisms were not explored. Consequently, expanded qualification testing for isolators already installed in nuclear plants is not considered necessary.

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Jack Semon	Westinghouse Electric Corp.
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William Howell	Westinghouse Electric Corp.
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1. INTRODUCTION

The "Adequacy of Electrical Isolation Device Acceptance Criteria" Program was funded by the U.S. Nuclear Regulatory Commission through FIN L-2158. The purpose of this program was to develop and implement an electrical isolation device major fault testing program that explores the effects of fault voltage and current levels of lesser magnitude than used in previous maximum credible potential testing. The results of this testing program, together with previous major fault testing, will determine whether a revision to the current NRC acceptance criteria is required.

Electrical isolation devices are used to maintain electrical separation between safety (Class 1E) and non-safety related circuits and systems in nuclear power plants. Isolation devices are required wherever signals from nuclear safety protection systems are transmitted to non-safety related controls or display systems. Their purpose is to ensure that any credible fault or transient occurring on the non-Class 1E side will not degrade the circuits connected to the device Class 1E or associated side below an acceptable level (Ref.1).

The criteria for qualification of electrical isolation devices to be used in nuclear power plants are mandated by the U.S. Code of Federal Regulations 10 CFR 50, Section 50.55a, paragraph (h) for protection systems (Ref. 2), which states:

> "For construction permits issued after January 1, 1971, protection systems shall meet the requirements set forth in editions or revisions of the Institute of Electrical and Electronics Engineers Standard: "Criteria for Protection Systems for Nuclear Generating Stations," (IEEE-279) in effect on the formal docket date of the application for a construction permit. Protection systems may meet the requirements set forth in subsequent editions or revisions of IEEE-279 which become effective."

Section 4.7.2 of IEEE Standard 279-1971 (Ref. 3) entitled Isolation Devices states:

> "The transmission of signals from protection system equipment for control system use shall be through isolation devices which shall be classified as part of the protection system and shall meet all the requirements of this document. No credible failure at the output of an isolation device shall prevent the associated protection system from meeting the minimum performance requirements specified in the design bases.
>
> "Examples of credible failures include short circuits, open circuits, grounds, and application of the maximum credible ac or dc potential. A failure in an isolation device is evaluated in the same manner as a failure of other equipment in the protection system."

Issues related to the adequacy of isolation devices acceptance criteria and performance of isolators in nuclear plants have been studied by the U.S. Nuclear Regulatory Commission for over a decade. Earlier major fault testing performed as part of the NRC's Isolation Devices Evaluation Criteria Program, and reported by Neilsen in NUREG/CR-3453 (Ref. 4), indicated that electronic isolation devices may experience severe damage and may pass some energy across the isolation barrier when subjected to faults at the maximum credible AC or DC voltage and current levels applied to the output side of the energized device. During subsequent field qualification testing, concerns were raised that similar or more severe problems might be realized at fault voltages and currents less than maximum credible levels (Ref. 5). Specifically, the worst case fault condition may not occur as the result of a fault at the maximum credible potential, but rather at some lower potential. The actual "reach-through" energy, passed across the isolation device during a fault condition, expressed by $\int V(t)*I(t)dt$, even while not attaining maximum credible voltage potentials, might still be large enough to inflict damage on sensitive electronic components. The maximum credible fault (MCF) for a given isolation device and application may thus be defined as that fault potential and waveform at which the maximum reach-through energy is passed across the isolation barrier.

The objective of this testing program is to determine whether the worst case fault, in regard to the reach-through energy, occurs when a high speed fault is applied to an isolator's output terminals at the maximum credible potential of 120 Vac, 60 Hz, or rather at some lower potential. Isolation barrier characteristics such as resistance and capacitance, and isolator function are monitored during the testing for significant changes or trends. Resources were not available to expand the testing to explore the effects of higher fault potentials, inter-channel reach-through energy (multiple channel isolators), sustained applied faults, nor a range of fault frequencies.

A review of the applicable standards, regulatory guides, previous testing work, and nuclear industry operating experience with isolation devices was performed to identify the problem areas and develop a testing program to address the concerns associated with major fault qualification testing. A group of isolators representative of the types and models found in nuclear plants was purchased and tested in accordance with the detailed test procedures developed.

The test report is organized into five major sections plus a references section and appendices. Section 1 is an introduction describing the purpose and objectives for the testing program, some of the regulatory background concerning isolation devices, and an outline of the report organization. Section 2 provides a brief description of the major types of electronic isolation devices, their basic operating principles, their application in nuclear plants, and the background of the concerns in the area of maximum credible fault testing. The details of the major fault testing program are presented in Section 3. The discussion includes the test objectives, relation to previous isolation device testing, test procedures, test equipment, and conduct of the test. The results of the testing are presented in Section 4 along with an analysis of the data. Recommendations and conclusions based upon the findings of the testing program are given in the 5th Section. A glossary of terms and phrases that are used throughout this report is provided at the end of the report. Appendix A is the test plan for the work, Appendix B contains the details of the test setup, Appendix C contains copies of the test equipment certifications for the measuring equipment used in the test program and Appendix D presents the test data in graphical form.

2. ELECTRONIC ISOLATION DEVICES

This section provides a brief description of the major types of electronic isolation devices used in nuclear power plants to provide signal isolation between Class 1E sensors, instrumentation and controls and non-Class 1E instrumentation, controls, and displays. The basic operation of each type is described. Some of the applications in which electronic isolators are utilized in nuclear plants is covered along with some of the major problem areas that have been encountered as revealed in the operating experience records. The origins of the concerns about maximum credible fault tests and faults at less than maximum credible potential are covered.

2.1 Descriptions of Electronic Isolators

There are two basic methods of electronic signal isolation commonly found in the isolation devices used in nuclear power plants: magnetically-coupled isolation and optically-coupled isolation. In the first method, input signals into the device are conditioned and modulated, passed through a transformer that serves as the isolating barrier, and then demodulated, filtered, and conditioned before being sent out of the device. In the latter method, the input signal is conditioned or converted to a digital signal, which in turn is converted to an optical signal. This optical signal is passed across an optical isolation barrier to an optical receiver, where it is conditioned for output from the device.

The basic components of a typical magnetically-coupled (transformer-coupled) electronic isolator are shown in Figure 2.1. The isolator may be either an analog device or a digital device depending upon the nature of the input and output signals which it is designed to handle.

The analog isolation device will be used in applications where the input signal is either an analog voltage signal or an analog current signal as would be found in an instrumentation loop. Digital isolation devices are used to isolate computer systems that are communicating via digital signals, or to accept and isolate the signals supplied from digital sensors. Typical voltage or current input and output ranges for analog and digital isolators encountered during research for this test program are listed in Table 2.1.

Upon entering the input terminals of an analog isolation device, the analog input signal will be conditioned, filtered, and amplified. The signal is then modulated and passed through a transformer which serves as the electrical isolation barrier, the signal being transferred via magnetic-coupling. The output signal is demodulated, filtered, and conditioned for output from the isolation device.

The power supplied to the isolation device to drive the active electronic subcomponents is usually a non-Class 1E source. It is therefore isolated from the input signal by an isolating transformer as well, as shown in Figure 2.1. Some of the typical power supply voltages levels found during this research are listed in Table 2.1.

The basic components of an optically-coupled electronic isolator are shown in Figure 2.2. The optical isolator is normally a digital signal device in which the electrical isolation is achieved by the conversion of the electrical signal into an optical signal that is transmitted through an optical dielectric medium. This optical link serves as the isolating barrier in this type of device. It may consist of: a phototransmitter and optical receiver back-to-back on a single optoisolator integrated circuit; a phototransmitter and

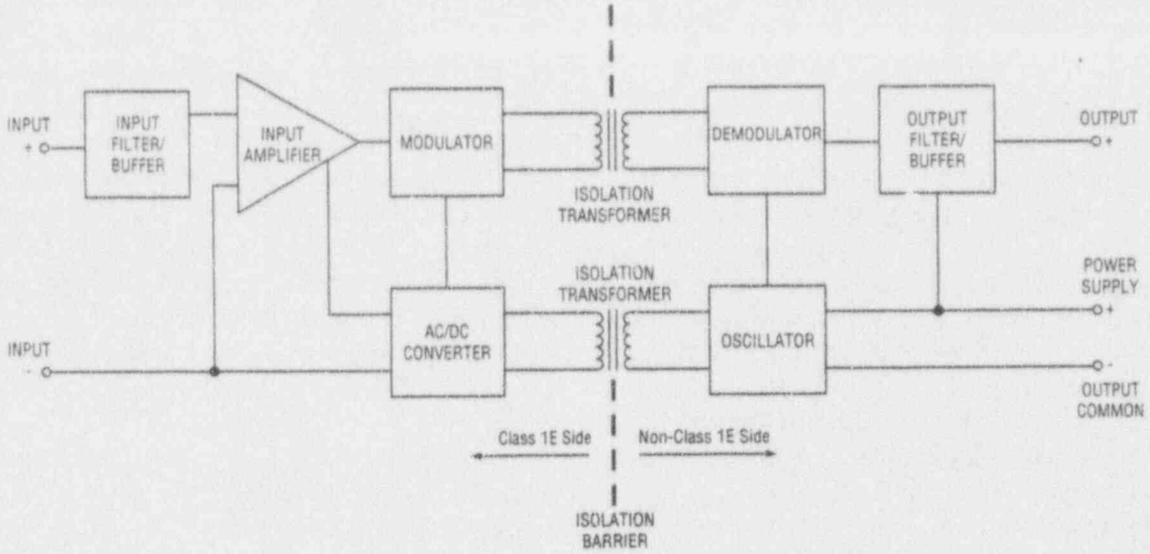

Figure 2.1 Block diagram of transformer-coupled isolator

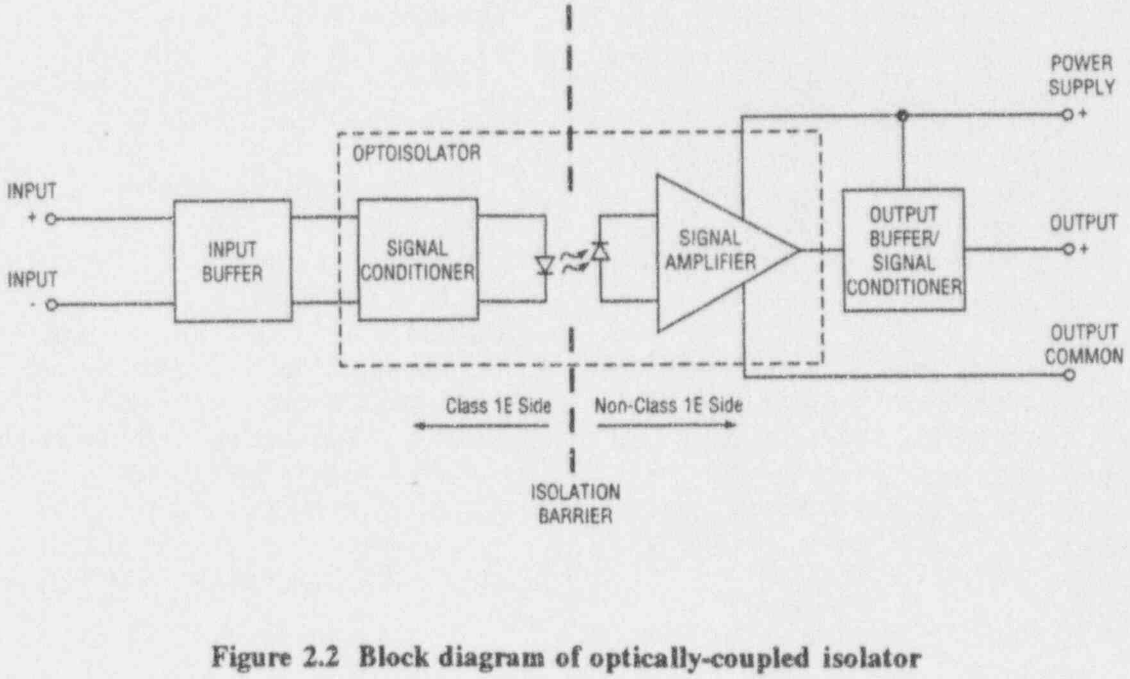

Figure 2.2 Block diagram of optically-coupled isolator

Table 2.1 Typical Isolation Device Power Source and Signal Input and Output Ranges

ANALOG ISOLATORS		
Signal Input Ranges	**Signal Output Ranges**	**Power Sources**
0 to 100 mVdc 0 to 51 mVdc 0 to 1 Vdc 0.25 to 1.25 Vdc 0 to 5 Vdc 1 to 5 Vdc 0 to 8 Vdc 0 to 10 Vdc 1 to 10 Vdc 2 to 10 Vdc -2 to +2 Vdc -5 to +5 Vdc -10 to +10 Vdc 0 to 20 Vdc 40 to 200 Vdc 0 to 120 Vac	0 to 180 mVdc 0 to 100 mVdc 0 to 48 Vdc 0 to 51 Vdc 0 to 1 Vdc 0 to 5 Vdc 1 to 5 Vdc 0 to 10 Vdc 1 to 10 Vdc 32 to 160 mVdc 0 to 3.5 Vac	115 Vac, 60 Hz 117 Vac, 60 Hz 120 Vac, 60 Hz 230 Vac, 60 Hz 5 Vdc 12 Vdc 15 Vdc ±15 Vdc 24 Vdc 25 Vdc 26 Vdc 48 Vdc
4 to 20 mAdc 10 to 50 mAdc 0 to 50 mAdc 0 to 1 mAdc 1 to 5 mAdc 0 to 20 mAdc	4 to 20 mAdc 10 to 50 mAdc 0 to 50 mAdc 0 to 1 mAdc 0 to 20 mAdc	
DIGITAL ISOLATORS		
0 to 51 mVdc 0 to 1 Vdc 0 to 5 Vdc 0 to 10 Vdc 0 to 48 Vdc 0 to 125 Vdc 0 to 120 Vac 4 to 20 mAdc 10 to 50 mAdc	0 to 51 mVdc 0 to ±5 Vdc 1 to 5 Vdc 0 to 10 Vdc 0 to 15 Vdc 0 to ±48 Vdc 0 to ±28 Vdc 5 to 100 Vdc 32 to 160 mVdc 32 to 160 mAdc	5 Vdc 15 Vdc ±15 Vdc 24 Vdc 48 Vdc

receiver connected by a short, optically conducting, quartz rod or some other type of fiber optic link on the same circuit board; or a fiber optic link ranging anywhere from a fraction of an inch to hundreds of feet.

The digital input signals to an optically coupled isolator are first buffered and conditioned upon entering the device, shown in Figure 2.2. If the input signal is analog, then it is converted to an equivalent electrical digital signal. The digital signals are converted to optical digital pulses for transmission through the optical coupler. As mentioned previously, the optical link may be a phototransmitter and receiver back-to-back, or separated by some distance, and in communication through an optical transmission medium. On the output side, the optical digital pulses are converted back to electrical digital signals, amplified, and conditioned prior to being sent out of the isolator. If the output is to be an analog signal, circuitry is provided on the output side of the optical coupling to convert the digital signals back to analog as required.

2.2 Background of the Maximum Credible Fault Concerns

Electronic isolation devices are used in nuclear power plants to maintain electrical separation between safety related and non-safety related systems. They provide electrical isolation of Class 1E electrical circuits and instrumentation from non-Class 1E circuits and equipment.

Isolators are used most extensively in Westinghouse and Combustion Engineering PWRs due to the design philosophy and the nature of the instrumentation and controls designs for the safety systems in these plants (Ref.5). Electronic process control systems are used extensively in the designs of these plants. Among the systems in PWR plants that utilize isolation devices are:

- Reactor Protection (RPS)
- Engineered Safety Features Actuation (ESFAS)
- Reactor Coolant (RCS)
- Main Steam
- Main Feedwater
- Chemical and Volume Control (CVCS)
- Residual Heat Removal/Low Pressure Safety Injection
- Auxiliary (Emergency) Feedwater (AFW)

Electronic isolators are also used in BWR designs, but to a more limited extent than in PWRs. In the BWR, the design approach applied to the control, logic, and instrumentation circuits for the reactor protection system, emergency core cooling system actuation, containment isolation system, and other safety systems relies more heavily on electromechanical relays with redundant hard wired circuits. The electromechanical relay itself then serves as a type of isolation device. Among the systems in BWR plants that sometimes utilize electronic isolation devices are:

- Reactor Protection (RPS)
- Reactor Recirculation
- Reactor Core Isolation Cooling (RCIC)
- Residual Heat Removal/Low Pressure Coolant Injection (LPCI)
- Feedwater
- Control Rod Drive (CRD)
- Nuclear Steam Supply Shutoff (NSSS)

Following the accident at Three Mile Island Unit 2, the NRC developed the TMI Action Plan NUREG-0660 (Ref. 6) and clarification NUREG-0737 (Ref. 7). Among its requirements, the TMI Action Plan included the implementation of a Safety Parameter Display System (SPDS) Console. To comply, each nuclear plant applicant and licensee was required to install an SPDS that could display to operating personnel in the control room, and to personnel in the Technical Support Center (TSC) and Emergency Operations Facility (EOF), a minimum set of parameters that define the safety status of the plant. Implementation in nuclear plants of the non-Class 1E SPDS in most designs necessitated the use of a number of electronic isolators to allow tapping into Class 1E instrumentation and controls loops in order to drive SPDS displays without compromising the integrity of the plant safety systems. This requirement significantly increased the number of electronic isolators found in all nuclear power plants.

During the testing and review of electronic isolation devices for use in SPDS systems, NRC raised concerns that isolation devices, when subjected to fault voltages or currents less than the maximum credible fault levels, may pass potentially significant levels of energy, but the same devices performed acceptably at the maximum credible fault level (Refs. 5,8,9).

As a result of the aforementioned observations made during SPDS evaluation tests, the problem was formally identified as Generic Safety Issue 142, Leakage Through Electrical Isolators in Instrumentation Circuits, in June 1987 (Ref. 10):

> "Recent observations have shown instances in which isolation devices subjected to failure voltages and/or currents less than maximum credible fault levels passed significant levels of voltage and current, but the same devices performed acceptably at maximum credible levels. The safety system on the Class 1E side of the isolation device may be affected by the passage of small levels of electrical energy, depending upon the design and function of the safety system."
>
> "In the event that safety systems are affected by less than maximum credible faults on the non-Class 1E side of isolators, the effects can range from degradation to failure of single or multiple trains of safety systems resulting in failure on demand or inadvertent operation. In one reported incident, a voltage transient induced by a power line fault caused a false indication that the turbine-generator output breaker had tripped, resulting in a reactor scram."

The present testing program was initiated to investigate the hypothesis that energy may leak across, or reach through, the isolation barrier in an electronic isolation device at fault levels less than the maximum credible fault. By measuring and quantifying the extent of the leakage problem, an assessment can then be made of the potential damage that could occur to various types of electronic and electrical devices that are used on the Class 1E side of isolation devices.

2.3 Electronic Isolation Devices Tested

NPRDS searches and sorts of reported failures that involved isolation devices were used to develop lists of isolation device model numbers that were considered as candidates for this testing program. This search provided information on the relative populations of the various isolators, and the types and model numbers that were in service in nuclear power plants. In addition, the isolators that were tested previously under NUREG/CR-3453 (Ref. 4), were given strong consideration, particularly those that were found to pass energy across the isolation barrier during the testing reported by Neilsen. Information obtained during discussions with manufacturers of electronic isolators and with nuclear plant personnel also contributed to the selection process.

Based upon the data and information gathered, a representative group of twelve isolators was established for testing. The final selection of isolators was based upon frequency of appearance in NPRDS reports, models specified by NRC, procurement availability, technical information availability, budget constraints, and schedule constraints.

One or more models of isolators manufactured by the following vendors were subjected to testing in this program. The models tested are identical to units used in nuclear power plants, and they present a representative sample of the major types of isolators. After BNL had completed its testing, Devar indicated that a nuclear service version of their isolators was available that included zener diodes and a fuse at the output to limit fault damage. This version of the Devar isolator was not tested by BNL. The Validyne isolators and their supporting equipment were obtained from a nuclear power plant where they had seen eight years of service as part of the isolation system interfacing with the plant's emergency response facilities. All the other equipment was purchased new.

Devar
Halliburton NUS
Foxboro
Rochester Instruments
Technology for Energy
Transmation
Validyne
Westinghouse Electric Corp.

The basic operating specifications for the isolation devices tested under this program are given in Table 2.2. The group tested included both magnetically and optically coupled isolators, and both analog and digital types. As indicated in the table, five units were multiple-channel devices.

2.3.1 Magnetically Coupled Isolators

The magnetically coupled isolators that were tested included three current-to-current analog isolators, five voltage-to-voltage analog isolators, and one digital isolator. These units are described briefly in this section.

Two of the current-to-current analog isolators tested, one manufactured by Transmation, Inc. and the other by Halliburton NUS Corp. are shown in Figure 2.3 (with and without the protective barrier covering the terminations). Both units are completely enclosed in metal cases with mounting provisions to allow installation in control panels throughout a plant.

Internally, the Transmation isolation transmitter consists of three individual circuit boards: the power supply board, the transmitter/signal conditioner board and the isolator board, each handling a major subfunction of the device. The Transmation isolators tested in this program were current-to-current units, which are identical to the voltage-to-voltage versions of the device also available, with the exception of factory installed resistors at the device input to adjust the voltage levels (Ref. 11, 12).

The Halliburton NUS isolation amplifier tested was a four-channel, encapsulated, surface-mount isolation device taking 4-20ma analog input signals and providing a 4-20ma output signal. This isolator is available in voltage-to-voltage configurations at a variety of input and output levels, and single, dual, or three channel versions are also available using the same operating principle. The major components are a I/O signal conditioning circuit board and a power supply circuit board, that are embedded in a potting matrix for seismic protection. The individual channel outputs and the power supply are protected by fuses accessible from the face of the unit as shown in Figure 2.4, and surge protection is provided on the power input and the signal inputs and outputs (Ref. 13).

Table 2.2 Electronic Isolators Tested

Isolator ID No.	Type of Isolation	Physical Configuration	No. of Channels	Signal Type	Signal Range		Power Supply	Used in		Freq of Occurrence in NPRDS Reports	Tested in NUREG/CR-3453
					Input	Output		BWR	PWR		
@DA-3-1	Magnetic Coupling	Enclsd Metal Case	One	Analog	1-5vdc	1-5vdc	120vac, 60Hz	x	x	L	
FA-3-1A/B	Magnetic Coupling	Circuit Card	Two	Analog	1-10vdc	1-10vdc	+/-15vdc	x	x	H	x
#RA-3-2	Magnetic Coupling	Enclsd Metal Case	One	Analog	1-5vdc	1-5vdc	115vac,60Hz,5W	x	x	L	x
*HNA-3-1A/D	Magnetic Coupling	Circuit Card	Four	Analog	0-5vdc	0-5vdc	+/-15vdc	x	x	None	x
VD-3-1	Magnetic Coupling	Potted, Metal Case	One	Digital	0-5vdc	0-2mvdc	5vac, 3KHz	x		None	x
WA-3-1	Magnetic Coupling	Circuit Card	One	Analog	0-10vdc	0-10vdc	26vdc		x	H	x
@#DA-2-3	Magnetic Coupling	Enclsd Metal Case	One	Analog	4-20ma	4-20ma	120vac, 60Hz	x	x	L	x
+HNA-2-1A/D	Magnetic Coupling	Potted, Metal Case	Four	Analog	4-20ma	4-20ma	117vac, 60Hz	x	x	None	
TRA-2-2	Magnetic Coupling	Enclsd Metal Case	One	Analog	4-20ma	4-20ma	120vac,60Hz,5W	x	x	M	&x
#*HND-4-2A/H	Optical Coupling	Circuit Card	Eight	Digital	0-120vac	0-48vdc	48vdc	x	x	None	x
TD-4-1	Optical Coupling	Sealed, Metal case	One	Digital	1-5vdc	1-5vdc	24vdc	x	x	None	x
TD-4-3A/D	Optical Coupling	Circuit Card	Four	Digital	1-5vdc	1-5vdc	15vdc	x	x	None	

@ Similar to nuclear service unit but w/o output diodes and fuse

Passed energy during testing for NUREG/CR-3453

* Isolator model similar to those used at Palo Verde

+ Four channel version of isolator requested for testing by NRC

& Model tested replaces earlier model tested for NUREG/CR-3453

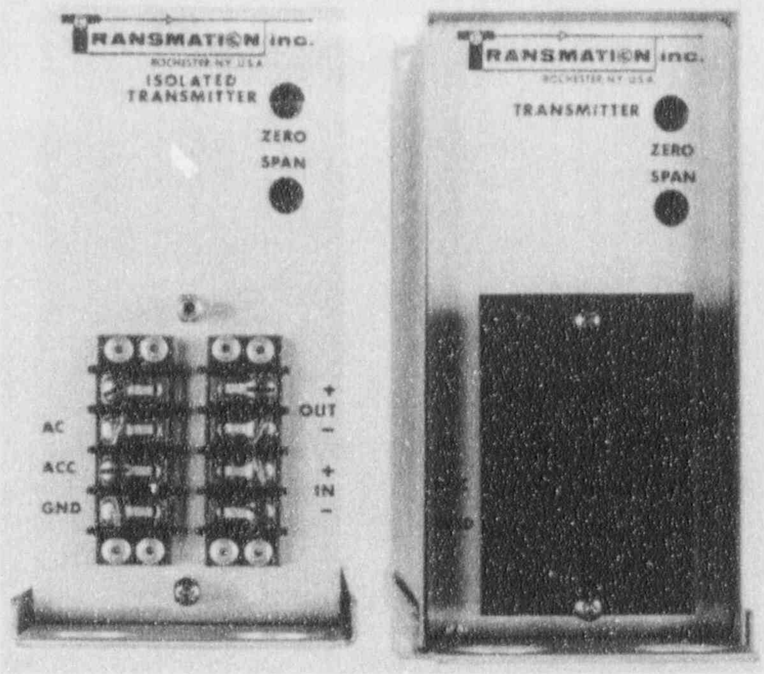

Figure 2.3 Transmation isolation transmitter

Figure 2.4 Halliburton NUS isolation amplifier

The third current-to-current analog isolator tested, manufactured by Devar, is shown in Figure 2.5. It is discussed later in this section along with the voltage-to-voltage version of this unit.

The voltage-to-voltage, magnetically coupled isolators tested included devices from Devar, Rochester Instruments, Foxboro, Halliburton NUS, Westinghouse, and Validyne. The Devar isolated transmitter, similar to the device pictured in Figure 2.5, and the Rochester Instruments isolated transmitter, shown in Figure 2.6 are both enclosed, single channel, surface mount units similar to the Transmation isolator discussed above. Both of these units are available in current-to-current configurations with the addition of selected input and output resistors.

Externally, the voltage-to-voltage and current-to-current (Figure 2.5) Devar isolators both appear to be physically identical. However, internal inspection reveals the selected calibrating resistors and jumpers required to convert the isolator from voltage to current output. These can be seen at the back of the circuit board (Ref. 14). As mentioned in Section 2.3, Devar also offers these units in a nuclear service version, with zener diodes and a fuse at the output to limit fault damage. This version of the isolator was not tested.

Similarly, the Rochester Instruments current-to-current isolator and the voltage-to-voltage isolator (left and right, respectively, in Figure 2.6) are identical in appearance externally. The minor differences can be seen on the circuit boards, where the voltage-to-voltage unit has modified values on some of the resistors and an additional shunt resistor at the output (Ref. 15).

The Westinghouse and Foxboro isolators are both open circuit card configured isolators with edge connectors designed for use as part of a large electronic process control system. In the case of the Westinghouse isolator, it is mounted in a card rack in the Westinghouse 7300 Series or 7100 Series Control Systems. Known as the Isolator and Loop Power Supply Card, or NLP Card, it provides an isolated, 0 to 10 Vdc signal output proportional to a 0 to 10 Vdc differential input signal. The normal primary power requirement for the card is 26 Vdc ±1 V (Ref. 16,17).

The Westinghouse Isolator and Loop Power Supply Card is shown in Figure 2.7. The 42-pin edge connector can be seen at the right in the figure. At the left in the figure are a red LED status indicator and various input and output signal test points as labeled. These are visible and accessible from the front of the 7300 or 7100 Series Control System equipment racks to facilitate maintenance testing and monitoring when the card is installed (Ref. 16,17).

The Foxboro dual output converter is a dual channel, rack mounted device designed for use in Foxboro's SPEC 200 control system. The standard version of this isolator converts inputs with spans from 2.5 to 10 Vdc within the limits of 0 and 10 V to proportional 4 to 20 mAdc output signals. The output is transformer isolated from the input. Decreasing output for increasing input is achieved by reversing input leads. Output is normally powered from an internal isolated 24 Vdc source. The units tested were modified by the factory to function as an isolated voltage-to-voltage converter (Ref. 18,19).

The Foxboro isolators are shown in Figure 2.8 in a frontal view (right) and from the side (left) revealing the face of the circuit board. The isolator slides into the SPEC 200 nest assembly and is held by two captive screws at the top and bottom. A power bus plug for field testing the unit is seen at the bottom of the left isolator in Figure 2.8. When installed the isolator receives its power at this point from the supply bus in the nest

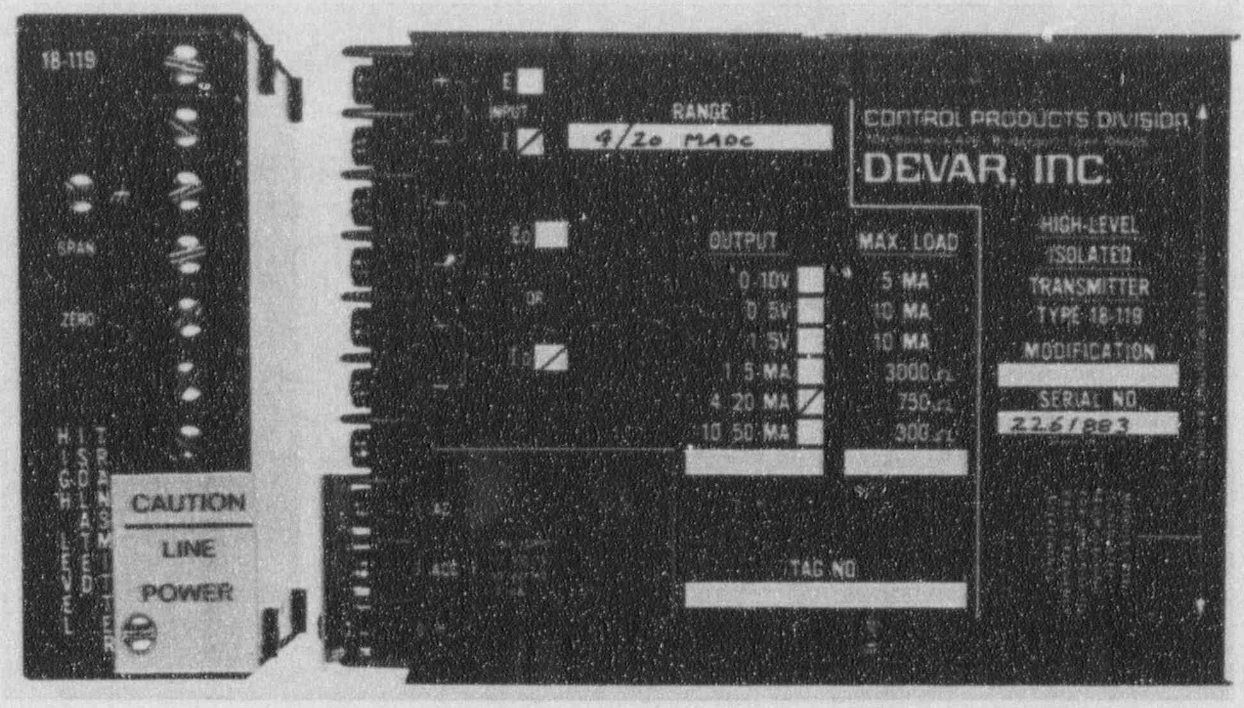

Figure 2.5 Devar isolated transmitter

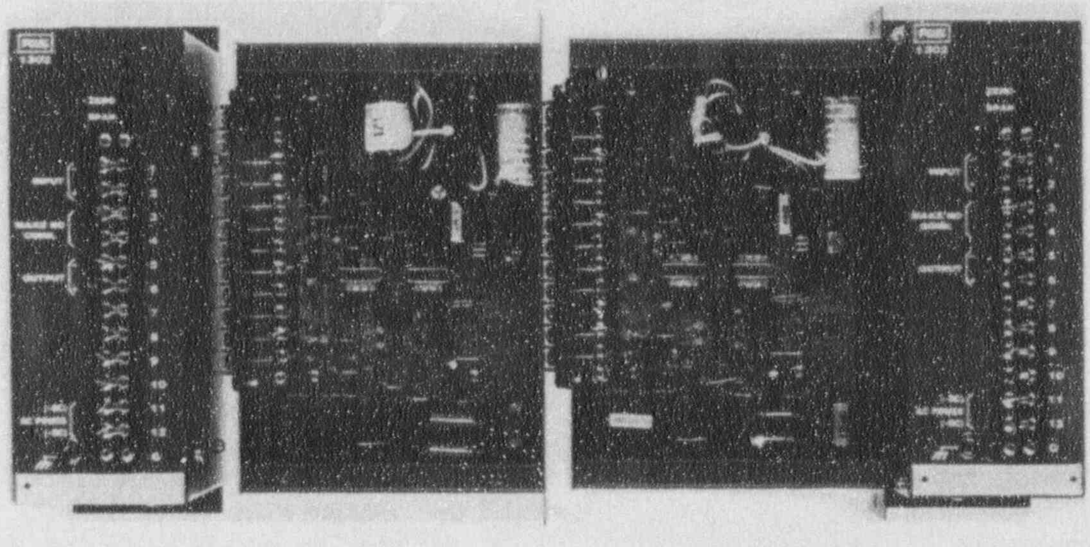

Figure 2.6 Rochester Instruments isolated transmitters-front view and circuit board: I-to-I isolator (left) and V-to-V isolator (right)

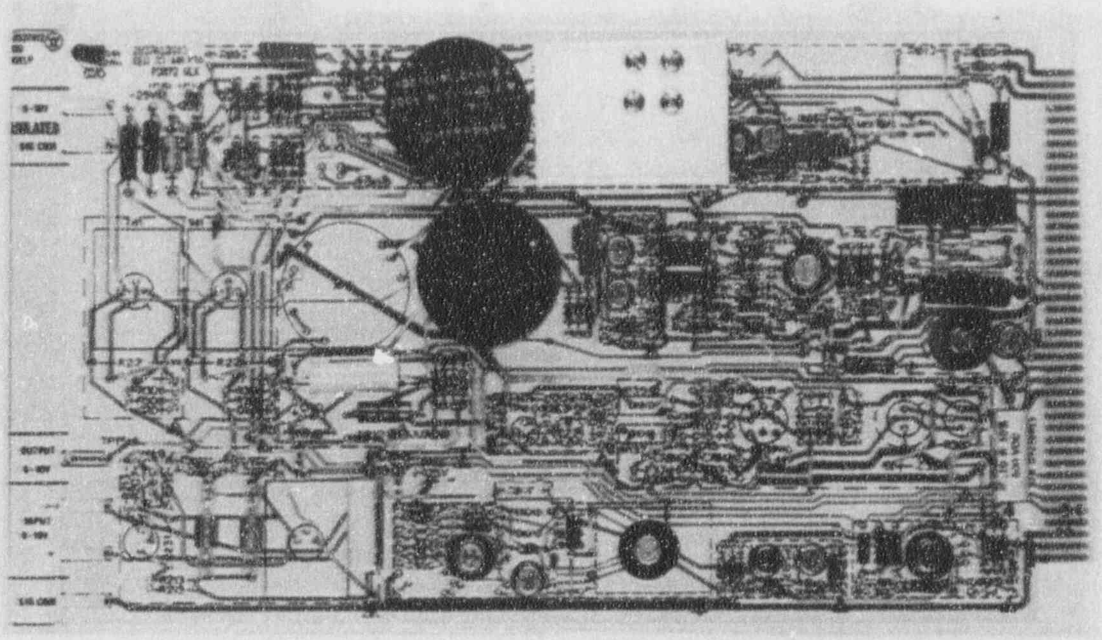

Figure 2.7 Westinghouse isolator and loop power supply (NLP) card

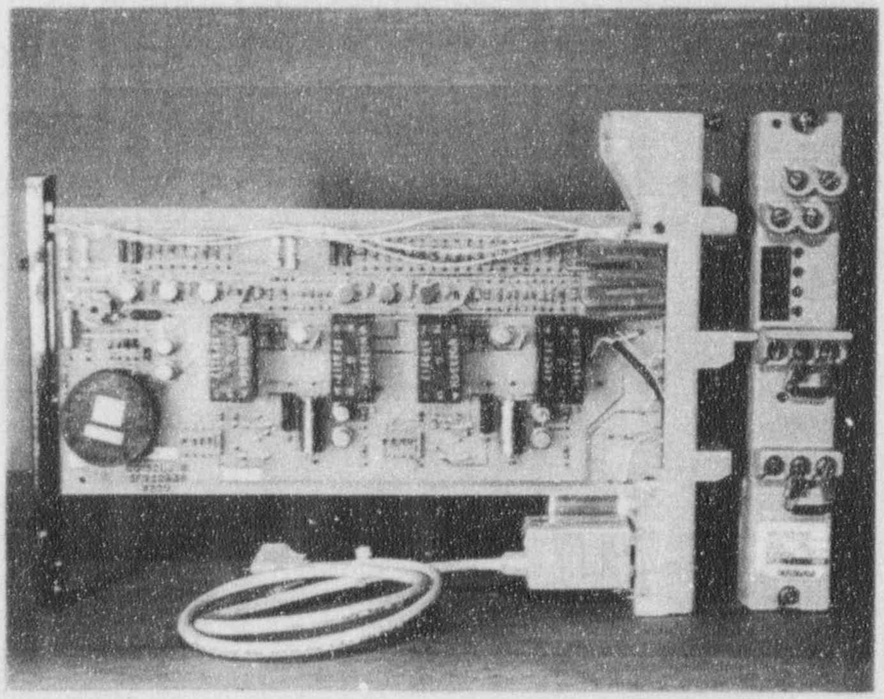

Figure 2.8 Foxboro isolators

assembly. The signal connections and calibration adjustments are accessible on the front plate of the device when it is installed (Ref. 19,20).

The Halliburton NUS analog isolator card, formerly built by Energy Incorporated (EI), is a four-channel analog isolation device with an open circuit card configuration, as shown in Figure 2.9. Isolation between the input and the output on the circuit board is provided by physical separation of the input and output circuits and a hybrid-circuit, transformer coupled isolation amplifier made by Burr-Brown. Input and output signals, and power sources are connected to the card through a 2x22-pin edge connector shown at the left (rear) in the figure. Calibration adjustment pots for each channel are accessible from the front (upper right in the figure) when the isolator card is installed in an isolator circuit card rack as part of a system. In addition, output signals from each channel are brought out to test points which are accessible from the front (lower right in the figure) to facilitate calibration and maintenance testing (Ref. 21).

The Validyne Engineering Corp. isolator, or Remote Carrier Modulator, is used to convert a DC or low frequency AC input to a High-Gain Carrier Demodulator card. It is designed for remote location at the signal source and derives its operating power from the 3kHz carrier excitation supply of the Carrier Demodulator. The Remote Carrier Modulator provides isolation to protect the signal conditioning system from damage and its low output impedance allows it to be operated with long signal cables. In the configuration tested in this program, the Remote Carrier Modulator served as a voltage-to-voltage digital signal isolator (Ref. 22).

The High-Gain Carrier Demodulator Plug-In Module is used to excite, amplify, and demodulate the output of the Remote Carrier Modulator signal isolator units. The Carrier Demodulator Plug-In Module is a circuit card device located in the Remote Multiplexer Module/ Case (or Module Case). The Module Case provides plug-in capability for up to 25 signal conditioning modules plus a Power Supply Module and supplies the necessary dc operating voltages and 3 kHz carrier for the modules and their associated transducers. The Module Case serves as the center of an isolation system with its capability to convert analog dc signals received from signal conditioning modules and directly from external sources, into serial digital data for transmission to a remote Master Receiver via a fiber optic link. It contains a built-in multiplexer that can sequentially sample up to 32 inputs for subsequent data transmission (Ref. 23,24).

The various components of the Validyne isolator and support equipment are shown set up in the BNL isolator test bed in Figure 2.10. The Module Case is the large electronic circuit card rack in the center of the photograph. The Power Supply Module is the plug-in unit at the right end of the card rack. The multiplexed circuitry and associated analog and digital electronics are enclosed in the upper part of the Module Case above the open circuit card racks. Signal connections are made at the rear of the unit via plug connectors or terminal blocks; power is provided through edge connectors to a power bus in the circuit card plug-in slots. The High-Gain Carrier Demodulator Plug-In Module undergoing fault testing is shown mounted in plug-in slot #1 at the left end of the card rack. Test points and calibration adjustments for the Carrier Demodulator are brought out to the end plate of the plug-in module so they are accessible while the unit is installed in the Module Case. The Remote Carrier Modulator signal isolator unit under test (labeled ERF B) is seen sitting upright on top of the Module Case.

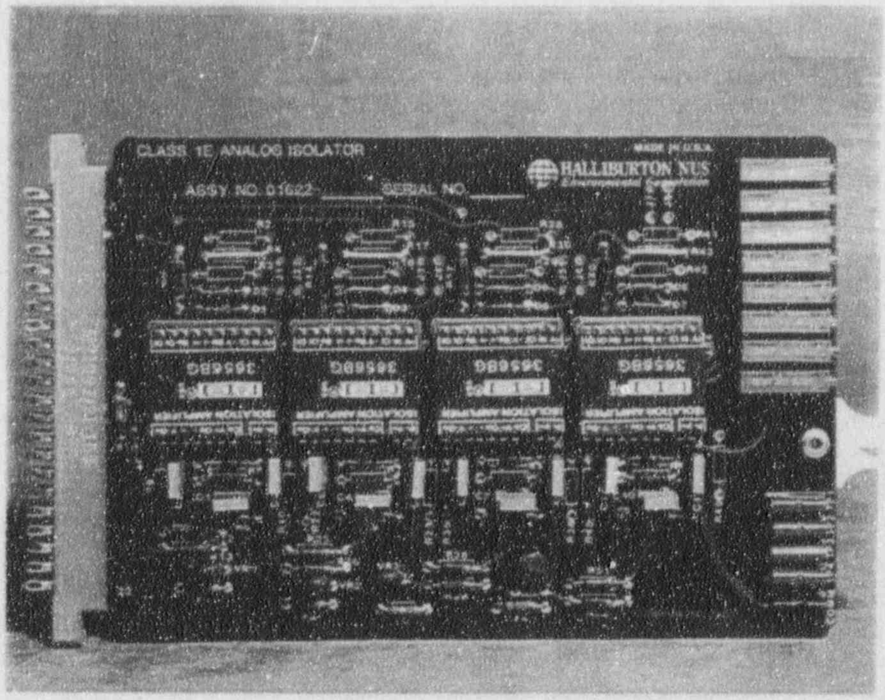

Figure 2.9 Halliburton NUS voltage-to-voltage isolation amplifier

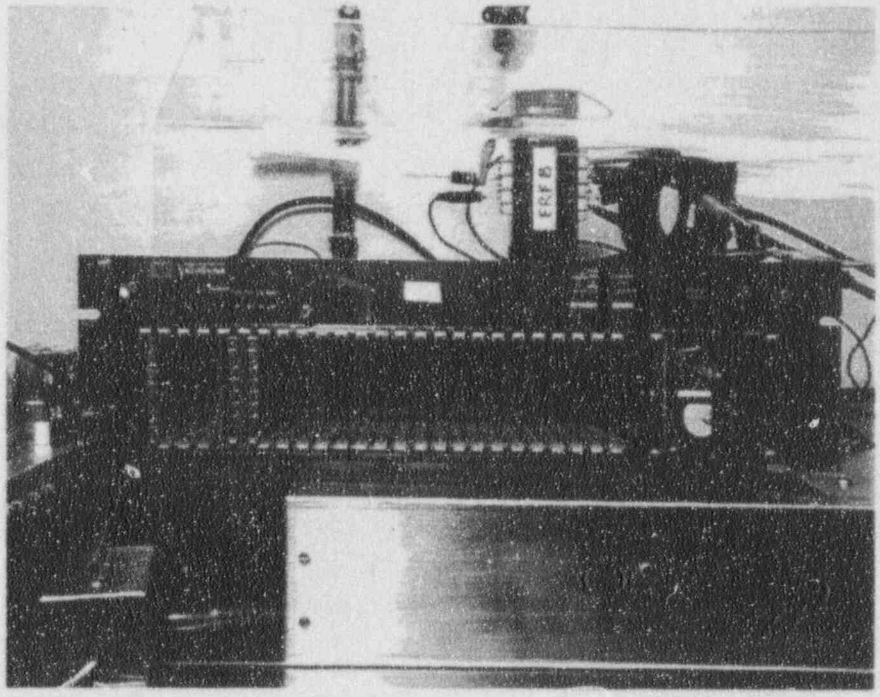

Figure 2.10 Validyne isolator and support equipment shown undergoing fault testing in the BNL isolator test bed

2.3.2 Optically Coupled Isolators

The optically coupled isolators which were tested included three digital isolators: two from the Technology for Energy Corp. and one Halliburton NUS unit. These isolation devices are described briefly in this section.

The Technology for Energy isolation device tested is an encapsulated, single channel digital isolator as shown in Figure 2.11. The sealed case is flanged to allow surface mounting, and the input signal connections and the output signal and power connections are made to terminal strips on opposite sides of the unit. The digital voltage signal is coupled through an optical isolator to assure positive isolation with the unit powered or unpowered (Ref. 25).

The other two optically coupled isolators are both multiple channel digital isolation devices utilizing an open circuit card configuration. The devices, one from the Technology for Energy Corp. and the other from Halliburton NUS, are designed to be plugged into slots in electronic circuit card racks used in isolation systems manufactured by these companies.

The Technology for Energy optically coupled isolator, shown in Figure 2.12, is a four-channel digital isolation module which plugs into Technology for Energy's Isolation Module Bin. As shown in the figure, all input signal, output signal, power and test connections are made to the Isolation Module Bin via the 3x36-pin plug connector at the rear of the circuit board (right in the figure). Two optical couplers are used in each channel

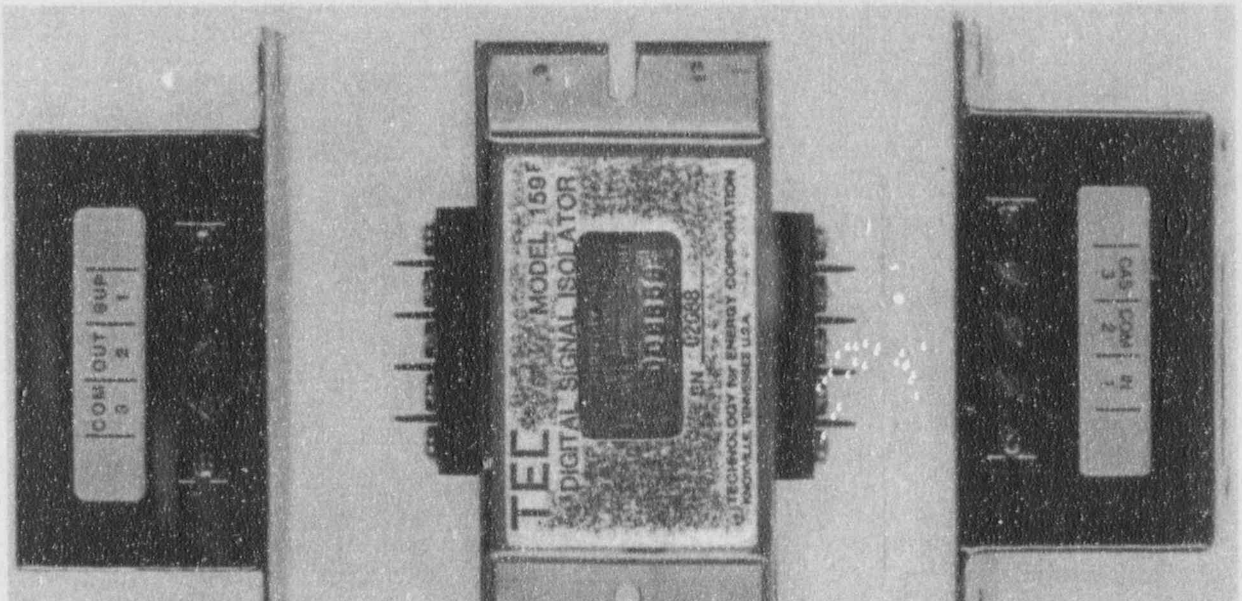

Figure 2.11 Technology for Energy single channel encapsulated digital signal isolator

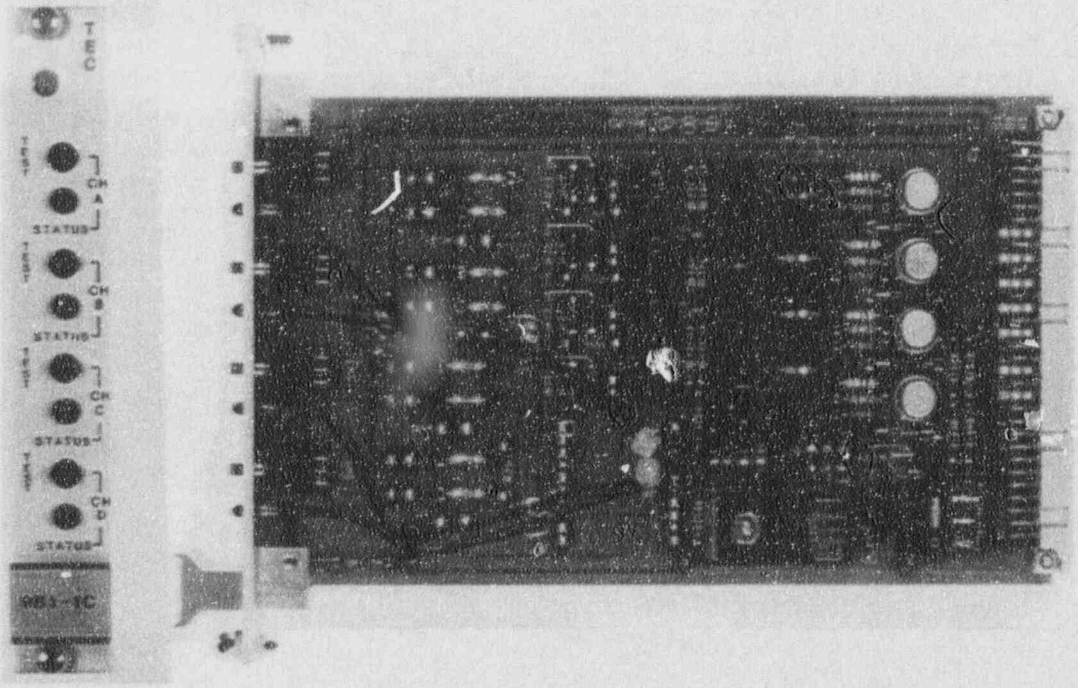

Figure 2.12 Technology for Energy four-channel digital isolation module

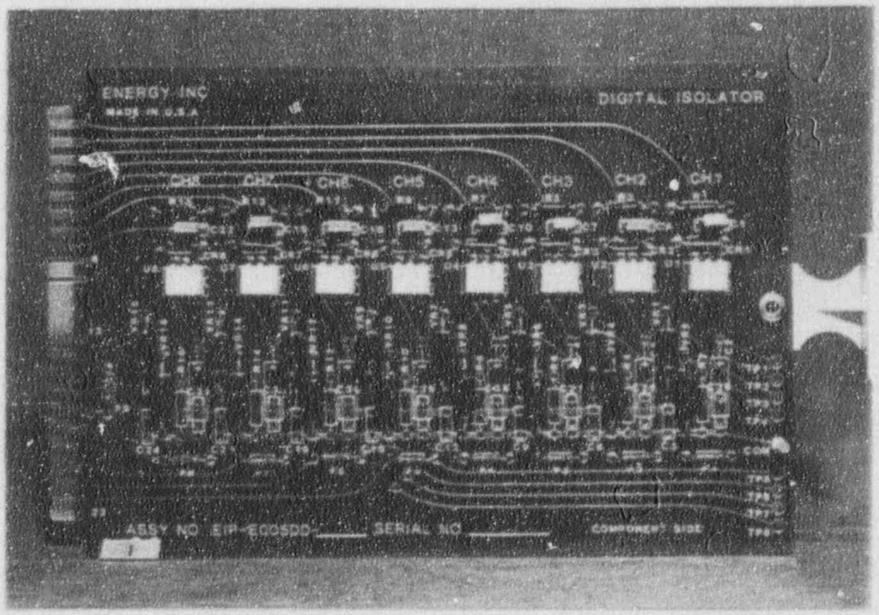

Figure 2.13 Halliburton NUS eight-channel digital isolator card

in this design: an AC/DC to Logic Interface Optocoupler (the four ICs vertically arranged below the serial number) and a Photovoltaic Optocoupler (vertically arranged below the "Made in USA"). The face plate of the card, shown face on and at the left in Figure 2.12, contains an LED status indicator and a push-to-test button for each of the four channels. This allows a common test signal to be applied temporarily to each channel to verify the system integrity (Ref. 26).

The Halliburton NUS optically coupled isolator, shown in Figure 2.13, is an eight-channel digital isolator card which plugs into an isolator card cage assembly manufactured by their company. As shown in the figure, all input signal, output signal, power, and test connections are made to the isolation card cage assembly via the 2x22-pin plug connector at the rear of the circuit board (left in the figure). Isolation is provided by the physical separation of the inputs and outputs and a type H11G1 optoisolator in each of the of the eight channels. The output of each channel is fused and a test point is provided that is accessible from the front of the card (lower right in Figure 2.13) when it is installed in the card rack assembly (Ref. 27).

3. TESTING PROGRAM

The details of the major fault testing program are described in the following sections. The objectives of the testing are given, together with descriptions of the testing equipment and the testing procedures.

3.1 Objectives

The present testing program will explore isolation barrier leakage problems that might arise at fault levels up to the maximum credible potential. This was accomplished by observing and measuring the reach-through energy that passes through the isolation devices during fault conditions. A series of fault conditions, increasing in 10% incremental steps from 10% to 110% of the maximum credible fault potential, was applied to each of the tested devices. The relationship between the reach-through energy and the applied fault voltage could then be obtained. From this data, susceptibility to potential damage for various families of electronic isolators may be correlated to their potential safety significance.

The BNL isolator testing facility (ITF) was designed to provide a detailed survey of specific potential power fault conditions affecting electronic isolators. Such isolator faults might degrade or prevent input connected Class 1E equipment and systems from meeting their minimum performance requirements. In earlier testing performed under the NRC's Isolation Devices Evaluation Criteria Program, and reported by Neilsen in NUREG/CR-3453 (Ref. 4), some electronic isolation devices experienced severe damage when subjected to maximum credible AC or DC voltage and current levels (e.g. 120Vac, 20A) applied to the output side of the energized device.

In addition to these maximum credible fault states, additional questions have surfaced suggesting that other, less-than-maximum voltage and current conditions might find a leakage path across the isolator allowing potentially destructive energy levels to breach the isolation barrier (see Section 2.2). The faults with less-than maximum credible potentials may contain other properties influencing damage to connected devices. Such power conditions might occur as a result of subtly induced power levels that are a function of power fault transients relating to wave shape, as well as amplitude. The maximum credible fault (MCF) for a given isolation device must thus be defined not only as that fault potential at which the maximum reach-through energy is passed across the isolation barrier, but also as a function of waveform dependent parameters.

3.2 Test Procedures

The general test procedure for this program is outlined below in Table 3.1. Each isolation device under test (DUT) was subjected to a series of fault conditions at the signal output terminals, increasing in 10% incremental steps from 10% to 110% of the maximum credible fault potential. For each 10% step of applied fault potential, a set of basic tests were performed: Pre-Fault Baseline and Functional Tests, a Fault Application Test, and Post-Fault Baseline and Functional Tests.

3.2.1 Baseline Electrical Tests

Prior to the application of fault waveforms, it is desirable to quantify the baseline electrical characteristics of the isolation barrier. Changes in the integrity of the isolation barrier due to subsequent application of fault waveforms may be reflected in corresponding changes in the electrical characteristics of the isolation barrier. This is the purpose of the baseline barrier tests listed in Table 3.1. Measurements of the isolation barrier resistance and capacitance are obtained as described in the following sections.

Table 3.1 General Test Procedure Sequence

- PERFORM BASE-LINE BARRIER TESTS

  Isolation barrier dc resistance test
  Isolation barrier ac capacitance test
  Record, store, and print results

- PERFORM FUNCTIONAL TEST

  Verify output signal consistent with applied input signal
  Record, store, and print results

- APPLY FAULT FUNCTION TO OUTPUT OF ISOLATOR

  Set fault waveform generator to desired amplitude
  Apply fault waveform to DUT output terminals
  Monitor all points
  Record, store, and print results

- REPEAT BASE-LINE BARRIER TESTS

  Isolation barrier dc resistance test
  Isolation barrier ac capacitance test
  Record, store, and print results

- REPEAT FUNCTIONAL TEST

  Verify output signal consistent with applied input signal
  Record, store, and print results

<u>Isolation Barrier Resistance</u> The configuration for this test segment is shown in Figure 3.1. Direct measurement of the isolation barrier resistance using a multimeter is impractical due to the high value encountered (generally >1 GΩ). In the method shown in Figure 3.1, a large sampling resistor (10 M Ω) is placed is placed in series with the positive input terminal of the isolator. A known dc voltage is then applied across the series combination of the sampling resistor and the isolation barrier resistance. The voltage drop (V_{SR}) is measured across the known sampling resistor to find the current (I_{IB}) flowing through the circuit. The dc resistance of the isolation barrier may then be calculated from the current (I_{IB}) and voltage drop (V_{IB}) across the isolator.

<u>Isolation Capacitance</u> The capacitive coupling across the isolation device is the primary means by which energy may be transferred across the isolation barrier. This isolation capacitance may be measured by the test configuration shown in Figure 3.2. The function generator is set to apply a low voltage (< $5V_{RMS}$), sinusoidal waveform of known frequency across the positive terminals of the isolation device. The current (I_{IB}) flowing across the isolation barrier is measured on the digital multi-meter (DMM). Isolation capacitance (C_{IB}) may then be calculated as:

$$C_{IB} = \frac{I_{IB}}{2\pi f\ V_{IB}}$$

3.2.2 Isolation Device Functional Test

Prior to the application of fault waveforms, the functional performance of the isolation device must be verified. This is achieved by applying signals to the input of the energized isolation device and measuring the corresponding output signal transmitted throughout the device.

The basic functional test configuration for analog or digital voltage-to-voltage isolators is shown in Figure 3.3. With the isolator powered, analog input signals may be applied at three levels (zero, midpoint, full span) or five levels (zero, 25%, 50%, 75%, and full span) of the specified device input range, and the corresponding outputs measured on a DMM as shown in the figure. For digital devices, the technique is the same except only two levels need be checked: the digital low and digital high.

In the case of current-to-current isolators, the functional test arrangement is as shown in Figure 3.4. An adjustable dc power supply is used to supply known currents at three or five levels, from zero (typically 4 ma) to full span (20 ma), to the input terminals of the powered isolation device. The input current may be measured directly with a DMM or as shown in the figure using a series 1KΩ sampling resistor at the input and measuring the voltage drop across the resistor with a DMM. The output of the device is connected across a load resistor R_L of the magnitude specified by the manufacturer. Output current is measured on the DMM by the voltage drop through the load resistor R_L.

3.2.3 Fault Application to DUT

For each electronic isolation device tested the AC fault voltage will be applied to the output terminals of the energized isolation device, as shown in Figure 3.5, in the form of a single, half-cycle, cosine waveform (see Figure 3.7 and associated discussion in Section 3.3) and in amplitude steps of 10% of maximum (120V rms) ranging from 0 to 110% with the input terminated in a resistance, *Rx*. The applied AC voltage starts at zero and slews rapidly to the maximum, continues for a half cycle and then slews rapidly from a negative maximum to zero. For maximum stress, the transition time should be as short as possible. For the fault pulse generator developed for this test program (described in Section 3.3), the typical transition time is no more than 50 nS for a 10% to 90% rise on the leading edge and 10 μS from 90% to 10% on the trailing edge. The AC voltage is applied in this form since it is expected that the isolation devices to be tested employ solid-state devices. This implies that whatever is to be measured will occur with a time-scale of microseconds, or perhaps milliseconds.

The applied fault voltage and current (at the DUT output terminals) were monitored and recorded at each incremental step, as was the output (if any) across the 1000 ohm input resistor, *Rx*. From this, reach-through energy was calculated (the integral of $[Vx(t)]^*[Vx(t)/Rx]^*dt$) at each amplitude step of applied fault potential.

The series of incremental fault steps was applied in an increasing sequence of 10% steps up to 110% of the maximum credible fault (MCF) potential selected for this testing. As mentioned above, electrical characteristics and functional tests were performed between each 10% step. The devices were visually monitored throughout the testing for physical signs of damage. When a device was found to no longer pass the functional test, no attempt was made to repair the problem or restore the

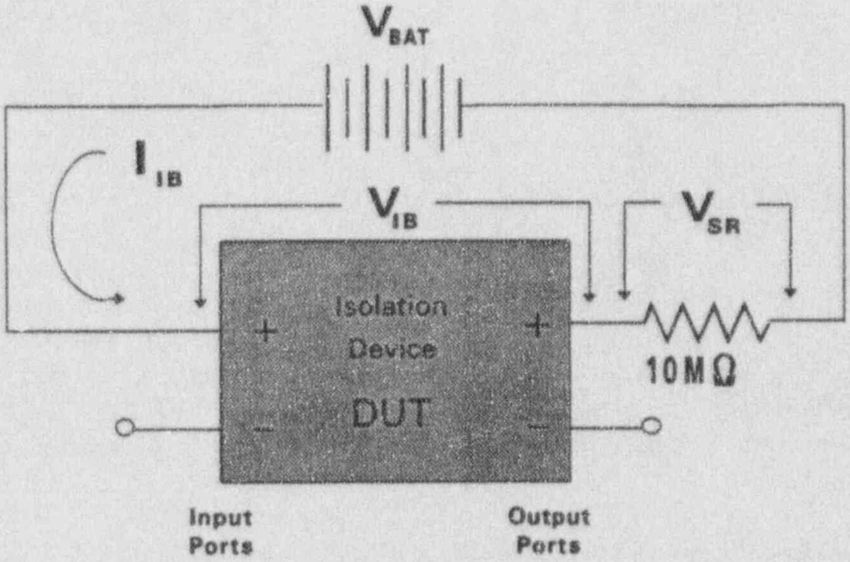

Figure 3.1 Isolation barrier resistance measurement

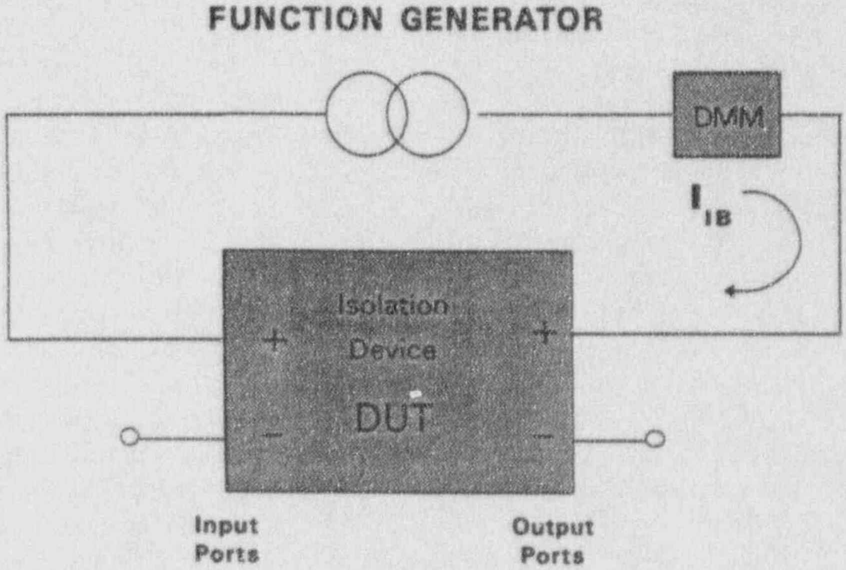

Figure 3.2 Isolation capacitance measurement

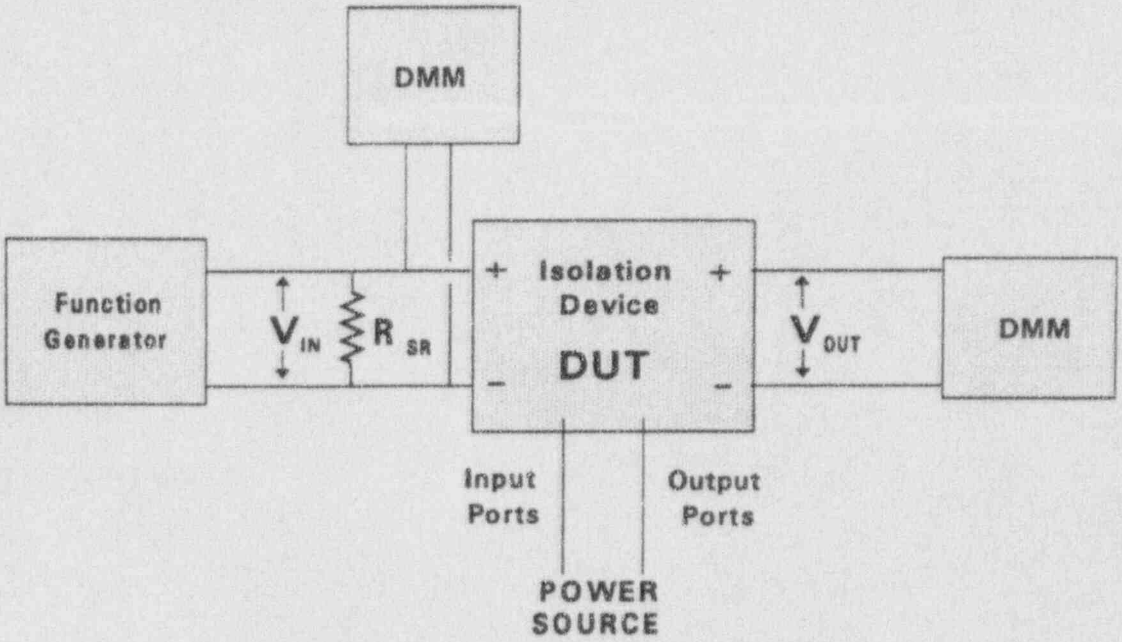

Figure 3.3 Voltage-to-voltage isolator functional test

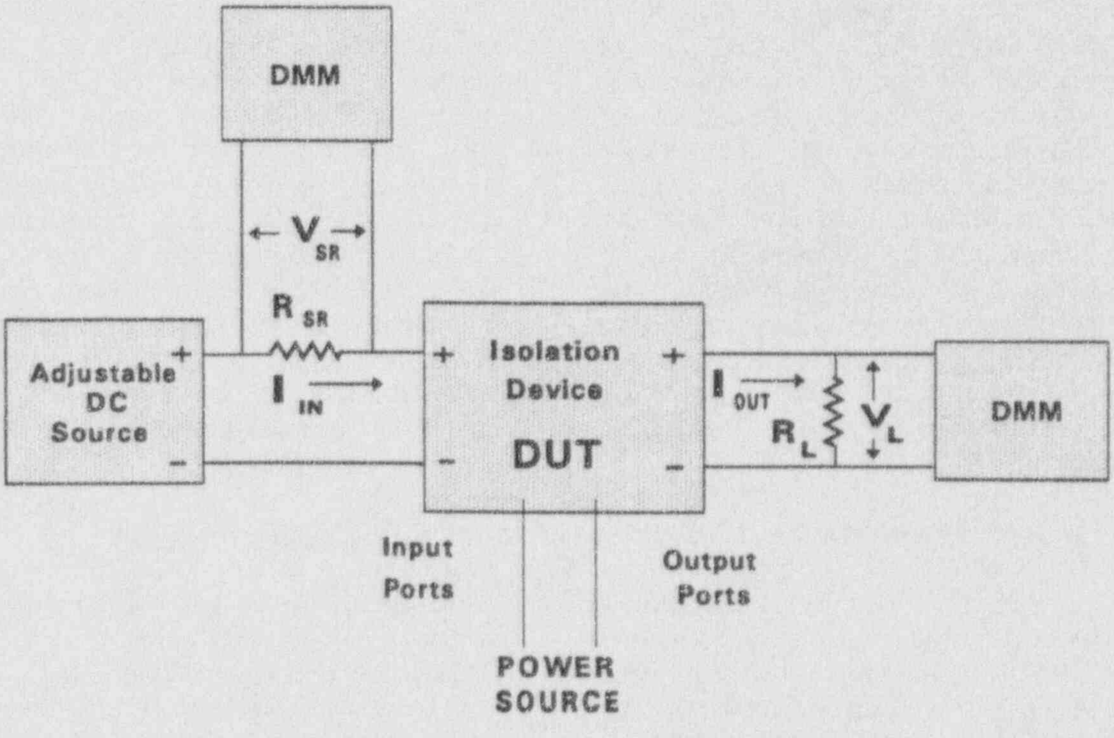

Figure 3.4 Current-to-current isolator functional test

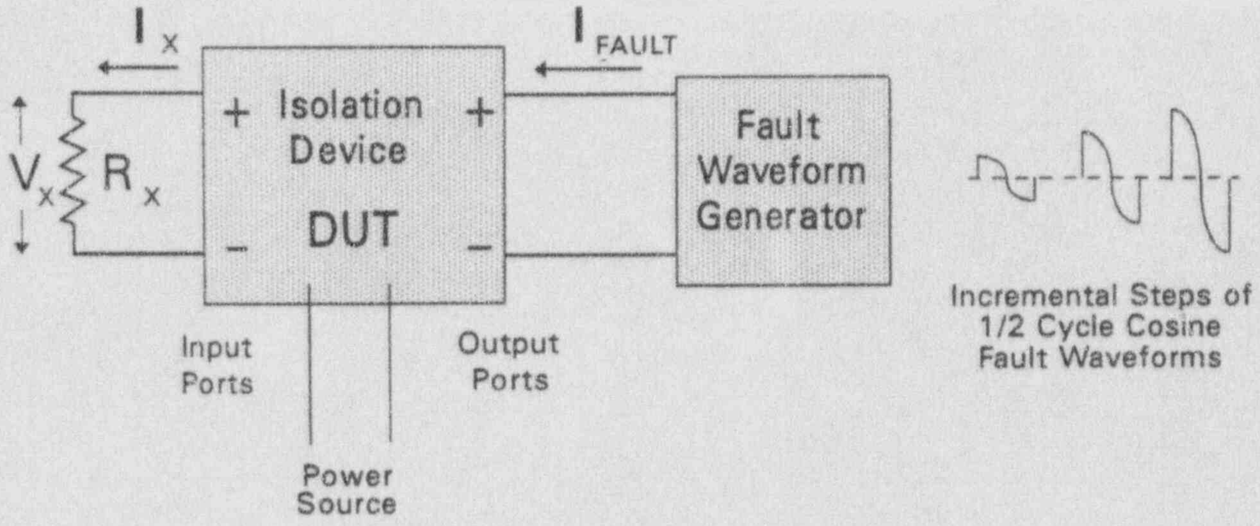

Figure 3.5 Isolator incremental fault application test

device to functional status. The fault step at which the functional failure occurred was noted and the test preceded on from there up to the 110% fault level. The isolation devices were kept energized at their normal power supply requirement for the functional testing and fault testing. No signal was applied to the input at the time of fault testing, since it was felt that for faults applied directly to the output terminals of an isolation device, the internal impedance of the fault generator was much lower than that of the isolator so that any signal voltage transmitted to the output would not significantly contribute to the overall fault voltage applied at the device output terminals.

3.2.4 Multiple Channel Isolators

Among the isolation devices tested for this program were several multiple channel units. When testing these isolators, one channel (designated Channel "A") was selected for full testing as described in the previous section. In addition, all the remaining channels in the device were subjected to full electrical characteristics measurements and functional verifications prior to the application of any faults. If the primary channel under test, Channel A, was found to have stopped functioning at some fault level, then all the remaining channels were again subjected to electrical characteristics measurements and functional verification before continuing to the next higher fault step. Finally, after the final 110% fault had been applied and the final post-fault electrical measurements and functional tests were performed on Channel A, then the remainder of the channels would also undergo a final set of post-test electrical measurements and functional tests (if they were still functional at the end of the test).

3.3 Test Equipment Setup

The isolator test facility (ITF) was designed to accurately and automatically monitor the vital connections to the isolation device under test while systematically applying predetermined fault profiles to the output terminals of the DUT. To ensure maximum detection capability, electronic measuring

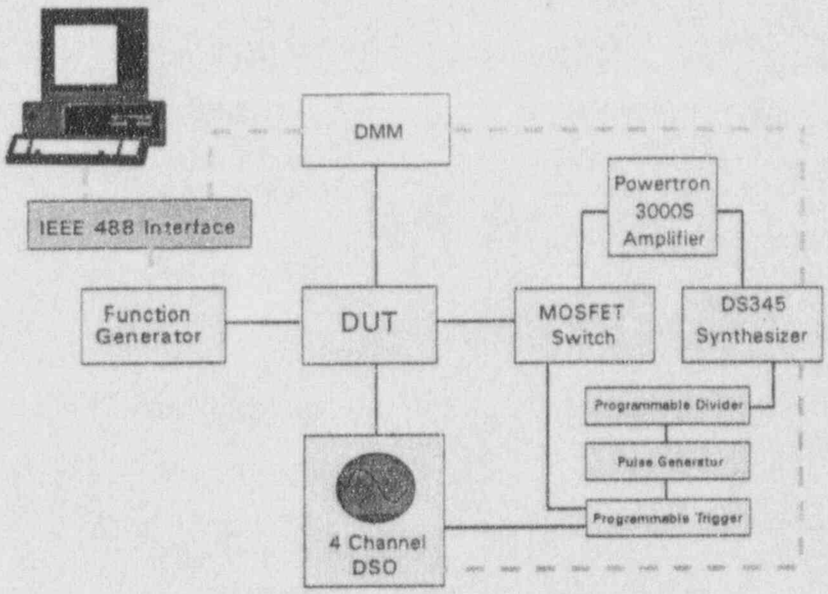

Figure 3.6 Basic test equipment setup

instruments were chosen that are capable of the highest sensitivity and resolution relative to the measurement objectives. These sensitive instruments permit minute currents to be detected, both statically and dynamically, so transient through-put phenomena can be observed and quantified.

The basic test set-up is shown in Figure 3.6. Program control is provided by National Instruments NI-488.2 software and Microsoft Quick BASIC software running on an IBM PS/2 Model 55X PC. An IEEE-488 Standard Bus digital interface provides for control of the LeCroy Model 9314M Digital Storage Oscilloscope (DSO), Keithley Model 2001 Digital Muli-meter (DMM), Stanford Research Systems (SRS) DS345 Synthesized Function Generator, and Hewlett Packard Model HP3325A Synthesizer/Function Generator. A list of the major equipment and software is provided in Table 3.2. Some technical details and specifications of the test equipment and software are found in Appendices A and B.

The fault waveform generator consisted of the SRS DS345 Synthesized Function Generator, the ITECo Powertron Model 3000s AC Amplifier, and the custom designed ITECo high-speed MOSFET switch/controller (see Appendix B). The DS345 served as both the waveform source (wave shape and amplitude) for the Powertron amplifier, and as the synchronizing clock to gate the MOSFET switch/controller and to trigger the LeCroy DSO via the BNL designed programmable trigger (see Appendix B). The Powertron operated as a continuous waveform (CW) amplifier. When the gate from the programmable trigger unit triggered the high-speed MOSFET switch/controller, it unblocked the CW output of the Powertron amplifier and directed the selected portions of the waveform to the DUT at electronic speeds.

The number of fault pulses to be applied to the DUT can be selected from the programmable trigger to be one and only one per event, up to 99 fault pulses per event. The programmable divider is used to select the delay between pulses (the duty cycle) in multiple fault pulse events (e.g., by setting the programmable divider to 5 and selecting 3 fault pulses on the programmable trigger, three cosine fault pulses will be applied to the DUT at an interval of one fault pulse every

Table 3.2 Equipment List for BNL Isolator Test Facility

Test Equipment	Mfg. & Model No. (where available)
Powertron, 3 KVA source, single ϕ	Model 3000S, Industrial Test Equipment Co., Inc.
MOSFET Power Switch/Controller	Custom Design, Industrial Test Equipment Co., Inc.
IEEE-488 Interface Board w/connecting cables	National Instruments MC-GPIB
Synthesized Function Generator	Stanford Research Systems Model DS345
Pulse Generator	Interstate Electronics Corp. Model P12
High Performance Digital Multi Meter	Keithley Model 2001 DMM w/10-channel scanner card
IBM PC/AT or better	IBM PS/2 Model 55X
5-Decade Programmable Divider	Custom Design, BNL
Programmable Pulse Trigger	Custom Design, BNL
4-Channel Digital Storage Oscilloscope	LeCroy Model 9314 M-MC01/04 w/Options WP01/02 and Trigger Out Provision
Regulated DC Power Supply	Power Designs Model 5015-S
MicroSoft Quick BASIC Software Version 4.5	MicroSoft Corp.
IEEE 488 Bus Language Interface and Device Drivers for MS-DOS	National Instruments NI-488.2 for MS-DOS Software
Current Transformer	Pearson Electronics Inc. Model 110A
Synthesizer/Function Generator	Hewlett-Packard Model 3325A

fifth cycle). The standard Powertron includes a provision to switch the unit automatically at a predetermined load current from the constant voltage mode into a constant current mode (20A max).

As mentioned in Section 3.2.3, the fault generator designed for this testing is capable of producing a cosine waveform with a leading edge rising transition time from 10% to 90% of no more than 50 nS, and no more than 10 μS from 90% to 10% on the trailing edge. Figure 3.7 is an oscilloscope trace of the cosine fault waveform produced by the fault generator. In Figure 3.8, the time base was expanded to show details of the leading edge (left) and the trailing edge (right) of the waveform in Figure 3.7.

Since the rapidity of the leading edge of a cosine wave can be expected to add significantly to the isolation barrier reach-through current through the output/input capacitance ($I = C \frac{dV}{dt}$), the cosine wave produces more testing stress in the DUT (as compared to a sine wave for the same peak amplitude), and the results thus obtained represent the upper bound of the

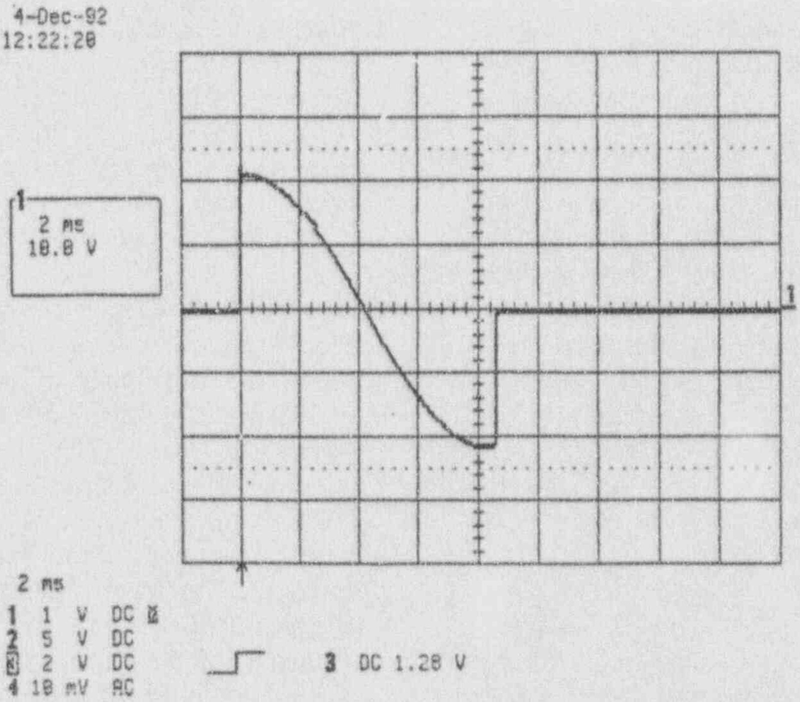

Figure 3.7 DSO trace of the cosine fault waveform

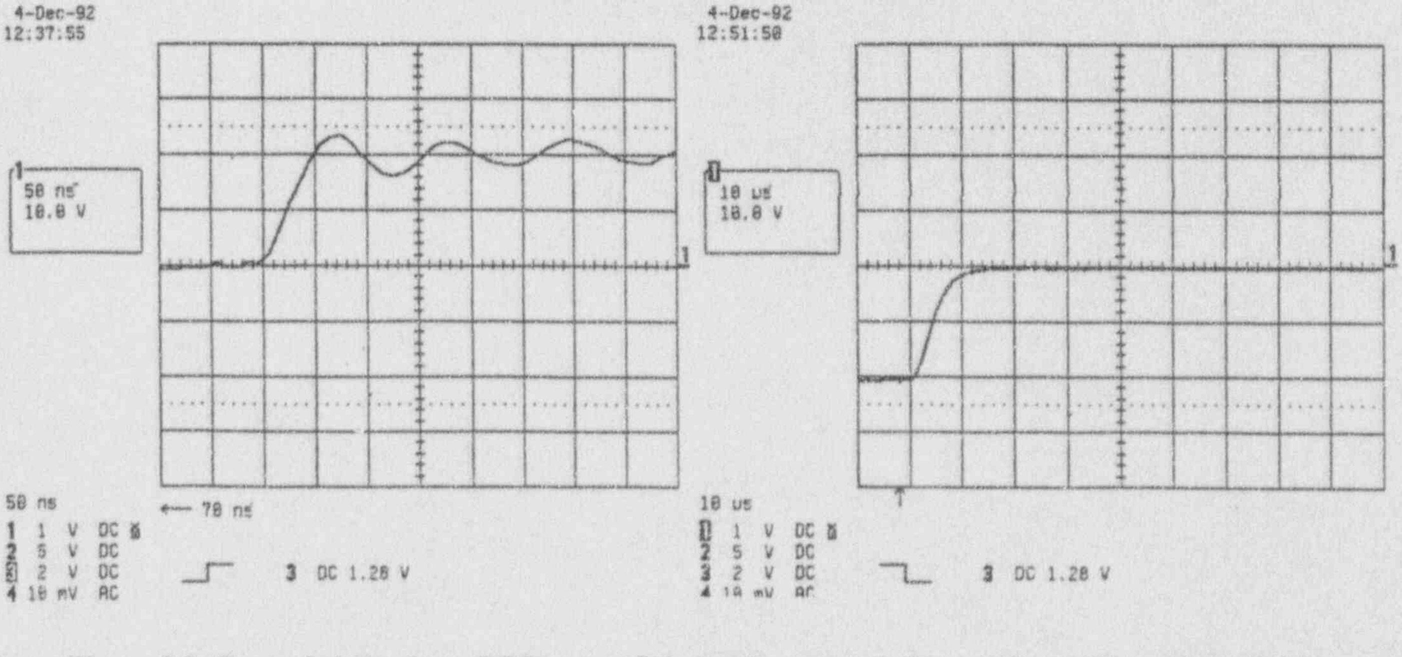

Figure 3.8 Expanded timebase DSO trace of the leading edge (left) and the trailing edge (right) of the cosine fault waveform

worst case fault conditions that will be experienced at each level. Consequently, the fault testing was conducted by applying one and only one cosine waveform of the proper magnitude to the output terminals of the DUT at each testing level.

Test measurements were made using either the Keithley DMM or the LeCroy DSO. Prior to the testing, a calibration check of the instruments was performed and documented by the manufacturers (see Appendix C). The DMM was used primarily in the performance of the baseline electrical testing of the DUT isolation barrier and for DUT functional testing. The LeCroy was used to capture the data associated with the fault application testing.

The LeCroy digital storage oscilloscope has the capability to record fast transient events such as those that occurred during the fault application testing of the isolation devices. These are time dependent voltages that are not possible to detect with a digital voltmeter or similar device. Such voltages are significant because they can be of sufficient amplitude to cause induced faults without being detected under normal operating conditions. With this instrument it is possible to record any potential transient effects and assess their potential to compromise critical protection systems.

The LeCroy oscilloscope used in the test is capable of recording four transient events simultaneously. Four input channels are used to monitor both input and output voltages to the DUT. It is also used to monitor input and output currents of the DUT through sensitive, fast-response current transformers connected at those respective locations. The resulting data acquisition from the digital recording oscilloscope is both controlled by, and transferred to, the computer through an IEEE-488 Standard Bus digital interface for display, storage, and analysis.

4. TEST RESULTS

This section offers a summary of the results obtained during this testing program. Twelve isolation devices, listed in Table 2.2, were subjected to the incremental series of fault application tests described in section 3.2.3. In accordance with the program objectives, it was demonstrated that all the isolators maintained the integrity of their isolation barriers throughout the testing, while passing only minute quantities of reach-through energy. The highlights of the testing are detailed below in Section 4.1. Additional observations that were made during the test program are discussed in Sections 4.2 and 4.3.

As a result of the faults applied during their testing runs, all but two of the units ceased to function electronically as instrument signal transmitters, i.e. they could no longer transmit signals accurately from input to output.

4.1 Reach-Through Energy

The primary objective of the testing was to study the reach-through energy characteristics of isolation devices when subjected to a series of applied faults ranging in magnitude from 10% to 110% of the maximum credible fault (MCF) potential selected for these tests (120V rms). The results of the testing are summarized in Table 4.1. The tested isolators are grouped into three categories: magnetically coupled voltage-to-voltage isolators, magnetically coupled current-to-current isolators, and optically coupled isolators.

The integrity of the isolation barriers in all of the units tested was maintained satisfactorily throughout their testing run. No attempt to repair damage or replace blown fuses was made before proceeding to the next higher step of fault potential. Units were physically inspected for signs of damage at the end of the test series (after the application of the 110% fault and completion of post-fault electrical and functional tests).

For each of the isolation devices tested, the reach-through energy was measured at each incremental step of applied fault potential in the testing progression. As described in Section 3.2.3, the applied fault was a single, 1/2 cycle cosine waveform injected at the output terminals of the isolator. The quantity of energy measured at the isolator input terminals is thus the corresponding 1/2 cycle reach-through energy resulting from that applied fault waveform. These reach-through energy data are plotted in Appendix D as a function of the applied fault potential (expressed as a fraction of the maximum credible fault (MCF) potential) for the twelve isolation devices tested.

The second column in Table 4.1 summarizes the trends observed in these graphs. For example, the graph for the first isolator DA-3-1 (Figure 4.1), displayed an increasing trend in reach through energy as the applied fault potential was increased from 10% up to 100% of the maximum; there was also a large peak of reach-through energy observed during the application of the 50% fault potential. In contrast, the graph for the second isolator in Table 4.1, isolator FA-3-1A (Figure 4.2), shows that this unit passed no significant reach-through energy for faults up to 90% of maximum; measurable reach-through energy was first observed at the 100% fault level and then increased again at the 110% level.

As can be seen from the summary table, the quantity of 1/2 cycle reach-through energy measured at the input terminals of the magnetically coupled isolators generally either increased steadily as the applied fault potential was increased, or remained relatively constant up to some point (where internal damage may have occurred), and then increased throughout the remainder of the series. The quantity of 1/2 cycle reach-

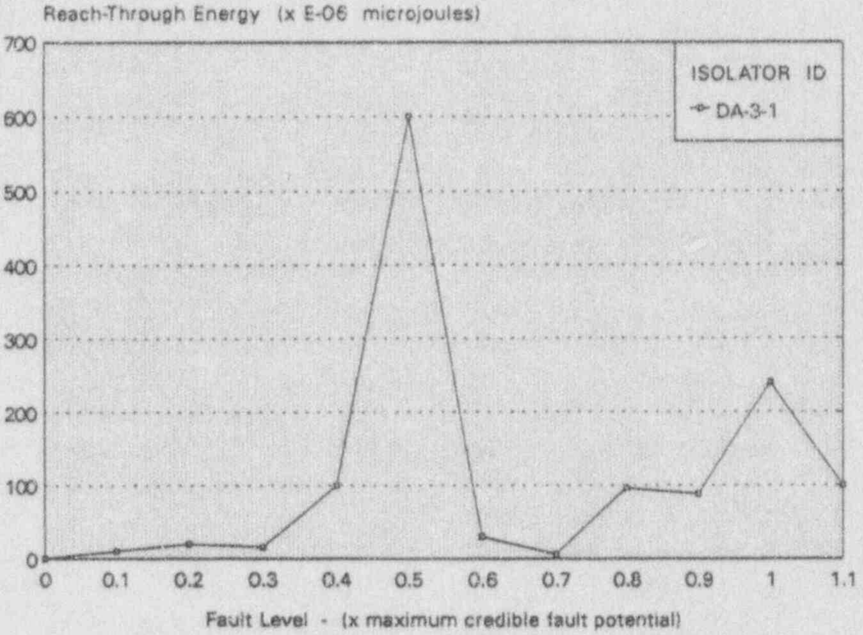

Figure 4.1 Reach-through energy vs. fault level-isolator DA-3-1

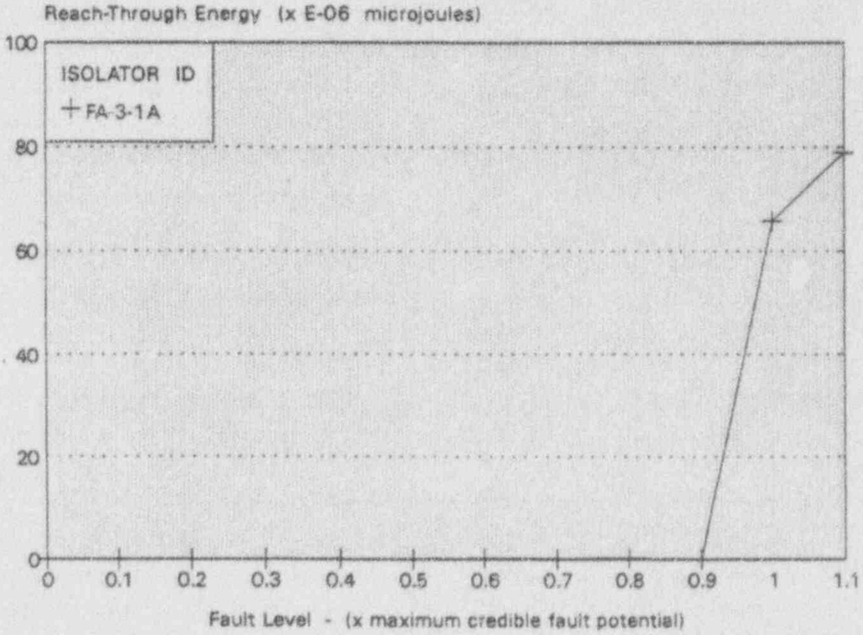

Figure 4.2 Reach-through evergy vs. fault level-isolator FA-3-1A

Table 4.1 Summary of Reach-Through Energy vs Fault Level Testing

		Isolator ID	Observed Trend of 1/2 Cycle Reach-Through Energy vs Applied Fault Potential (Fraction of MCF Potential)	Fault level at which Max 1/2 Cycle Reach-Through Energy Was Measured (Fraction of MCF Potential)	Magnitude of Max Reach-Through Energy in microjoules	Fault Level After Which Device No Longer Transmitted Signals (Fraction of MCF Potential)	Other Observations
MAGNETICALLY	V to V	DA-3-1	increasing, peak @ 0.5xMCF	0.5	6E-4	0.2	Op amp at device output failed.
		FA-3-1A	constant then increasing at 1.0xMCF and greater	1.1	2E-6	Did Not Fail	Both channels on card continued to transmit signal throughout the fault application testing.
		HNA-3-1A	increasing, peak @ 1.0xMCF	1.0	2E-4	0.1	All 4 chans on board no longer transmitted signal after fault at .1xMCF potential on Chan A.
		RA-3-2	constant then increasing after peak @ 0.6xMCF	0.6	0.54	0.4	Drew large fault current. Device output noisey.
		VD-3-1	constant except for peak @ 0.1xMCF	0.1	0.014	0.1	
		WA-3-1	constant then increasing after peak @ 0.8xMCF	0.8	2.4E-4	Did Not Fail	
COUPLED	I to I	DA-2-3	increasing, peaks @ 0.1 and 0.9xMCF	0.9	349	0.1	Large fault current. Reach-through energy level couldn't be repeated during retest.
		HNA-2-1A	constant until peak @ 1.0xMCF	1.0	8E-4	0.1	All 4 chans in device no longer transmitted signal after fault at .1xMCF potential on Chan A.
		TRA-2-2	constant then increasing at 0.8xMCF and greater	1.0	4.1E-3	1.0	Zero end of range only failed afte fault at 1.0xMCF potential; ful range failed at next fault step
OPTICALLY COUPLED		HND-4-2A	constant except for peak @ 0.4xMCF	0.4	0.4	0.1	All 8 chans on board no longer transmitted signal after .1xMCF fault on Chan A.
		TD-4-1	constant, peak @ 1.0xMCF	1.1	8.4E-4	0.1	
		TD-4-3A	constant except for peak @ 0.9xMCF	0.9	2.1E-4	0.1	Chan B, C, and D continued to transmit signals throughout the fault application testing.

through energy measured at the input terminals of the optically coupled isolators tended to remain relatively constant throughout the series of tests, but typically exhibited one or more peaks of higher reach-through energy.

Table 4.1 also indicates the fault level, as a fraction of the MCF potential, at which the maximum reach-through energy was measured for each of the isolators tested. The basis for the qualification testing of electronic isolators at a fault equal to the maximum credible potential is that this condition would simulate the worst case fault in regard to the measured reach-through energy. This was not always the case as observed in the present test program. For example, Figure 4.3 shows the plot of 1/2 cycle reach-through energy verses applied fault potential for one of the voltage-to-voltage magnetically coupled isolators, RA-3-2. In this test, the reach through energy was minimal until the 0.4xMCF potential,increased slightly at 0.5, and peak reach-through energy was measured at the 0.6xMCF level. For this particular isolator then, the maximum credible fault potential in regard to reach-through energy was not the maximum credible potential of 120 Vac, but rather 0.6x120Vac rms, or 72Vac rms. Figure 4.4, presents another example of a voltage-to-voltage magnetically coupled isolator, HNA-3-1A, in which the testing did find that the peak reach-through energy occurred at the maximum credible potential. Hence for this isolator, maximum credible potential was representative of the worst case, or maximum credible, fault.

For most of the isolators tested, however, the maximum credible potential did not produce the maximum credible fault in terms of the measured reach-through energy. In the magnetically coupled isolators, the fault level at which maximum reach-through energy was measured encompassed the entire range of applied fault potentials from 0.1 to 1.1xMCF, with a mean of 0.683 for the voltage-to-voltage isolators and a mean of .967 for the current-to-current isolators. For the optically coupled isolators, the mean fraction of MCF potential at which the maximum reach-through energy was measured was 0.8.

Table 4.1 lists the maximum magnitudes of the reach-through energies measured for each isolation device tested. These ranged from $2x10^{-6}$ microjoules up to 349 microjoules, and this latter measurement could not be repeated during retesting. It should be noted that these are the energies measured at the input terminals during the application of 1/2 cycle of the cosine shaped waveform described in earlier in Section 3.3 and shown in Figures 3.7 and 3.8. This waveform represents the worst case fault in terms of the isolation barrier capacitance, since the rate of change of voltage is extremely rapid. This was reinforced during the data analysis where it was found that when reach through energy was observed, the peaks usually accompanied the rapid voltage changes at the leading and trailing edges of the applied fault waveform. Therefore, sustaining the fault application time for a 60 Hz waveform would not have changed the picture significantly in terms of reach-through energy.

Nevertheless, the magnitudes of the maximum reach-through energies were very low. A determination of whether fault energy of the order of magnitude observed in the testing is potentially damaging to components connected at the input of an electrical

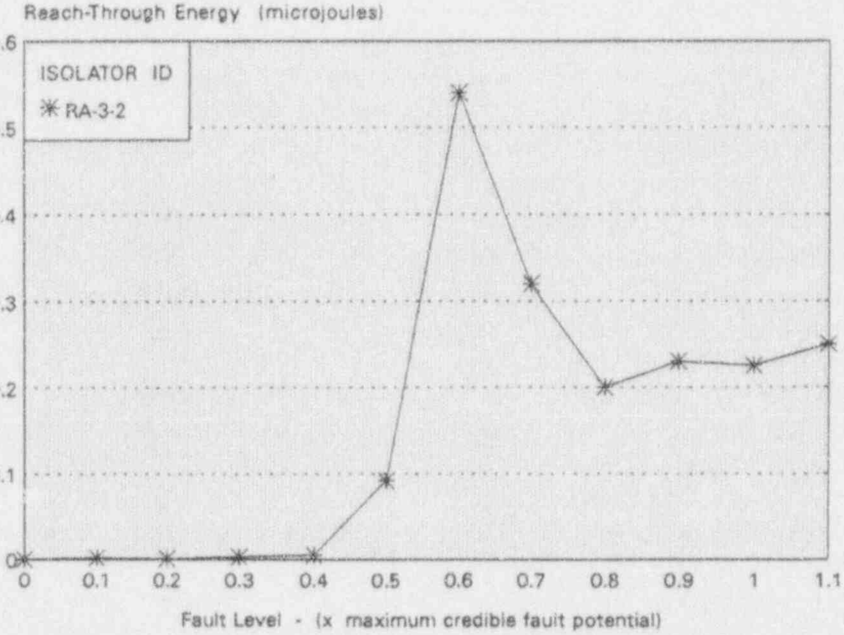

Figure 4.3 Reach-through energy vs. fault level-isolator RA-3-2

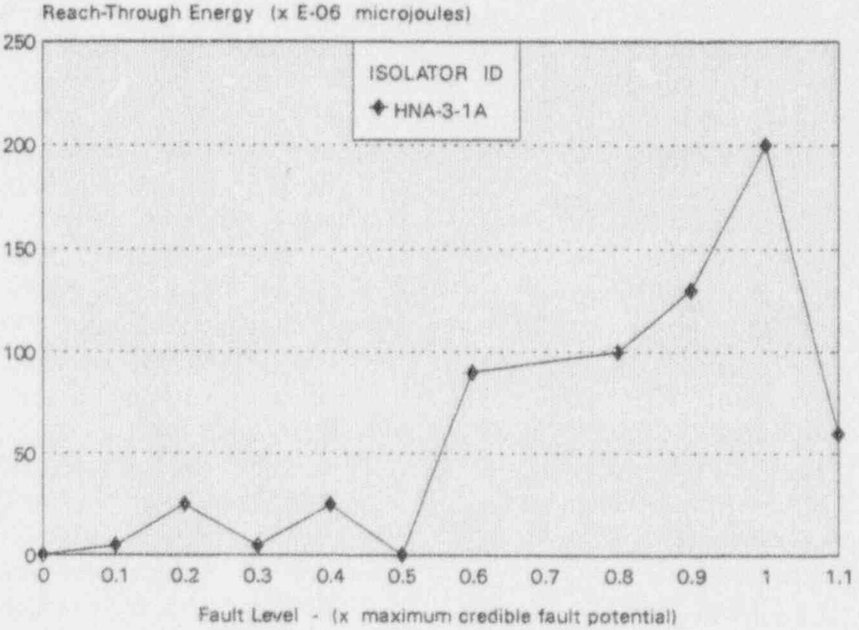

Figure 4.4 Reach-through energy vs. fault level-isolator HNA-3-1A

isolation device is difficult to make. First of all, it is dependent upon the types of components that may be found at the input of the isolation device. Secondly, data regarding damage threshold energies for electrical components is difficult to obtain and by its nature is not precise. However, general estimates for families of components indicate that semiconductors, CMOS circuits, and other electronic integrated circuits are the most sensitive to electrostatic discharge induced fault damage, as seen in Figure 4.5 (Ref. 28). Using the figure as a guide, the maximum reach-through energies observed for the worst case waveform (fault with rapid voltage rise time), could present a problem for semiconductors. In actual application, however, the isolation devices are not likely to be exposed to a such a severe fault waveform as in the testing, so the reach-through energies seen in the field would be much less. In addition, semiconductors and other electronics would not be located right at the isolator terminals, but rather are some distance away, further attenuating the effects of any reach through energy. The likelihood of damage to equipment on the input side of electrical isolation devices resulting from faults at the output is thus considered to be low.

4.2 Isolator Functional Tests

Prior to the application of each incremental fault level, the isolation device under test (DUT) was subjected to a functional test as described in Section 3.2.2. This was done to determine whether an applied fault had affected the basic functional capability of the DUT to transmit signals from input to output. The fifth column of Table 4.1 indicates the applied fault level, as a fraction of the MCF potential, at which each isolator no longer transmitted signal from input to output.

All but two of the isolators stopped transmitting signal at some point during the series of fault tests. Both of these isolation devices were of the magnetically coupled, voltage-to-voltage type. In addition, one other unit, a magnetically coupled current-to-current unit, continued to function up to the full MCF potential at which time the zero end of the 4-20ma output range failed. After application of the next higher fault level (110%), the entire output range of that device then ceased functioning as well. As shown in the table, most of the units lost the capability of transmitting signals, after the 10% fault was applied. It should be noted that most isolation devices are not designed to continue operating after withstanding this type of fault; the primary function of the isolation device in such a circumstance is to maintain electrical isolation even though its signal transmitting capability may have been lost.

Another noteworthy finding arising during the functional tests involved the integrity of isolation channels on multiple channel isolation devices. As described in Section 3.2.4, when testing multiple channel isolators, the series of fault tests was only applied to one channel (Channel A) on the device. However, functional tests were performed on all channels prior to the first fault application, after functional failure of the channel under test, and following the completion of the fault testing series. Among the five multiple channel units that were fault tested, in three of them, when the channel under test stopped functioning, all of the other channels in the device were found to have stopped functioning as well. The most likely reason for this is that a common power supply was shared by all the channels on the isolator on the Non-Class 1E output side of the device. Thus, when the fault applied to the output side of the channel under test caused the failure of the common power supply, all channels on the board were affected. System designers should therefore be aware of, and consider, this aspect in the selection and grouping of signals to be processed through multiple channel isolators.

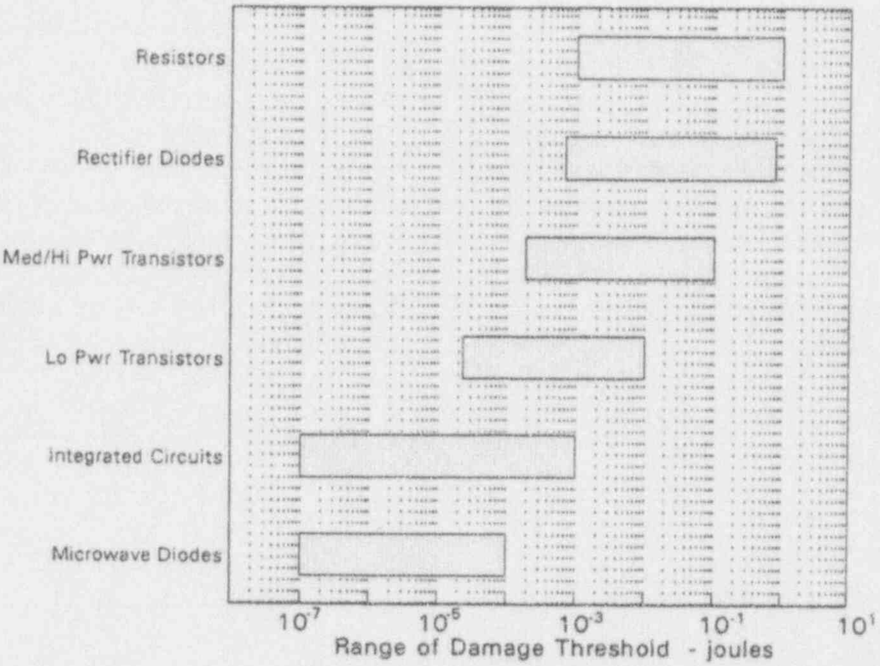

Figure 4.5 Estimation of the vulnerability of various components to ESD-induced damage (Ref 28).

4.3 Barrier Electrical Characteristics

The baseline electrical characteristics of the isolation barrier were measured throughout the fault testing of the isolators as described in Section 3.2.1. The purpose of this is twofold: to identify if and when an isolation barrier has been compromised, and to determine whether progressive deterioration of the integrity of the isolation barrier might be accompanied by measurable changes in electrical characteristics.

On the first point, the isolation barrier integrity was not compromised in any of the devices during fault testing. It must be emphasized that the purpose of this test program was the investigation of reach-through energy characteristics, and accordingly only single, half cycle bursts of fault energy were applied to the isolators. The thermal and electrical effects of longer applied fault times on the isolation barrier integrity, therefore should not be implied from this test program.

In pursuit of the second point, barrier resistance and capacitance measurements taken during the fault testing runs were plotted as function of applied fault level. These may be seen in Appendix D. The measurement of the isolation barrier resistance using the technique described in Section 3.2.1 proved to be a difficult task. The difficulties of this sensitive measurement are reflected in the fair amount of data scatter that was observed (see graphs in Appendix D). In those cases where it was difficult to obtain a reliable reading of this characteristic, a direct measurement was made using the DMM, to establish a lower limit on the actual value (i.e., greater than 1.05 Gigaohms, the upper limit of the ohmmeter range of the DMM). This still allowed the verification of the integrity of the isolation barrier, as shown by the high value of barrier resistance.

Linear regression of the barrier resistance data for those cases where measurements could be obtained indicated that barrier resistance showed a slight tendency to decrease as the applied fault level was increased. However, this trend is not conclusive due to the amount of scatter observed in these data measurements. Graphs of the isolation capacitance measured at 50kHz as a function of applied fault level generally remained constant throughout the series of tests, however fluctuations coincided with those applied faults that caused damage to internal components. There may therefore also be some relationship between the electrical characteristics, and hence the reach-through energy, and the age of the isolator. However, further testing would be required to firmly establish this relationship.

5. CONCLUSIONS AND RECOMMENDATIONS

A total of twelve models of isolation devices were subjected to incremental fault testing under this program. This section lists the conclusions resulting from the testing, and identifies potential problem areas requiring further research and investigation.

5.1 Conclusions and Observations

From the test data obtained during testing of the twelve models of isolation devices the following conclusions and major observations are made:

- All of the devices tested demonstrated their ability to withstand and isolate a series of incremental faults, in increasing increments of 10% of the maximum credible fault (MCF) potential from 10% up to 110% of MCF potential, applied directly to the signal output terminals, without transferring significant quantities of energy across the isolation barrier to the input side. This was the main objective of the testing program.
- Peak 1/2 cycle reach-through energy measured at the input terminals of the isolation devices during fault application testing did not always occur at the level defined as the MCF potential, particularly in the magnetically coupled voltage-to-voltage isolators. However, the magnitudes of the reach-through energies measured even at their peak were very small (less than 350 microjoules) and are considered insignificant.
- Nine of the twelve models of isolators tested failed electronically, i.e. functionally lost the capability to transmit signals from input to output, during the incremental fault testing process. Two magnetically coupled, voltage-to-voltage isolators continued to function throughout their test series up to the 110% applied fault level. One magnetically coupled, current-to-current isolator continued to transmit signals until it experienced a partial output failure at the 100% level, and a complete loss of signal transmission capability at the 110% level. This result is not unexpected, since most isolators are not designed to continue transmitting after being subjected to such fault conditions, even though they do continue to maintain electrical isolation.
- Three of the five multiple channel isolators tested failed electronically in all of their channels even though only one of the channels was subjected to the incremental applied fault testing process. The cause attributed to these failures was the loss of a common power supply on the output side used to power all of the isolator channels on a device. System designers should consider this aspect in the selection and grouping of signals to be processed through multi-channel isolators.
- From the data gathered, it appeared that there may be a relationship between the reach-through energy and the age of an isolation device. Reach-through energy is a function of the isolation barrier impedance, and this

characteristic will change with time, as reflected by the changes in the barrier resistance and capacitance data during the incremental fault application testing sequences. Additional testing with aged isolation devices would be needed to verify this observation.

5.2 Recommendations

The following recommendations are made regarding the application and qualification of electronic isolation devices for use in nuclear power plants:

- Qualification of electronic isolation devices by testing only at the maximum credible potential fault level to meet the requirements of 10 CFR 50, Section 50.55a, paragraph (h) for protection systems is not considered adequate if the intention is to assure that the isolators are qualified for worst case, credible fault conditions. In the future, the major fault qualification test should be expanded to test at several levels up to and including the maximum credible potential to ensure that a worst case condition is not missed.

- It should be noted that the reach-through energies measured during this testing program were considered insignificant, even in the worst case faults. Further, previous qualification tests for the twelve isolator models in this test program were adequate to demonstrate their acceptability as isolators even though all mechanisms were not explored. Consequently, expanded qualification testing for isolators already installed in nuclear plants is not considered necessary.

- It was observed in three of the five multiple channel isolators that were fault tested, that when the channel under test stopped functioning, all of the other channels in the device were found to have stopped functioning as well, most likely due to the failure of a common power supply. Further investigation is recommended to verify that this was the underlying common cause of these failures, the potential safety implications of this problem, and the prevalence of this type of design among multiple channel isolation devices used in nuclear power plants.

- Two isolators were found to continue to transmit signals normally from input to output throughout the entire sequence of incremental fault application testing. A review of the design features which contributed to the ruggedness of these devices should be undertaken, to identify the strong points of these designs.

- Environmental stresses and aging can affect isolator subcomponents, such as capacitors, and result in degradation of the electrical characteristics. This could lead to degraded isolator performance, potential loss of isolator function, or degradation of the isolating barrier. An aging study of isolation devices and subcomponents could identify these factors and quantify their effects.

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7. GLOSSARY

Cosine Waveform - Waveform used to represent a worst case applied fault in this testing program. It is a basic 60 Hz sinusoidal that has been chopped electronically such that it is characterized by a rapid leading edge rising transition time from 10% to 90% of no more than 50 nS at the 90° point and no more than 10 μS from 90% down to 10% on the trailing edge at the 270° point. The resulting fault waveform looks like the first half cycle of a cosine function (see discussion in Section 3.3 and oscilloscope trace in Figure 3.7).

Device Under Test (DUT) - Refers to the electrical isolation device under test in the testing apparatus.

Digital Multi-Meter (DMM) - Digital test instrument that provides high precision, DC and AC voltage and current measurements and resistance measurements over a wide dynamic range.

Digital Storage Oscilloscope (DSO) - Digital oscilloscope that has the capability to measure, store, record, display, and process fast transient events.

Electrical Isolation Device (Isolator) - "A device in a circuit which prevents malfunction in one section of a circuit from causing unacceptable influences in other sections of the circuit or other circuits," (Ref. 1). "A device is considered an electrical isolation device for instrumentation and control circuits if it is applied so that (a) the maximum credible voltage or current transient applied to the device's non-Class 1E side will not degrade the operation of the circuit connected to the device Class 1E or associated side below an acceptable level; and (b) shorts, grounds, or open circuits occurring in the non-class 1E side will not degrade the circuit connected to the device Class 1E or associated side below an acceptable level," (Ref. 1).

Half-Cycle Reach-Through Energy - The quantity of reach-through energy measured at the input terminals of an isolation device during the application of a half cycle of sinusoidal fault potential at its output terminals.

Isolation Barrier - That part of an isolation device which provides the actual electrical isolation between the input and output terminals of the device.

Isolation Barrier Capacitance - The electrical capacitance of the isolation barrier in an electrical isolation device.

Isolation Barrier Resistance - The electrical resistance of the isolation barrier in an electrical isolation device.

Magnetically Coupled Isolator - Electrical isolation device that uses a transformer to provide electrical isolation.

Major Fault Test - Qualification test to verify that the application of the maximum credible ac or dc potential at the output of the isolation device shall not prevent the associated protection system channel from meeting the minimum performance requirements specified in the design bases (Refs. 2,3).

Maximum Credible Fault (MCF) - In this test program, the fault potential, and waveform, applied in the transverse mode to the output terminals of an isolation device at which the maximum reach-through energy is passed across the isolation barrier to the input terminals of the isolation device. In the industry, the MCF is considered application specific, and is the maximum fault potential expected at the output terminals of the isolation device.

Maximum Credible Potential (Voltage) - The highest credible electrical potential or voltage that an isolation device could be exposed to under fault conditions during its service life. Current methods for qualification testing of isolation devices are based upon the assumption that the maximum credible potential would result in the maximum credible fault; i.e., maximum credible potential is the same as the MCF potential.

MOSFET - Metal-Oxide-Semiconductor Field-Effect Transistor, an insulated gate field-effect transistor characterized by its gate electrode which is insulated from the conductive semiconductor channel by a thin layer of an insulating metal oxide. The resulting device typically has an extremely high input impedance, low leakage, and low driving power requirements.

Optically Coupled Isolator - Electrical isolation device that uses a photo semiconductor, or a photo transmitter and receiver connected by a optical link to provide electrical isolation.

Reach-Through Energy - The energy passed across the isolation barrier of an isolation device, expressed by $\int V(t)*I(t)dt$, and appearing at its input terminals during a fault applied to its output terminals.

Transverse Mode Fault - In this test program, a fault applied in the transverse mode means that it is applied to the output terminals of the isolation device. The input terminals are simultaneously monitored to determine whether any portion of the fault has propagated back through the isolation device to appear at the input terminals. During its normal mode of operation, the isolation device receives signals at its input terminals and transmits an equivalent signal from its output terminals.

APPENDIX A

TEST PLAN

BNL Technical Report No. L2158 - 3/93
Revision 1

A TEST PLAN FOR FAULT TESTING OF NUCLEAR POWER PLANT ELECTRONIC ISOLATION DEVICES

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Office of Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555

FIN L-2158

ABSTRACT

Described in this report is a proposed test plan for fault testing of electronic isolation devices commonly used in nuclear power plants. Since 1984, over 700 events involving failures of isolation devices in nuclear power plant service have been reported to the Nuclear Plant Reliability Data System (NPRDS). As plants incorporate more electronic and computerized instrumentation and controls systems, the use of isolation devices is increasing. Proposed control systems for the next generation of advanced reactors will depend heavily upon the use of isolation devices. Earlier testing programs (Reference 2) have indicated some isolation device problems when subjected to a maximum credible fault (MCF). The present test program will investigate whether problems can arise at fault levels up to the MCF, by measuring the fault energy passed through an isolation device, and determining the fault energy levels that can result in damage, degraded performance, or loss of function.

CONTENTS

1. INTRODUCTION

1.1 Background

Isolation devices are used in a nuclear power plant to isolate a safety system from a non-safety or commercial system in such a way that a failure on the non-safety system does not affect operations on the safety system. In particular, the worst kind of failure is a situation where a stressed non-safety circuit causes a direct conductive path to appear between the two sets of ports. There would then be a potential for upsetting the safety system without prior warning, the normal flow of information or data not being affected by this condition.

Figure 1 portrays this situation where there would ideally exist no coupling between the input and output port. Yet the ports are coupled by resistors *Rc* which in an extreme case might be zero (short circuit). The gain "box" may be expected to override the effects of coupling resistors *Rc* so that in the normal course of plant operation involving the transmission of signals from the input to output port there would be no reason to become aware of the (unwanted) coupling. It might be noted that when a coupling path is resistive, the term leakage is sometimes employed to describe the transfer of energy between ports. In what follows below the transfer of energy will be termed "reach-through," whatever the nature of the coupling path is.

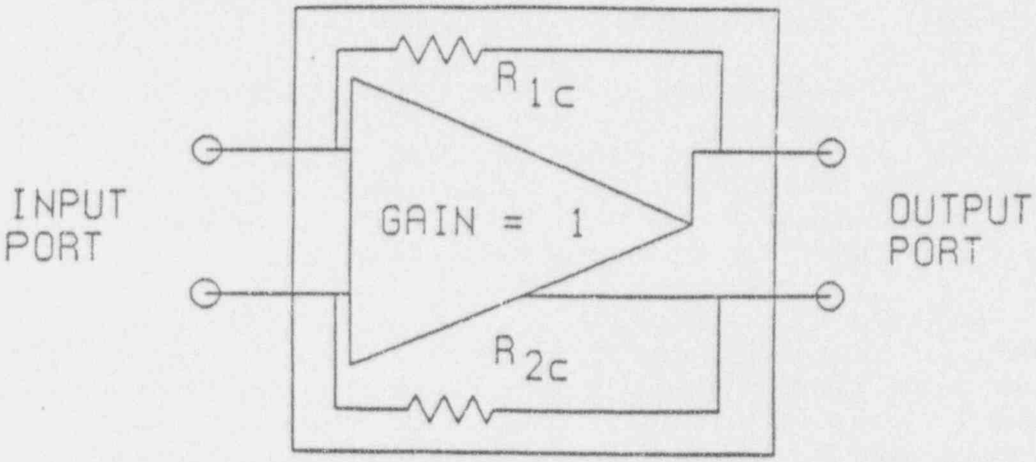

Figure 1. Non-ideal isolator

Since 1984, more than 700 failures involving electronic isolation devices in nuclear power plant service have been reported to the Nuclear Plant Reliability Data System (NPRDS). The use of electronic isolation devices continues to increase as plants upgrade older equipment and incorporate more electronic and computer-based instrumentation and controls into their operating systems. The proposed control systems for the next generation of advanced nuclear power plants will depend heavily upon the use of isolation devices to achieve the required degree of signal isolation.

Earlier testing programs (Ref. 1) have indicated that electronic isolation devices may experience severe damage when subjected to the maximum credible AC or DC voltage (Ref. 2) and current levels, particularly when applied to the output side of the energized device. For the testing program in Reference 1, the maximum credible AC voltage was taken to be 120 Vac, ±10%, 60 Hz, 20 A source, and the maximum credible DC voltage was taken to be the power supply voltage of the isolator. Concerns have been raised that similar or more severe problems might be realized at fault voltages and currents less than maximum credible levels. The actual "reach-through" energy* passed across the isolation device during the duration of a fault condition, even while not attaining maximum credible voltage potentials, might still be large enough to inflict damage on sensitive electronic components. The maximum credible fault (MCF) for a given isolation device is thus defined as that fault potential at which the maximum reach-through energy is passed across the isolation barrier.

1.2 Objectives

The present testing program will investigate whether such problems can arise at fault levels up to the maximum credible potential, by measuring the reach-through energy passed through several different types of electronic isolation devices during a fault. An increasing, incremental series of fault conditions will be applied to each isolation device, up to the full maximum credible potential level, to determine the relationship between the reach-through energy and the applied fault voltage. The susceptibility to potential damage for various families of electronic components can then be ascertained for applications utilizing the tested isolation devices.

In the testing to be described below, a digitally controlled source of 0-120 Vac (60 Hz) will be applied to the output side, in an incremental series of steps designed to uncover "blind spots" (Ref. 3), i.e. ranges of fault voltages and currents lower than the "safe" maximum credible potential which in fact may pass through sufficient energy to damage the isolation device. As discussed in Reference 3, equipment containing protective devices may perform well at maximum stress (120Vac) and yet not perform as intended at some intermediate level (<120Vac).

While driving the output side with the AC voltage, the input side will be terminated in a nominal resistance, *Rx*, of 1000Ω. The reach-through voltage, *Vx*, across the resistance will be monitored and $\int Vx(t) * Ix(t) * dt$ will be calculated to give the reach-through energy in watt-sec or joules as a function of the applied AC voltage, Vac. This will give a quantitative value to the reach-through energy which can then be related, for example, to published values of lethality in various logic component families. Since it is difficult to characterize all the variations of the "real-world" environment by a single value of input impedance, for the purposes of this testing program, a representative value of input resistance, *Rx*, was chosen. The test data thus obtained will allow the plotting of the relation between reach-through energy and applied AC voltage Vac for each isolation device. If these graphs are not monotonic functions but instead show a peak (corresponding to the MCF) at values less than Vac maximum (120V AC), the testing program will be able to identify such potential problem areas.

One such possible graph is sketched in Figure 2. The reach-through energy is shown increasing linearly from zero at a threshold value of *THR* of 10 Vac. At a value of Vac = 50 V, the

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*"reach-through" energy is the integral of the voltage * current * dt at a particular voltage level.

reach-through energy, ϵj, picks up more rapidly, reaching a maximum of 90 μjoules at Vac = 80 V, after which ϵj decreases to <40 μjoules at 140 V. It should be noted that the maximum ϵj (MCF) does not occur at the maximum credible potential of 120 Vac so that the situation portrayed is an example of a blind spot. From Figure 3, which shows the range of damage threshold (in units of energy) for various devices, it will be seen that a medium and high-power transistor suffers damage at a level somewhat >100 μjoules. In the preceding example, the reach-through energy of 40 + μj passed across the isolation device at the MCP fault level clearly does not indicate how close to the threshold of damage this device (had it been deployed) would have come (assuming a value of *Rx* = 1000Ω is the appropriate value to be used). Figure 3 shows the energy range (in joules) for damage to a variety of devices. It will be seen that for medium and high-power transistors damage occurs at a level somewhat in excess of 100 μjoules. In the preceding illustrative example, at the maximum credible potential of 120 Vac, the amount of reach-through is well below this, yet the margin of safety at the peak value of 90 μjoules is very slim.

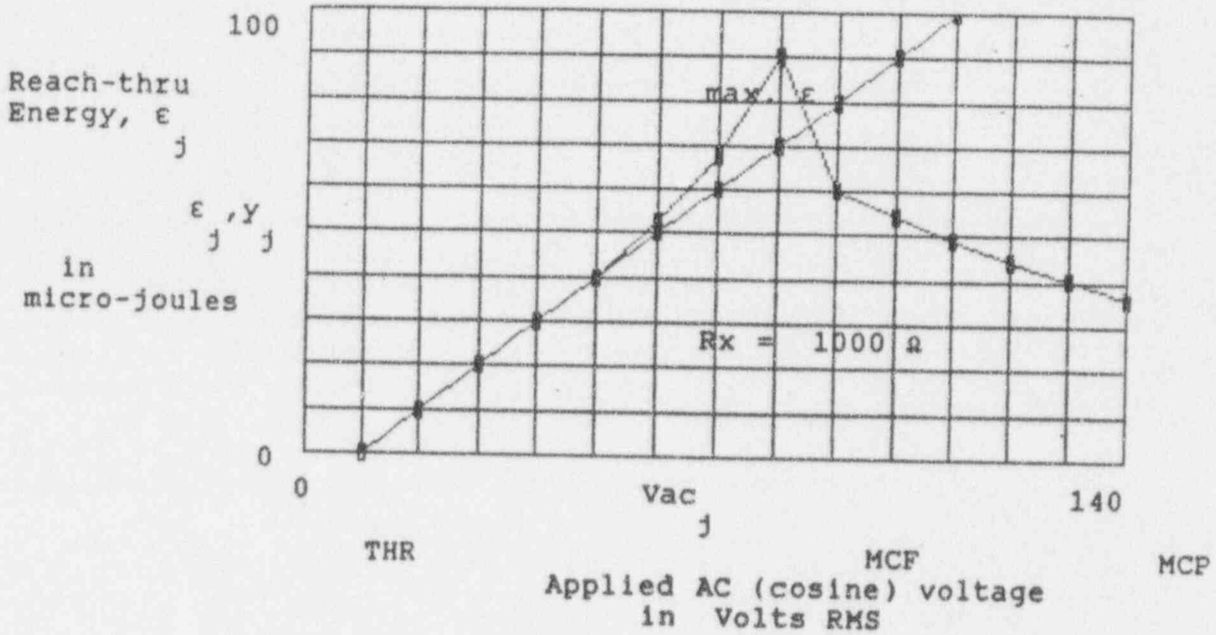

Figure 2. Reach-through energy vs. applied AC voltage, in volts RMS

Isolators may be divided into four generic groups, as discussed in Reference 1. These are:

1. Fiber optic devices
2. Devices using transformer modulation and having voltage inputs and outputs
3. Same as 2 above, except outputs are current
4. Isolators using photo-semiconductors to achieve isolations.

One or more of the most widely used nuclear power plant electronic isolation devices from each group will be included in the test program.

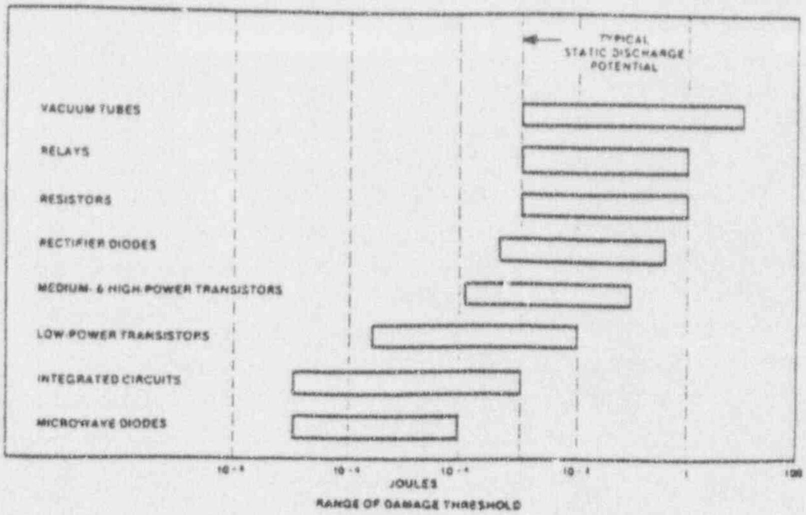

Figure 3. Range of damage threshold for electronic devices

1.3 Isolation Devices to be Tested

The isolation devices to be tested in this program will include a group of approximately ten different models that are representative of the equipment utilized in nuclear power stations. Surveys of the Nuclear Plant Reliability Data System (NPRDS) were conducted to gather the necessary background information such as manufacturers, model numbers, and operating and application data. Over 700 reports of isolation device failures were identified, categorized, and reviewed to aid in the selection process. The isolation devices tested previously in the NUREG/CR-3453 (Ref. 1) testing program were also taken into consideration.

The present fault testing program for isolation devices will include equipment from the following manufacturers:

Devar Inc.
Foxboro
NUS Corporation (formerly Energy, Inc.)
Rochester Instrument Systems
Technology for Energy Corp.
Transmation Inc.
Validyne Engineering Corp.
Westinghouse

The test sample of isolation devices will include at least one device from each of the four generic groups identified in Section 1.2 above and Reference 1. The equipment tested will represent the devices and model numbers most frequently identified in isolation device failures reported to the NPRDS data base from 1974 through mid-1991. The final selection of the test sample will be subject to the availability of the specific models which BNL intends to procure, since some of the devices may no longer be available.

1.4 Scope

The object of this testing program is to investigate and understand the amount of "reach-through" energy passed through various kinds of isolation devices using AC voltage as the disturbing factor (120 V rms max, 60Hz) with proper attention to "blind spots," as defined previously in Section 1.2.

The testing will be under the control of a PC in communication with the AC source and various recording devices. The IEEE 488 Standard Bus under control of the PC using National Instruments NI-488.2 software and Microsoft Quick BASIC software will be used to operate the instrumentation and record pertinent data on floppy disk data files.

It should be noted that the maximum credible potential assumed is the (mis)application of an AC voltage to the output side at 120V rms. This testing program shall determine useful information on the reliability and robustness of isolation devices at much lower levels of disturbance than the MCF (120V rms AC max, 20A max). The present testing will build upon the earlier results of major fault testing described in Reference 1, and investigate areas not covered in the previous work, in order to quantify the relationship between *Vac* applied to the isolation device output, and reach-through energy. The information gained will enhance the knowledge about the performance of electronic isolation devices. The final report will seek to relate the test results to those of Reference 1.

It will also be noted that fault application to the isolator output is required by IEEE Std 279-1971 (Ref. 2) Section 4.7.2. Criterion 24 of 10 CFR 50, Appendix A (Ref. 6) also requires "that failure of equipment common to protection and control (i.e. isolators) leaves intact a system satisfying all reliability ... requirements of the protection system and requires that safety not be impaired..." We shall therefore be concerned with the lethality of the reach-through energy upon equipment on the safety side of the isolation device and whether such destructiveness occurs at Vac max or a lesser value.

Useful test results should facilitate the in-house surveillance testing of isolation devices at various nuclear plants without requiring expensive surge simulation equipment.

In case of destructive failure, a physical inspection of the isolation device together with clues from the testing data should pinpoint the exact causes of the destruction. In fact, care will be taken prior to the testing of each specific device under test to anticipate (as far as possible) destructive levels of Vac from studies of the schematic and other vendor information and coordinate this information with test abort programming. (For example, "crowbars," "clamps," and the like will be factored into account).

2. TEST SET-UP

The basic test set-up is shown in Figure 4. Program control is provided by National Instruments NI-488.2 software and Microsoft Quick BASIC software running an IBM PC or 100% compatible IBM PC clone. An IEEE-488 interface provides for control of the POWERTRON Model 3000S AC amplifier, HP3325 Synthesizer, Keithley Model 2001 DMM, SRS DS345 Synthesizer, and Lecroy Model 9314M DSO. Some technical details of the test equipment and software are shown in Appendix A. It should be noted that the AC voltage can be either a sine or cosine wave (or something in-between) when it is applied to the device under test (DUT). In the latter case, the time duration of the transient between 0 and Vpeak will be no worse than 50 nS. The number of fault pulses to be applied to the DUT can be selected from the programmable trigger to be one and only one per event up to 99 fault pulses per event. The programmable divider is used to select the delay between pulses (the duty cycle) in multiple fault pulse events (e.g., by setting the programmable divider to 5 and selecting 3 fault pulses on the programmable trigger, three cosine fault pulses will be applied to the DUT at an interval of one fault pulse every fifth cycle). The standard generator includes a provision to switch the unit automatically at a predetermined load current from the constant voltage mode into a constant current mode (20A max).

The rapidity of the starting edge of a cosine wave can be expected to add to the reach-through current through the output/input capacitance by three orders of magnitude or more, by virtue of the ratio of rate of change of voltage (for the same peak amplitude) for the cosine wave as compared to a sine wave. For this reason, the cosine wave produces more testing stress in the DUT, and the results thus obtained represent the upper bound of the worst case fault conditions that will be experienced at each level.

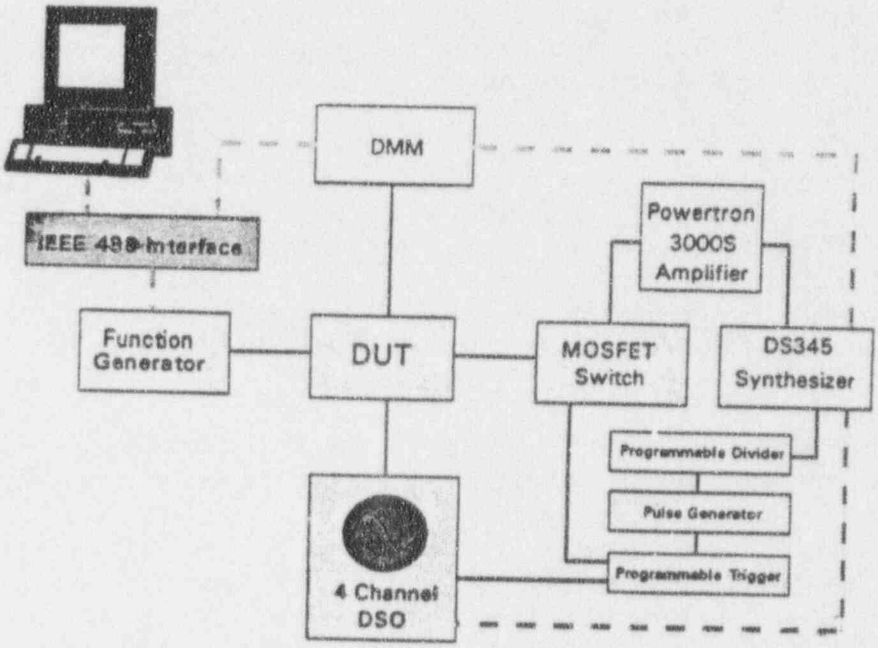

Figure 4. Basic test setup

As described above, the AC source can be programmed in time duration from fractional cycles to many cycles. It is proposed to run most interference tests using half-cycles of non-contiguous cosine waves of different amplitudes to cover the requirement of blind spot testing. It may be seen that the possibility of avoiding DUT destruction exists by aborting the test when high input currents from the AC source are starting to be sensed, or limiting applied faults to a single half cycle burst thereby minimizing the danger of destroying a DUT while still achieving the objective of measuring energy passed through the isolation barrier.

2.1 Test Equipment List

The test equipment to be used for this test program is listed below. Details and specifications of the more specialized equipment and software are included in Appendix A.

Test Equipment	Mfg. & Model No. (where available)
Powertron, 3 KVA source, single ϕ	Model 3000S, Industrial Test Equipment Co., Inc.
MOSFET Power Switch/Controller	Custom Design, Industrial Test Equipment Co., Inc.
IEEE-488 Interface Board w/connecting cables	National Instruments MC-GPIB
Synthesized Function Generator	Stanford Research Systems Model DS345
Pulse Generator	Interstate Electronics Corp. Model P12
High Performance Digital Multi Meter	Keithley Model 2001 DMM w/10-channel scanner card
IBM PC/AT or better	IBM PS/2 Model 55X
5-Decade Programmable Divider	Custom Design, BNL
Programmable Pulse Trigger	Custom Design, BNL
4-Channel Digital Storage Oscilloscope	LeCroy Model 9314 M-MC01/04 w/Options WP01/02 and Trigger Out Provision
MicroSoft Quick BASIC Software Version 4.5	MicroSoft Corp.
IEEE 488 Bus Language Interface and Device Drivers for MS-DOS	National Instruments NI-488.2 for MS-DOS Software
Current Transformer	Pearson Electronics Inc. Model 110A
Synthesizer/Function Generator	Hewlett-Packard Model 3325A

3. TEST PROCEDURE

In this section, each of the major sequential test segments will be discussed.

3.1 Isolation Impedance Measurement

Prior to the application of fault waveforms, it is desirable to establish the value of the baseline electrical characteristics of the isolation barrier. Changes in the integrity of the isolation barrier due to subsequent application of fault waveforms may be reflected in corresponding changes in the electrical characteristics of the isolation barrier. This is done by obtaining measurements of the isolation barrier resistance and capacitance as described in the following sections.

3.1.1 Isolation Barrier Resistance

The configuration for this test segment is shown in Figure 5. Direct measurement of the isolation barrier resistance using a multimeter is impractical due to the high value encountered (> 1 GΩ generally). In the method shown in Figure 5, a large sampling resistor (10 M Ω) is placed in series with the positive input terminal of the isolator. A known dc voltage is then applied across the series combination of the sampling resistor and the isolation barrier resistance. The voltage drop (V_{SR}) is measured across the known sampling resistor to find the current (I_{IB}) flowing through the circuit. The dc resistance of the isolation barrier may then be calculated from the current (I_{IB}) and voltage drop (V_{IB}) across the isolator.

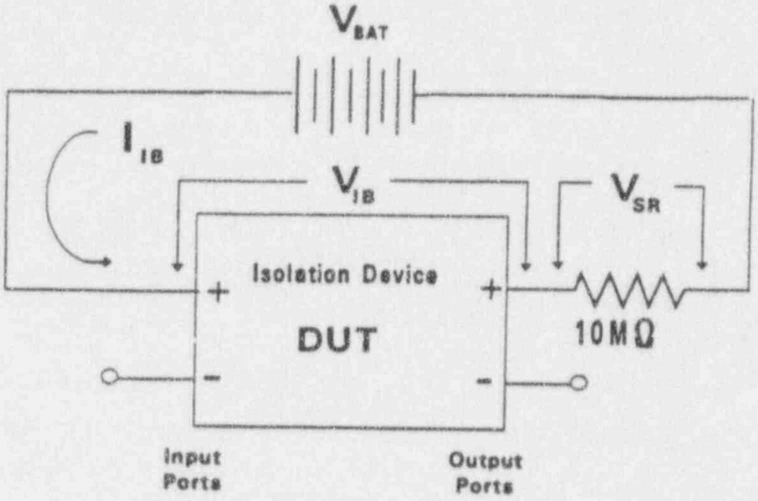

Figure 5 Isolation barrier resistance measurement

3.1.2 Isolation Capacitance

The capacitive coupling across the isolation device is the primary means by which energy may be transferred across the isolation barrier. This isolation capacitance may be measured by the test configuration shown in Figure 6. The function generator is set to apply a low voltage (< 5V $_{RMS}$) sinusoidal, waveform of known frequency across the positive terminals of the isolation device. The current (I_{IB}) flowing across the isolation barrier is measured on the DMM. Isolation capacitance (C_{IB}) may then be calculated as:

$$C_{IB} = \frac{I_{IB}}{2\pi f\, V_{IB}}$$

3.2 Isolation Device Functional Test

Prior to the application of fault waveforms, the functional performance of the isolation device must be verified. This is achieved by applying signals to the input of the energized isolation device and measuring the corresponding output signal transmitted throughout the device.

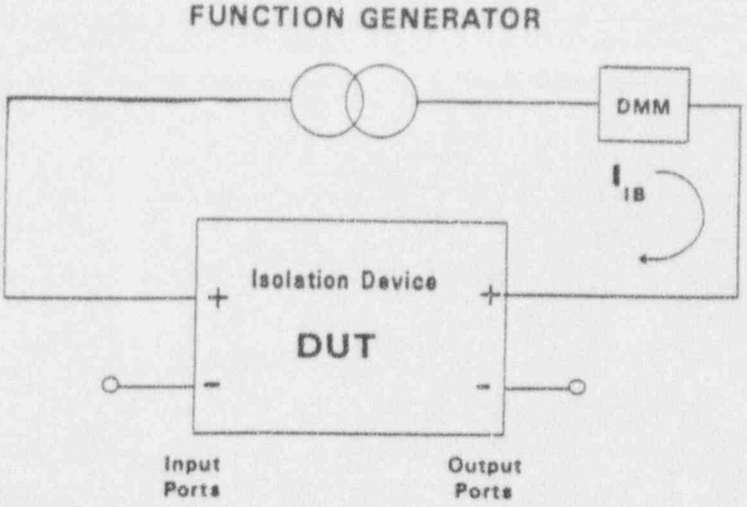

Figure 6 Isolation Capacitance Measurement

The basic functional test configuration for analog or digital voltage-to-voltage isolators is shown in Figure 7. With the isolator powered, analog input signals may be applied at three levels (zero, midpoint, full span) or five levels (zero, 25%, 50%, 75%, and full span) of the specified device input range, and the corresponding outputs measured on a DMM as shown in the figure. For digital devices, the technique is the same except only two levels need be checked: the digital low and digital high.

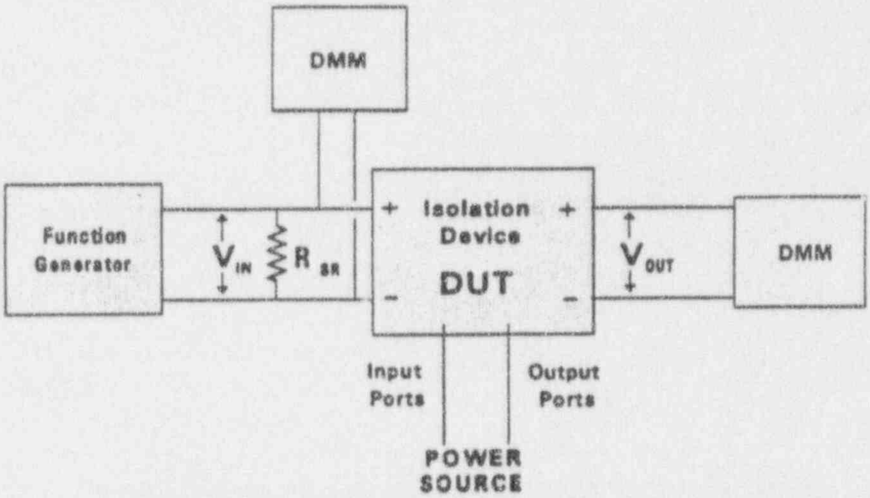

Figure 7 Voltage-to-voltage isolator functional test

In the case of current-to-current isolators, the functional test arrangement is as shown in Figure 8. An adjustable dc power supply is used to supply known currents at three or five levels, from zero (typically 4 ma) to full span (20 ma), to the input terminals of the powered isolation device. The input current may be measured directly with a DMM or as shown in the figure using a series $1K\Omega$ sampling resistor at the input and measuring the voltage drop across the resistor with a DMM. The output of the device is connected across a load resistor R, of the magnitude specified by the manufacturer. Output current is measured on the DMM by the voltage drop through the load resistor R_L.

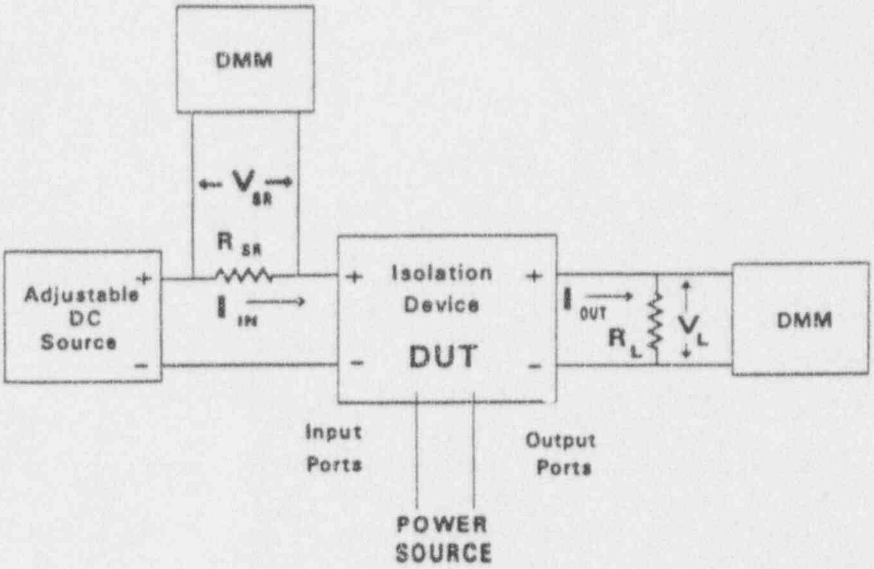

Figure 8 Current-to-current isolator functional test

3.3 Fault Testing

In this test segment, as shown in Figure 9, the AC fault voltage will be applied to the output terminals of the energized isolation device in the form of a single, half-cycle, cosine waveform and in amplitude steps of 10% of maximum (120V rms) ranging from 0 to 110% with the input terminated in a resistance, *Rx*. The applied AC voltage starts at zero and slews rapidly to the maximum, continues for a half cycle and then slews rapidly from a negative maximum to zero. For maximum stress, the transition time should be as short as possible. For the fault pulse generator described in Section 2, the typical transition time is no more than 50 nS for a 10% to 90% rise on the leading edge and 10 μS from 90% to 10% on the trailing edge. The AC voltage is applied in this form since it is expected that the isolation devices to be tested employ solid-state devices. This implies that whatever is to be measured will occur with a time-scale of microseconds, or perhaps milliseconds.

The input current will be monitored and recorded at each incremental step as will the output (if any) across the input resistor, *Rx*. From this, reach-through energy will be calculated (the integral of $[Vx(t)]*[Vx(t)/Rx]*dt$ at each amplitude step).

Upon completion of each incremental test segment, the isolation impedance will be tested as described in Section 3.1. and a functional test performed as described in Section 3.2.

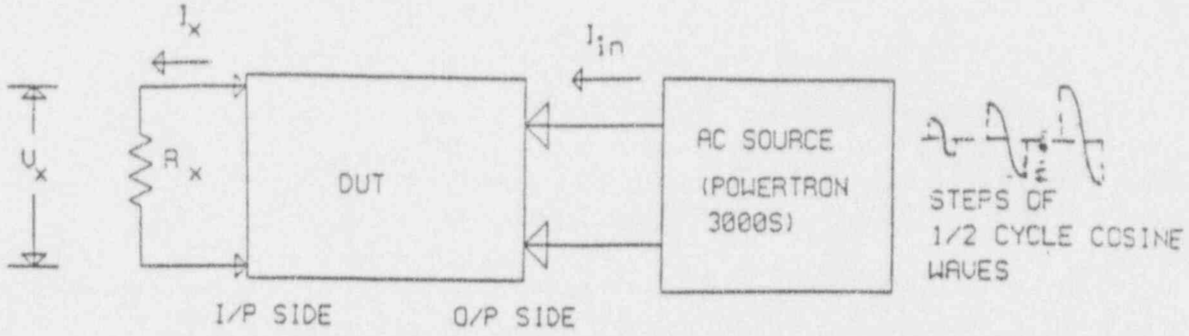

Figure 9 Isolator incremental fault testing

Finally, a graph of reach-through energy vs AC voltage amplitude will be produced. A plot of input current as a function of Vac will also be made.

By comparing the responses at the front and back AC transitions at each amplitude step as well as between amplitude steps some conclusions should be possible as to linearity of response as well as sensitivity to polarity of applied AC signal. A rapid increase in input current (to the output port) with AC voltage may signal, in the absence of device protective elements such as crowbars, clamps, etc., close proximity to the level of device destruction.

3.4 Test Data Acquisition

Performance of test segments is conducted under control of the PC. Consequently, the collection of the data from each test level will likewise be controlled through the IEEE 488 bus by the interfacing software, via the preprogrammed sequence commands. Data will be stored on floppy disks for later display and analysis.

3.5 Miscellaneous

It should be noted that most tests, where a choice logically exists, will be performed with power on to the equipment under test.

4. EXPECTED RESULTS

The results from this test program will identify and characterize the following:

4.1 Physical Inspection – At the end of the various automated test segments,a physical inspection of the device under test will be made to identify any damaged components (such as iou or burned resistors, peeling circuit board traces, etc) and relate them to appropriate test data and test conditions to pinpoint specific problems and weaknesses. Where necessary the testing will be stopped and such parts will be replaced or repaired to return the DUT to normal conditions and then the testing will continue.

4.2 Analysis of Test and Monitoring Data – Each device will be characterized by a maximum reach-through energy number and applied AC voltage (sine or cosine amplitude), and impedance level (*Rx* required to produce it. Also furnished will be the linear response range since it is likely that from this, a judgement of how close to destruction the device came, can be made.

4.3 Recommendations for the Improvement of Plant Maintenance and Surveillance Procedures for Isolation Devices – Certain procedures and results from the test program will be examined for application to the plant as isolation device surveillance testing. An example might be the isolation impedance test described in Section 3.1.

4.4 Analysis of Circuit Design – Where possible study of the device circuitry and schematic will be made to correlate observed performance with results obtained. Also, where possible, the results will be correlated with those of Reference 1.

5. REFERENCES

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TEST PLAN APPENDIX A

Test Equipment and Software

Powertron INDUSTRIAL TEST EQUIPMENT CO., INC.
21 Yennicock Avenue, Port Washington, NY 11050 • (516) 883-1700

AMPLIFIERS - SERIES 1000S, 1500S, 2000S, 3000S

GENERAL SPECIFICATIONS

Output Circuit: Single phase isolated (Ground terminal is provided for optional grounding of output.)

Load Power Factor: 0.7 Lead through 0.7 Lag for full power. Useable to 0.2 at reduced power.

Output Voltage Range: 0-130 V RMS. (An output connector provided at the rear of the unit may readily be reconnected to provide optimum power output at other voltages. Ranges available are: 0-300 V*, 0-260 V*, 0-150 V, 0-140 V, 0-130 V, 0-76 V, 0-65 V.)
* With internal strapping

Output Distortion: 0.5% mid band.

Load Regulation: Factory set to ±0.5% mid band. (A control is provided for zero regulation adjustment over most of the frequency range.)

Line Regulation: ±0.1% for ±5% line change.

Transient Response: 50 microseconds.

Hum Level: 70 db approx. below rated output voltage.

Short Circuit Protection: Output may be shorted indefinitely without damage to unit.

Thermal Overload Protection: Output transistors protected by thermal cutout circuit.

External Amplifier Input: An input connector is provided on the rear of the unit when it is desired to drive the amplifier from an external source. Model XA-1 plug-in module is required for this mode of operation.

External Sync Input: An input connector is provided at the rear when it is desired to synchronize the plug-in oscillator with an external frequency source.

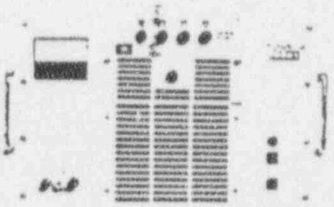
Convenience Outlets: An auxiliary power outlet, controlled by the power switch, is provided at the rear of the unit. This permits single control operation of one or two additional amplifiers when 2ϕ or 3ϕ outputs are required.

Meter: A voltmeter with range of 0-150 V RMS is provided to monitor the output voltage. When used on higher output voltage, meter reads ½ voltage.

Input Power: 208 V RMS line to line, 3ϕ, 50-60 Hz. Also available 190 V RMS, 225 V RMS, 240 V RMS, 380 V RMS, 450 V RMS.

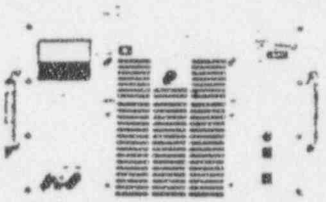
Ambient Temperature Range: 0°C to 50°C.

MODEL 1000S



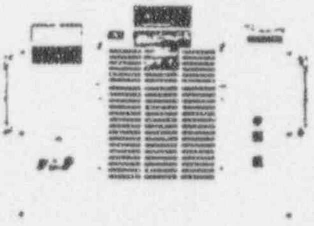
Output Power:
1 KVA
Freq. Range:
45 Hz—
5 KHz (full power)
20 HZ—10 KHz (reduced Power)
Size: 12¼" x 19" rack panel x 22" deep
Weight: 210 lbs.

MODEL 1500S



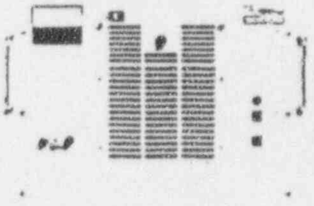
Output Power:
1.5 KVA
Freq. Range:
45 Hz—
5 KHz (full power)
20 Hz—10 KHz (reduced power)
Size: 12¼" x 19" rack panel x 22" deep
Weight: 225 lbs.

MODEL 2000S



Output Power:
2 KVA
Freq. Range:
45Hz—
5 KHz (full power)
20 Hz—to 10 KHz (reduced power)
Size: 17½" x 19" rack panel x 22" deep
Weight: 250 lbs.

MODEL 3000S



Output Power:
3 KVA
Freq. Range:
45 Hz—
5 KHz (full power)
20 Hz—10 KHz (reduced power)
Size: 17½" x 19" rack panel x 22" deep
Weight: 260 lbs.

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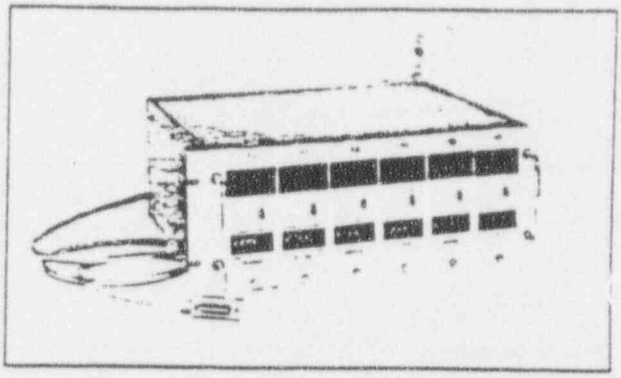
Powertron INDUSTRIAL TEST EQUIPMENT CO., INC.
21 Yennicock Avenue, Port Washington, NY 11050 • (516) 883-1700

MODEL 5700 BCD, IEEE BUS PROGRAMMER



The AC Power Programmer 5700 is used in conjunction with the various AC power amplifiers to provide precisely controlled frequency, amplitude, and phase angle displacement. The programmer includes the capability for 3 modes of control, by front panel BCD thumbwheel switches, by remote BCD signals, or by remote IEEE-488 GPIB. The modular construction of the programmer allows the user to purchase only the modules required for the application, and to expand the system as required. Thus, a single-phase application would require only a frequency module, and an amplitude module, a two-phase application requires a frequency module, two amplitude modules, and a phase shift module, and a three-phase system requires the full compliment of frequency module, three amplitude modules, and two phase shift modules. Remote programming is also optional and expandable in that separate modular plug-ins are available for remote BCD, or IEEE operation.

The digital techniques employed in the frequency and phase modules of the programmer insure precise control of these functions. The amplitude modules provide servo loop control of the respective output amplifiers insuring precise amplitude stability and control. Local or remote programming for each function is selected by a front panel switch. Remote programming status is displayed on LED indicators of the respective control modules.

MAINFRAME

The mainframe contains the support components of this building block system: The DC power supply, the "mother board," and the cabinetry. The appropriate plug-ins can be added as needed.

In order to identify the programmer correctly, use the ordering designations shown in the example below:

500S - 23 - 5700

Powertron Model Number

Programming Designation

-1- 1 phase for use with 1 Powertron
Contains 1 amplitude and 1 frequency module

-23- 2 phase for use with 2 Powertrons
Contains 2 amplitude, 1 frequency, and
1 phase shift module

-3- 3 phase for use with 3 Powertrons
Contains 3 amplitude, 1 frequency, and
2 phase shift modules

Mainframe

Special options to meet specific requirements are available. Please prepare a specification and consult the factory for details.

Powertron INDUSTRIAL TEST EQUIPMENT CO., INC.
21 Yennicock Avenue, Port Washington, NY 11050 • (516) 883-1700

PROGRAMMABLE OSCILLATOR MODULES

SPECIFICATIONS

FREQUENCY CONTROL MODULE

The frequency control module provides 3 programmable ranges with provisions for locking out any range. Frequency accuracy is ±.005% as determined by internal crystal reference oscillator.

Ranges: 40.00 Hz to 99.99 Hz in .01 Hz steps
40.0 Hz to 999.9 Hz in .1 Hz steps
40 Hz to 9999 Hz in 1 Hz steps
Distortion: Less than 1%

AMPLITUDE CONTROL MODULE

The amplitude control module provides 2 ranges with provision for range programming when used with appropriately modified amplifiers. Independent or simultaneous programming capability is provided for polyphase applications.

Ranges: 0—130 volts RMS or 0—260 volts RMS
Resolution: 0.1 volt steps
Load Regulation: ±.01%
Line Regulation: ±.01%

PHASE SHIFT CONTROL MODULE

The phase shift control module provides precise digital phase control over the frequency range of the equipment. Overall phase displacement accuracy will depend upon the amplifier and amplifier load symmetry.

Range: 0 to 399 degrees
Resolution: 1 degree steps
Accuracy: ±0.1 degrees

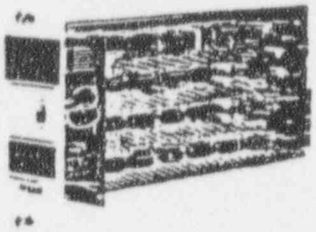
IEEE BUS INTERFACE MODULE

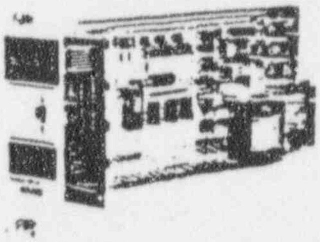
The IEEE bus module is interchangeable with the BCD interface module and is readily installed by simply plugging in at the rear of the equipment. The GPIB interface connector is included on the module. The module is microprocessor controlled with programming codes residing in PROM. This arrangement allows for modifications to meet special user requirements. Automatic diagnostics are provided to indicate incorrect character prefix, incorrect place, incorrect digit, incorrect function, and too low frequency. Error lights and audible alarm indicate fault.

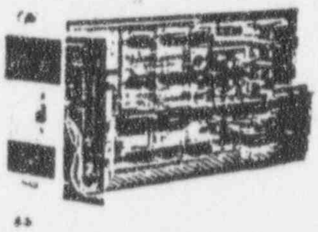
BCD INTERFACE MODULE

The BCD interface module is interchangeable with the IEEE bus module and is readily installed by simply plugging in at the rear of the equipment.

Appropriate interface connectors are included on the modules. The input is TTL compatible.


FREQUENCY CONTROL MODULE


AMPLITUDE CONTROL MODULE


PHASE SHIFT CONTROL MODULE


IEEE BUS INTERFACE MODULE


BCD INTERFACE MODULE

TEST PLAN APPENDIX B

Fault Testing Procedure

B. FAULT TESTING PROCEDURE

B.1 Purpose

This procedure provides a performance document for use in verifying the fault withstanding capabilities of electronic isolation devices. Tests include the application of AC voltage across the output of the isolator in incremental steps from .1 × MCP to 1.1 × MCP, at 20 amp maximum.

B.2 Test Equipment Used

Test Equipment	Mfg. & Model No. (where available)
1. Powertron, 3 KVA source, single ϕ	Model 3000S, Industrial Test Equipment Co., Inc.
2. MOSFET Power Switch/Controller	Custom Design, Industrial Test Equipment Co., Inc.
3. IEEE-488 Interface Board w/connecting cables	National Instruments MC-GPIB
4. Synthesized Function Generator	Stanford Research Systems Model DS345
5. Pulse Generator	Interstate Electronics Corp. Model P12
6. High Performance Digital Multi Meter	Keithley Model 2001 DMM w/10-channel scanner card
7. IBM PC/AT or better	IBM PS/2 Model 55X
8. 5-Decade Programmable Divider	Custom Design, BNL
9. Programmable Pulse Trigger	Custom Design, BNL
10. 4-Channel Digital Storage Oscilloscope	LeCroy Model 9314 M-MC01/04 w/Options WP01/02 and Trigger Out Provision
11. MicroSoft Quick BASIC Software Version 4.5	MicroSoft Corp.
12. IEEE 488 Bus Language Interface and Device Drivers for MS-DOS	National Instruments NI-488.2 for MS-DOS Software
13. Current Transformer	Pearson Electronics Inc. Model 110A
14. Synthesizer/Function Generator	Hewlett-Packard Model 3325A

B.3 Precautions

1. All equipment is to be used in accordance with the manufacturer's instructions. Technical literature and specifications for each device are to be reviewed prior to testing to identify potential problem areas.

2. Cautions should be exercised when working on or around energized electrical components to avoid the hazard of shock.

3. Personnel should be clear of the testing area when testing is in progress to avoid injury.

B.4 Setup

1. The DUT should be inspected and calibrated in accordance with the manufacturer's specifications. Record results on Data Sheet B.1.

2. Setup the DUT and test equipment in accordance with Figure 4.

3. Driver software should be running with the testing sequence command program loaded.

4. Load the data disk for the recording of test data. Record the disk number and test run number on Data Sheet B.1.

B.5 Test Performance

1. Run Barrier Resistance measurement as described in Section 3.1.1 and record the results on the Data Sheet B.1.

2. Run Barrier Capacitance measurement as described in Section 3.1.2 and record the results on the Data Sheet B.1.

3. Apply power to the DUT and perform the Isolator Functional Test measurement as described in Section 3.2 and record the results on the Data Sheet B.1.

4. Set the fault level input to the fault pulse waveform generator as described in Section 3.3.

5. Apply incremental fault waveform to DUT output terminals as described in Section 3.3.

6. Calculate $\int [V_x(t)]*[V_x(t)/R_x]*dt$ to find reach-through energy for the fault level.

7. Download fault voltage and current waveforms, and reach-through voltage, current, and energy waveforms to PC floppy disks. Record the storage disk information on the Data Sheet B.1.

8. Inspect the DUT for any damage which may have occurred. Record any findings or observations on Data Sheet B.1.

9. Repeat steps 1 through 8 in 10% increments of fault voltage up to 110% of MCF.

10. Repeat steps 1 through 3 after application of the 110% of MCF fault level.

B.6 Post-Test Procedure

1. Remove power from the DUT.
2. Verify that test data has been recorded on data disk.
3. Disconnect DUT from all test connections.

FAULT TEST DATA SHEET B.1

Isolation Device:

MAKE: ______________________
MODEL: ______________________
SERIAL#: ______________________

DATE: __________ TIME: __________
TEST RUN #: ______________________
FAULT LEVEL: __________ X MCF

Pre-Test Calibration and Inspection:

OBSERVATIONS: ____

____

____

Barrier Resistance Measurement:

OBSERVATIONS: ____

____

____

____

____

Barrier Capacitance Measurement:

OBSERVATIONS: ____

____

____

____

____

FUNCTIONAL TEST:	INPUT	OUTPUT
	______	______
	______	______
	______	______
	______	______
	______	______

FAULT TEST:

DISK #: ____
OBSERVATIONS: ____

____

APPENDIX B

BNL

ISOLATOR TEST FACILITY

DESCRIPTION OF
BNL ISOLATOR TEST FACILITY

The BNL Isolator Test Facility (ITF) was designed to provide a detailed survey of specific potential power fault conditions affecting electronic isolators. Such isolator faults might prevent input connected critical protection systems from meeting their minimum performance requirements. In earlier testing performed under the NRC's Isolation Devices Evaluation Criteria Program, and reported by Neilsen in NUREG/CR-3453 (Ref. B.1), some electronic isolation devices experienced severe damage when subjected to maximum credible AC or DC voltage and current levels (e.g. 120vac, 20a) when applied to the output side of the energized device.

In addition to these maximum credible fault states, additional questions have surfaced suggesting that other, less-than-maximum voltage and current conditions might find a leakage path across the isolator allowing potentially destructive energy levels to breach the isolation barrier. The below maximum credible voltage potentials may contain other properties influencing damage to connected devices. Such power conditions might occur as a result of subtly induced power levels that are a function of power fault transients relating to wave shape, as well as amplitude. The maximum credible fault (MCF) for a given isolation device must thus be defined not only as that fault potential at which the maximum reach-through energy is passed across the isolation barrier, but also as a function waveform dependent parameters.

To satisfy the critical investigation process the ITF was developed to accurately and automatically monitor the vital connections of the isolator while systematically applying predetermined fault profiles to the output of the isolator. To ensure maximum detection capability, electronic measuring instruments were chosen that are capable of the highest sensitivity and resolution relative to the measurement objectives. These sensitive instruments permit minute currents to be detected, both statically and dynamically, so transient through-put phenomena can be observed and quantified.

THE TEST INSTRUMENTS

The complete test setup is constructed from carefully selected instruments so they can be functionally integrated through a small computer for maximum flexibility. The computer controls, monitors, and records all the critical parameters important for determining isolator barrier integrity. The major instruments that comprise the ITF and their function are listed below.

Test Equipment	Mfg. & Model No. (where available)
Powertron, 3 KVA source, single ϕ	Model 3000S, Industrial Test Equipment Co., Inc.
MOSFET Power Switch/Controller	Custom Design, Industrial Test Equipment Co., Inc.
IEEE-488 Interface Board w/connecting cables	National Instruments MC-GPIB
Synthesized Function Generator	Stanford Research Systems Model DS345
Pulse Generator	Interstate Electronics Corp. Model P12
High Performance Digital Multi Meter	Keithley Model 2001 DMM w/10-channel scanner card
IBM PC/AT or better	IBM PS/2 Model 55X
5-Decade Programmable Divider	Custom Design, BNL
Programmable Pulse Trigger	Custom Design, BNL
4-Channel Digital Storage Oscilloscope	LeCroy Model 9314 M-MC01/04 w/Options WP01/02 and Trigger Out Provision
Regulated DC Power Supply	Power Designs Model 5015-S
MicroSoft Quick BASIC Software Version 4.5	MicroSoft Corp.
IEEE 488 Bus Language Interface and Device Drivers for MS-DOS	National Instruments NI-488.2 for MS-DOS Software
Current Transformer	Pearson Electronics Inc. Model 110A
Synthesizer/Function Generator	Hewlett-Packard Model 3325A

Digital Storage Oscilloscope, LeCroy Model 9314M, has the capability to record fast transient events. These are time dependent voltages that are not possible to detect with a digital voltmeter or similar device. Such voltages are significant because they can be of sufficient amplitude to cause induced faults without being detected under normal operating conditions. With this instrument it is possible to record any potential transient effects and assess their potential to compromise critical protection systems.

The LeCroy oscilloscope used in the test is capable of recording four transient events simultaneously. Four input channels are used to monitor both input and output voltages to the DUT. It is also used to monitor input and output currents of the DUT through sensitive, fast-response current transformers connected at those respective locations. The resulting data acquisition from the digital recording oscilloscope may then be both controlled by, and transferred to, the computer through an IEEE 488 interface for display, storage, and analysis.

Synthesizer/Function Generator, Hewlett Packard Model HP3325A, serves two purposes: first, it is used for functional testing by supplying a defined input signal to the DUT which is then compared to the signal at the output to determine functional integrity, and second, it provides an alternating current source to assess AC barrier integrity. It is configured to the testing apparatus for both applications via computer control (IEEE 488 Bus) and the associated switchgear.

Synthesized Function Generator (Stanford Research Systems Model DS345) provides high resolution, digitally synthesized, waveforms to 30 MHz. Outputs can be standard waveforms or complex arbitrary signals with up to 16,300 sampling points and 25 ns sampling times. Modulation capabilities include amplitude, frequency, phase, burst, along with phase continuous linear and logarithmic sweeps controlled via the IEEE 488 Standard Bus.

Precision Digital Multi-Meter (Keithley Model 2001 DMM) provides high precision, 7 1/2 digit resolution, DC and AC voltage and current measurement over a very wide dynamic range. A ten channel scanner allows multiplexed monitoring of up to ten inputs. The DMM can be controlled via the IEEE 488 Standard Bus.

Fault Waveform Generator consists of the SRS DS345 Synthesized Function Generator, the **Industrial Test Equipment Company (ITECo) Powertron Model 3000s 3kVA AC Amplifier**, and the ITECo designed **MOSFET Switch/Controller**. The DS345 serves as both the waveform source (wave shape and amplitude) for the Powertron amplifier, and as the synchronizing clock to gate the MOSFET Switch/Controller and to trigger the oscilloscope via the BNL designed **Programmable Trigger**. The Powertron operates as a continuous waveform AC amplifier. The MOSFET switch/controller allows the high speed switching of the Powertron output. The number of fault pulses generated is selected and controlled by the programmable trigger to be from one, and only one, fault pulse per event up to 99 fault pulses per event. The BNL designed **Programmable Divider** is used to select the delay between pulses (the duty cycle) in multiple fault pulse events.

IEEE 488 Standard Bus Digital Interface (National Instruments, MC-GPIB interface board and NI-488.2 software), also known as the General Purpose Interface Bus (GPIB), is the standard interface for the remote control of electronic instruments. The interface between the computer and the respective connected instruments is accomplished via the NI-488.2 software using standard protocols for communication. By utilizing the IEEE 488 interface, supplemented by the flexibility afforded by the control and data acquisition software, it is possible to direct a variety of adaptable options for adjusting and monitoring various testing configurations and activities.

Control and Monitoring Computer (IBM PS/2, Model 55X) is used for the instrumentation control and data acquisition and analysis. Data logging and control functions are accomplished through the installation of special purpose data acquisition and control boards (such as National Instruments MC-GPIB, MC-DIO-24, SC-2051, and SC-2062), running the appropriate software (such as Microsoft Quick BASIC, and National Instruments LabWindows and NI-DAQ for DOS), and the IEEE 488 Standard Bus digital interface. The block diagram of the test configuration for the fault testing of electronic isolation devices is shown in Figure 1. The Device-Under-Test (DUT) is subjected to the application of fault pulse waveforms generated at the output of the MOSFET Switch/Controller. Monitoring of various test parameters and data acquisition are accomplished with the connected test equipment via the IEEE-488 Standard Bus and computer control.

Figure B.1 BNL Isolator Test Facility (ITF)

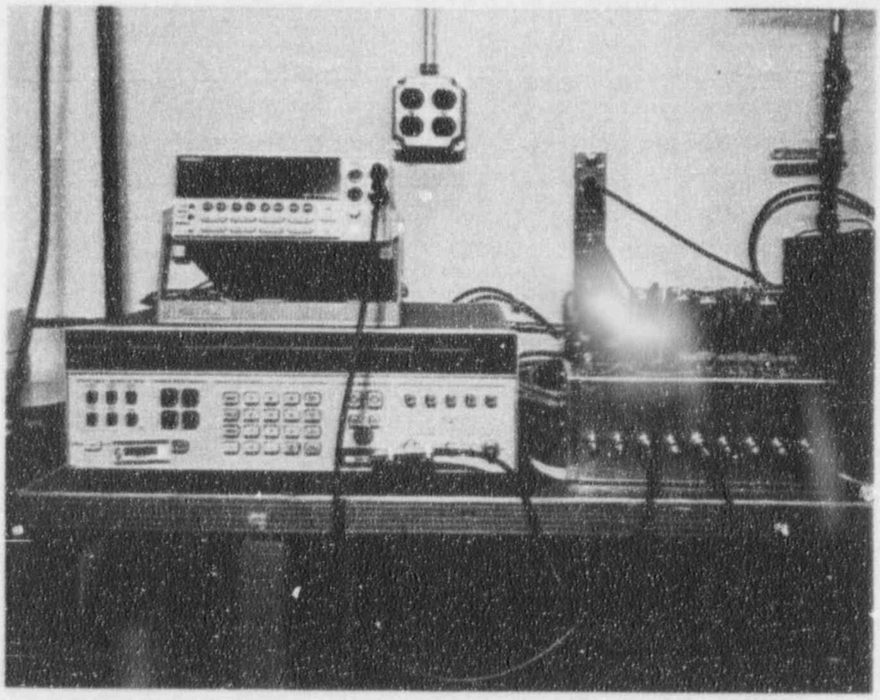


Figure B.2 Detail of ITF showing control relays, CT amplifiers, DMM, and synthesizer/ function generator

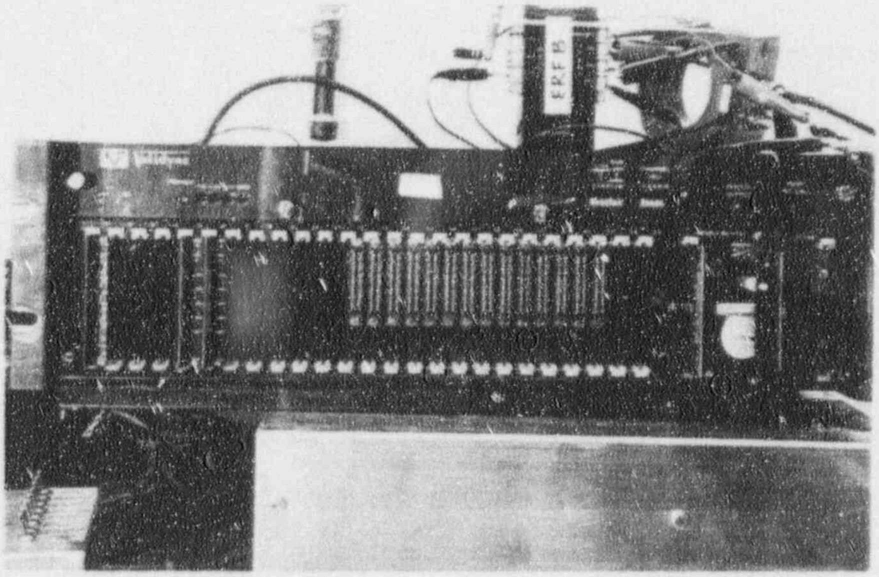


Figure B.3 Detail of ITF showing isolator test bed with a device under test (DUT)

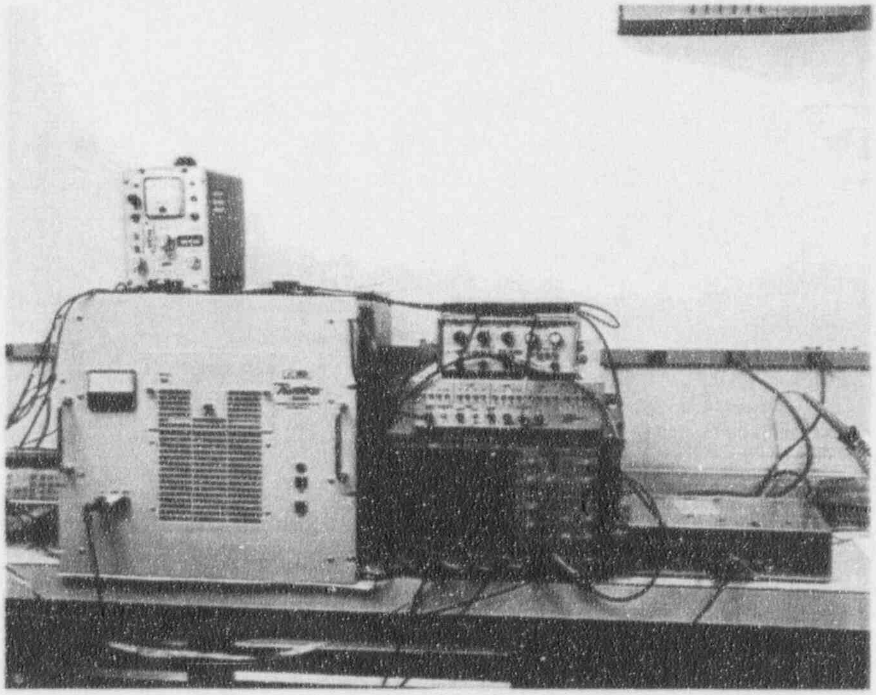


Figure B.4 Detail of ITF showing the fault waveform generating equipment and the DSO

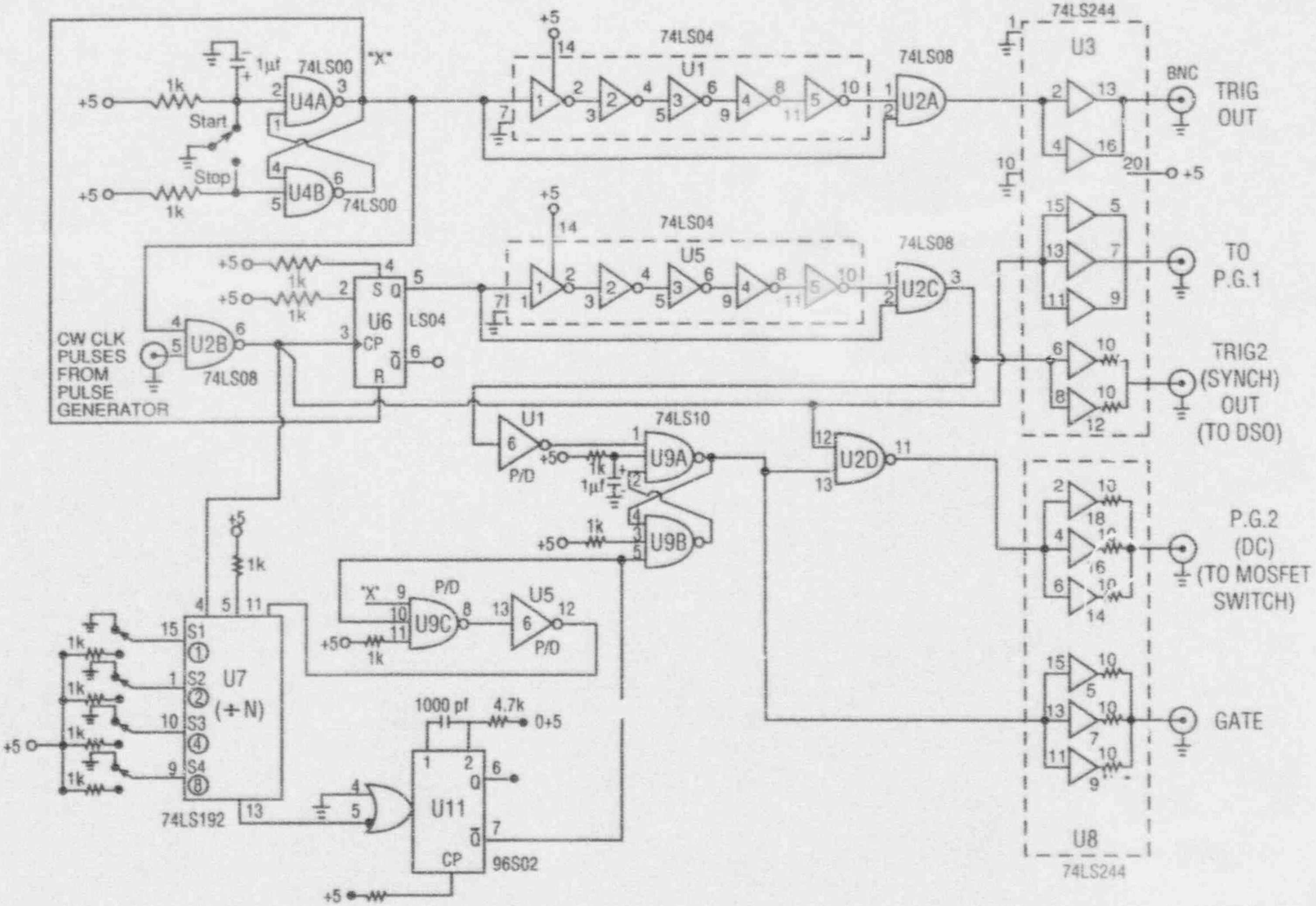
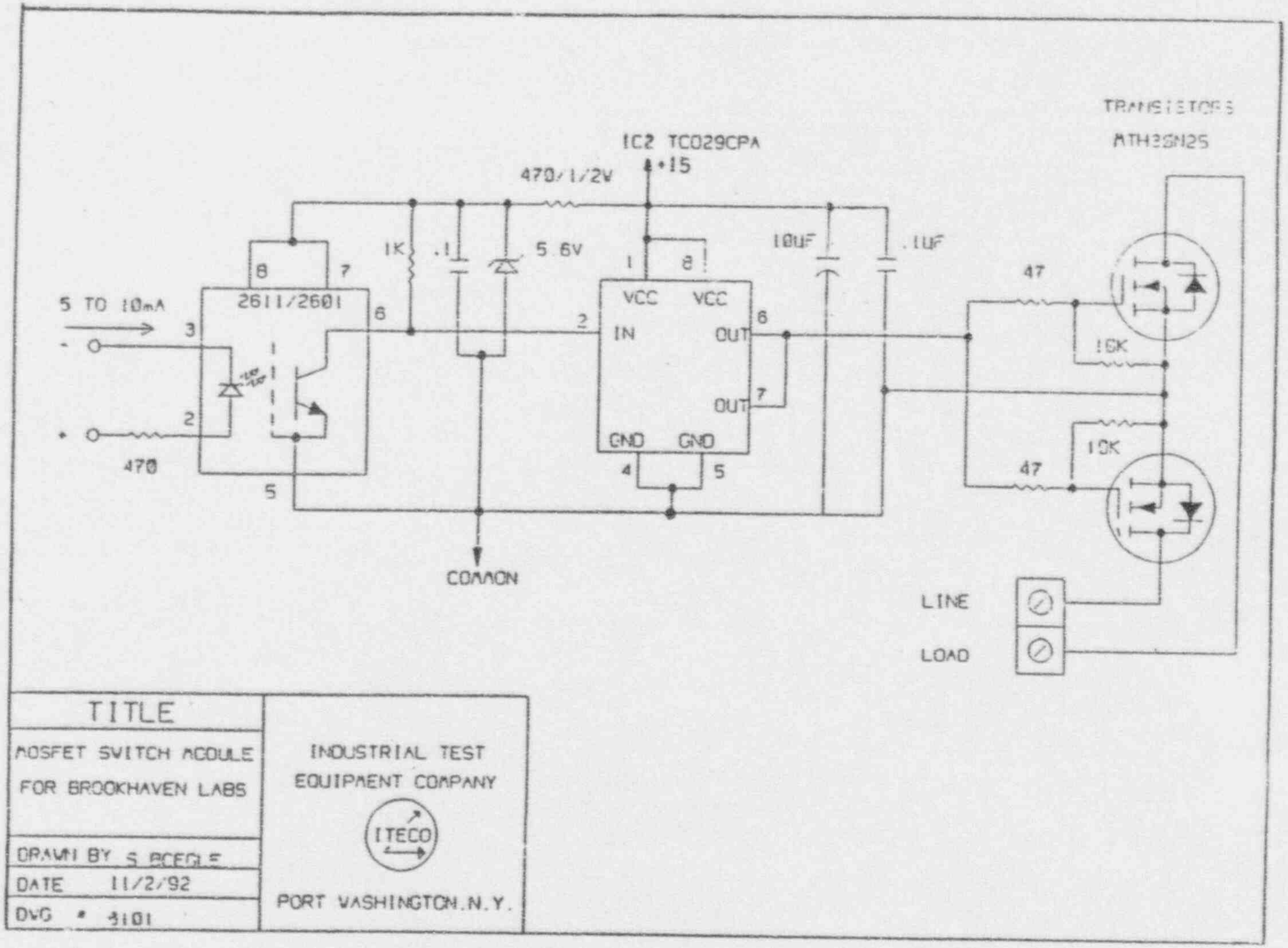


Figure B.5 Block Diagram of the programmable trigger designed by BNL for the fault waveform generator



TITLE

MOSFET SWITCH MODULE
FOR BROOKHAVEN LABS

DRAWN BY S BOEGLE
DATE 11/2/92
DWG # 3101

INDUSTRIAL TEST
EQUIPMENT COMPANY

PORT WASHINGTON, N.Y.

Figure B.6 Schematic of MOSFET switch module designed by Industrial Test Equipment Company (ITECo) for fault waveform generator (Ref. B.2) (Printed with permission of Industrial Test Equipment Co.)

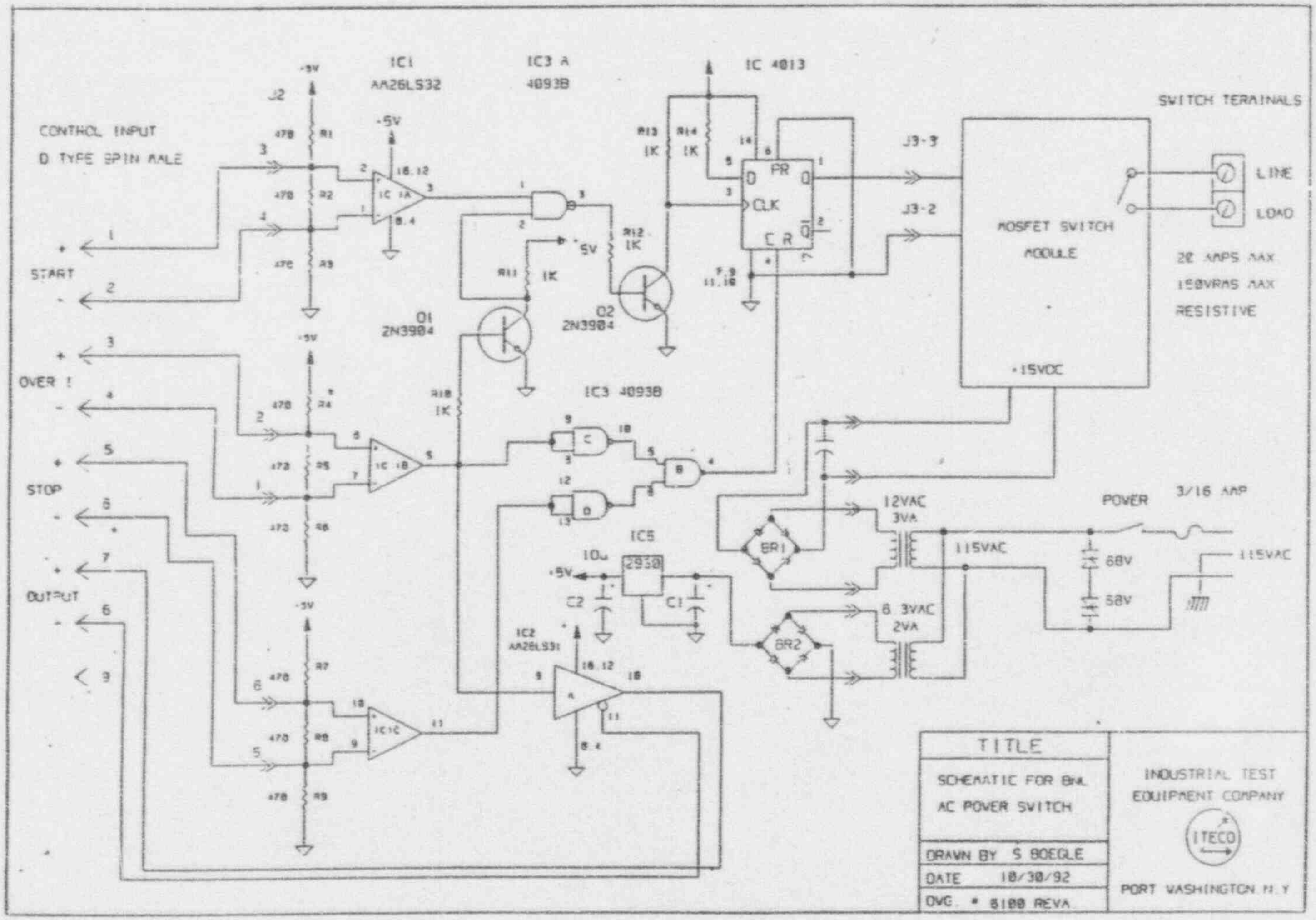


Figure B.7 Schematic for MOSFET switch/controller designed by ITECo for fault waveform generator (Ref. B.2) (Printed with permission of Industrial Test Equipment Co.)

References for Appendix B

B.1 Neilsen, J.R., "Electronic Isolators Used in Safety Systems of U.S. Nuclear Power Plants," NUREG/CR-3453, EGG-2444, EG&G Idaho, Inc., March 1986.

B.2 "Instruction Manual for AC Power Switch," Industrial Test Equipment Co., Port Washington, New York. October 1992.

APPENDIX C

TEST EQUIPMENT CERTIFICATIONS

Serial # 931401897 Software version 02.4

*** CERTIFICATE OF CALIBRATION ***

The DSO listed above, LeCroy 9314M, S/N 931401897, Software version 02.4 has been checked and calibrated against our working standards listed below and following the procedure documented in "CS01 Calibration Software Package for Digital Oscilloscopes" Operator's Manual. It meets or exceeds all published specifications.
LeCroy calibrations are traceable to the US National Institute of Standards and Technology [NIST] to the extent allowed by the Organisation which accredits this calibration facility. This unit meets IEEE-STD 1057 as specified in its data sheet.

Date of cal. Sep 16, 1992 Place of cal. LeCroy-GENEVA

Temperature: 23°C Humidity: 69% Technician: M.C.

Cal. due date : Sep 16, 1993 Cal. Report Nb. : FL-9314M1897

Quality Assurance: M.COLLET
Approved: Metrology Analyst.

```
            ============  SETUP Nb = 5          ============

Voltage generator               Cal Due Date : FEB 17.1993
Type              Description                               Serial Nb
PS5004            TEKTRONIX PWR SUPPLY/01450                B011736
Radio Frequency generator    Cal Due Date : FEB 06.1993
Type              Description                               Serial Nb
2030              MARCONI SIGNAL GENERATOR/1705             119305-001
Audio Frequency generator    Cal Due Date : FEB 06.1993
Type              Description                               Serial Nb
2030              MARCONI SIGNAL GENERATOR/1705             119305-001
Voltage Step generator          Cal Due Date : SEP 01.1993
Type              Description                               Serial Nb
4969              LECROY STEP GENERATOR                     460
Multiplexer                     Cal Due Date : OCT 22.1992
Type              Description                               Serial Nb
705/E             KEITHLEY SCANNER                          514245
Digital MultiMeter              Cal Due Date : DEC 21.1992
Type              Description                               Serial Nb
199               KEITHLEY DMM/SCANNER                      514086
```

KEITHLEY INSTRUMENTS, INC.

REPORT OF CALIBRATION

DATE: 12-Oct-92
REPORT NUMBER: A-00808-W01009151+1
PA-387

UNIT UNDER TEST	Keithley Model 2001
PROCEDURE REVISION	MS-1574 A
SERIAL NUMBER	0545677
RESULT	PASS
TIME TO CALIBRATE	41 Minutes
TIME OF DAY	14:27
CALIBRATED BY	Tech
TEMPERATURE	23°C
RELATIVE HUMIDITY	47%

STANDARDS USED		CAL DUE
5084	Fluke 5700A	20-Oct-92
5085	Fluke 5725A	20-Oct-92
5077	Keithley 775A	22-Oct-92

This instrument was calibrated on the above date and conditions with standards traceable to the National Institute of Standards and Technology (NIST). The measurement standards listed were calibrated to their specified uncertainty and evidence of traceability is on file in our Metrology Laboratory. The tolerances of the instrument listed in the calibration report are one year specifications.

This calibration is intended to comply with MIL-STD-45662A. The collective uncertainty of the listed measurement standards do not exceed 25% (TUR >= 4:1) of the instrument specifications under calibration unless otherwise noted. Calibration interval assignment and adjustment are the responsibility of the end-user.

At the time of instrument calibration, measurement results were recorded and are listed on the attached pages.

NOTE: Tests 62 and 63 test the frequency function using a Keithley Instruments Model 775 Frequency Counter. The units on these tests are Hertz, not Volts as shown in this report.

Applicable NIST Test Report numbers are listed below:

DC Voltage - 247945
AC Voltage - 238764
Resistance - 247956
Temperature - 246568
Frequency - WWVB

Edward T. Kifer

Quality Assurance Manager

APPENDIX D

TEST DATA

TABLE D.1 LIST OF FIGURES IN APPENDIX D SHOWING GRAPHICAL PRESENTATION OF TEST DATA FOR EACH ISOLATOR MODEL TESTED

		Isolator ID	Reach-Through Energy vs Fault Level	Barrier Resistance vs Fault Level	Barrier Capacitance vs Fault Level
MAGNETICALLY	V to V	DA-3-1	D.1	D.2	D.3
		FA-3-1A	D.4	D.5	D.6
		HNA-3-1A	D.7	D.8	D.9
		RA-3-2	D.10	D.11	D.12
		VD-3-1	D.13	D.14	D.15
		WA-3-1	D.16	D.17	D.18
COUPLED	I to I	DA-2-3	D.19	D.20	D.21
		HNA-2-1A	D.22	D.23	D.24
		TRA-2-2	D.25	D.26	D.27
OPTICALLY	COUPLED	HND-4-2A	D.28	D.29	D.30
		TD-4-1	D.31	D.32	D.33
		TD-4-3A	D.34	D.35	D.36

Figure D.1 Reach-Through Energy vs Fault Level
Isolator DA-3-1

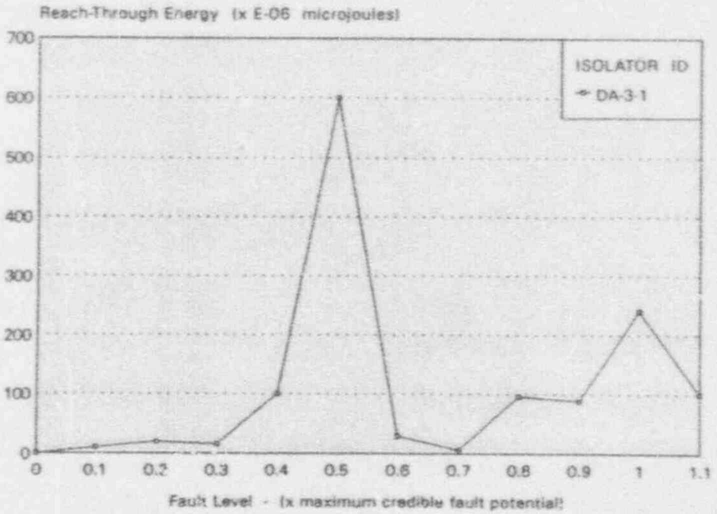
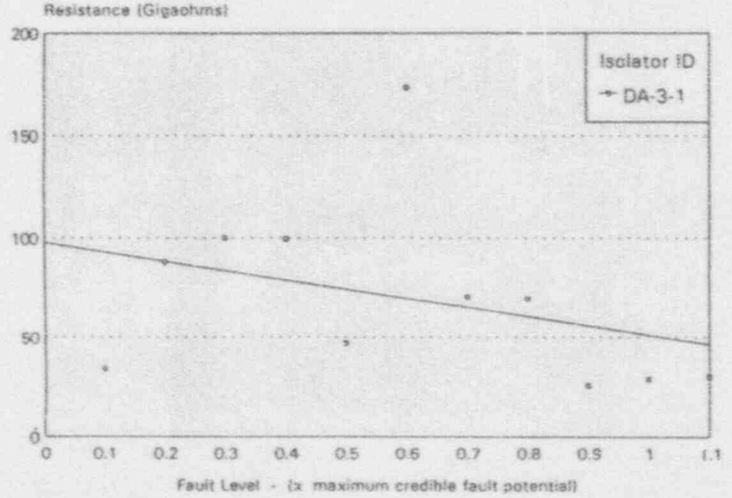
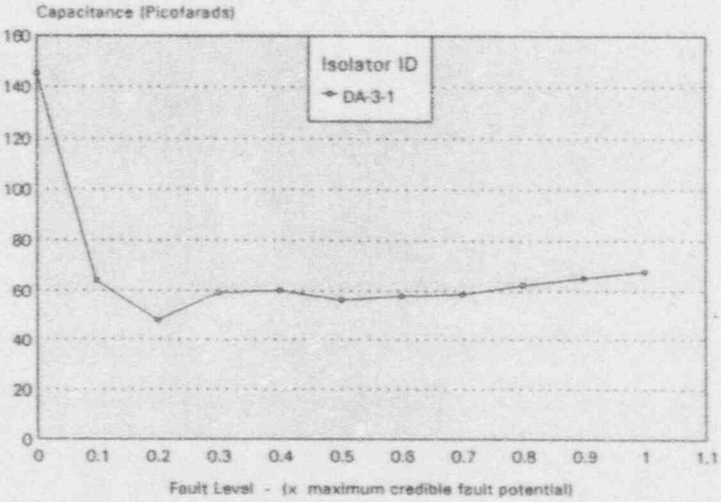


Figure D.2 Barrier Resistance vs Fault Level
Isolator DA-3-1



Resistance as measured after application of indicated fault level.

Figure D.3 Barrier Capacitance vs Fault Level
Isolator DA-3-1



Capacitance as measured after application of indicated fault level.

Figure D.4 Reach-Through Energy vs Fault Level
Isolator FA-3-1A

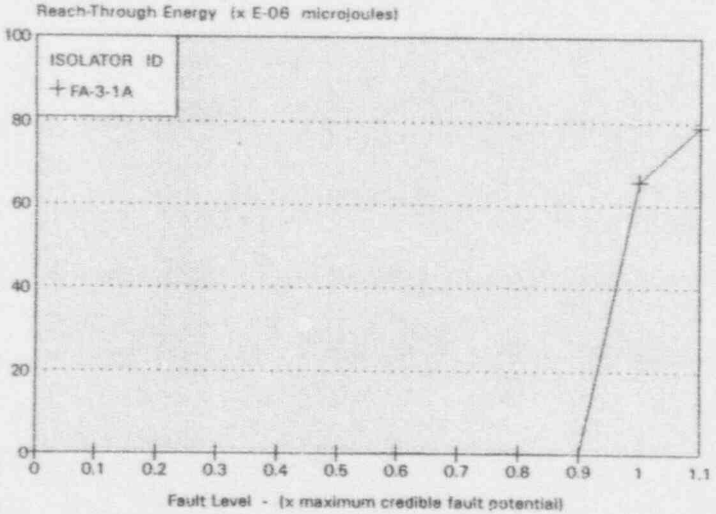
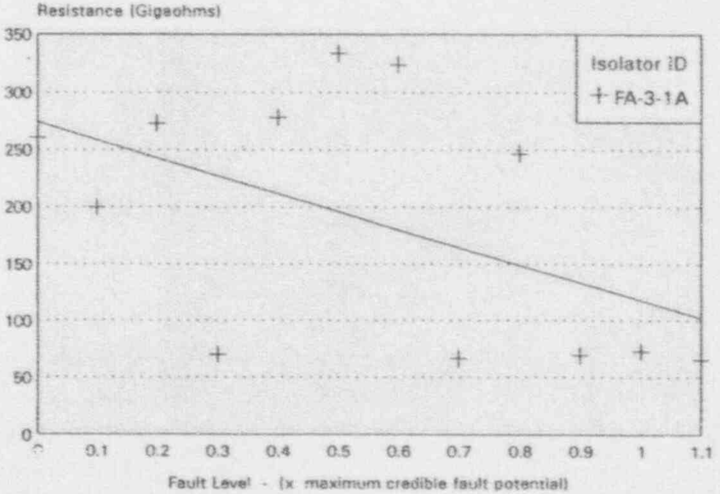
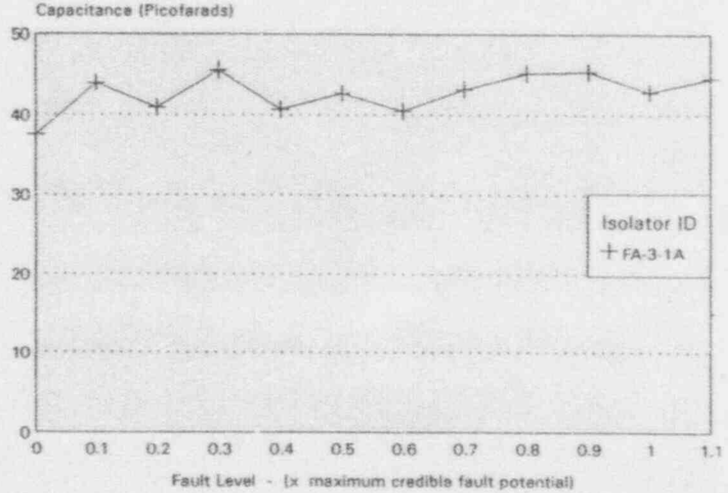


Figure D.5 Barrier Resistance vs Fault Level
Isolator FA-3-1A



Resistance as measured after application of indicated fault level.

Figure D.6 Barrier Capacitance vs Fault Level
Isolator FA-3-1A



Capacitance as measured after application of indicated fault level.

Figure D.7 Reach-Through Energy vs Fault Level
Isolator HNA-3-1A

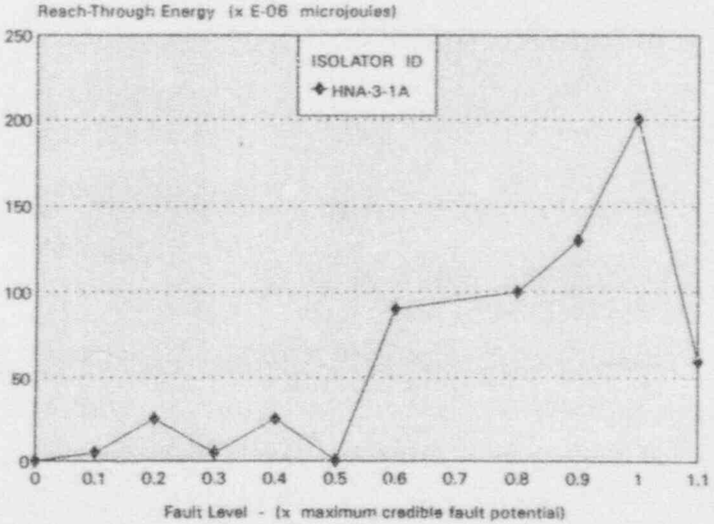
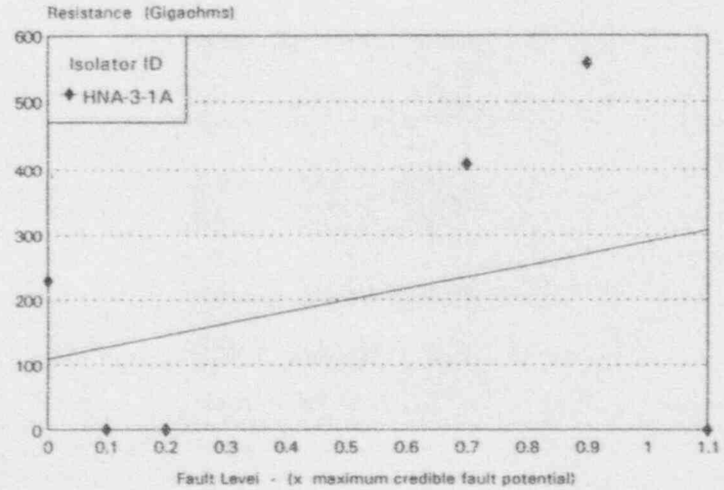
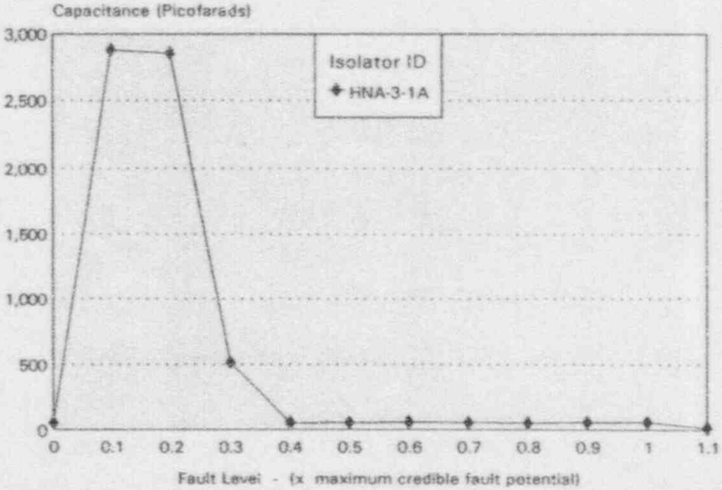


Figure D.8 Barrier Resistance vs Fault Level
Isolator HNA-3-1A



Resistance as measured after application of indicated fault level.

Figure D.9 Capacitance vs Fault Level
Isolator HNA-3-1A



Capacitance as measured after application of indicated fault level.

Figure D.10 Reach Through Energy vs Fault Level
Isolator RA-3-2

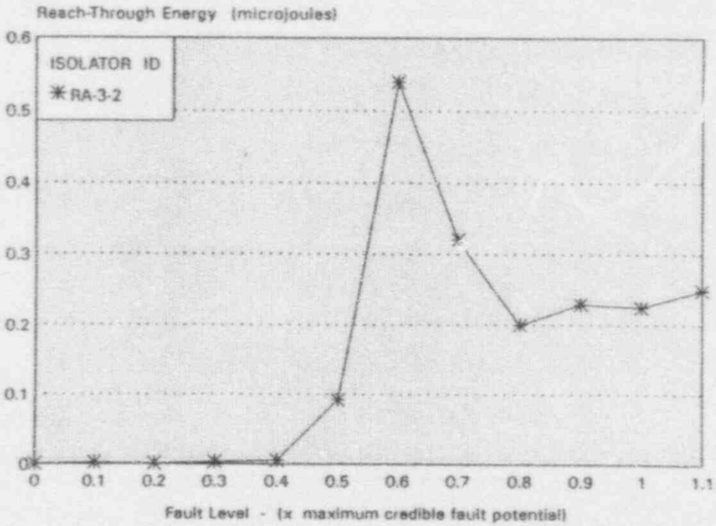
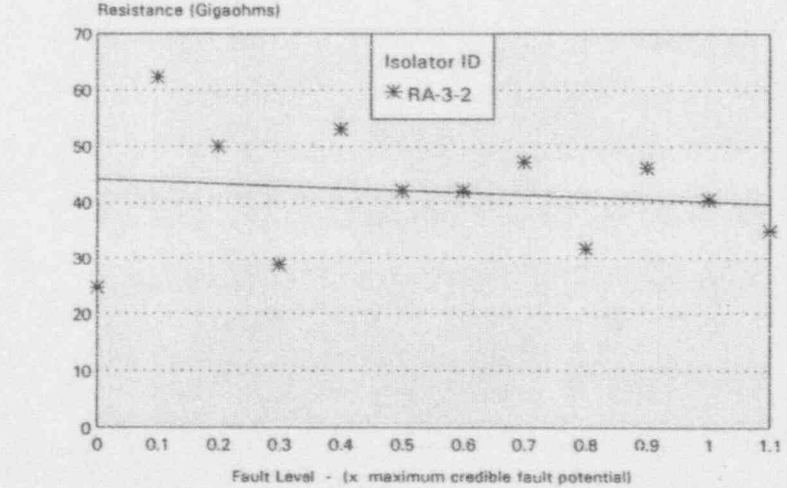
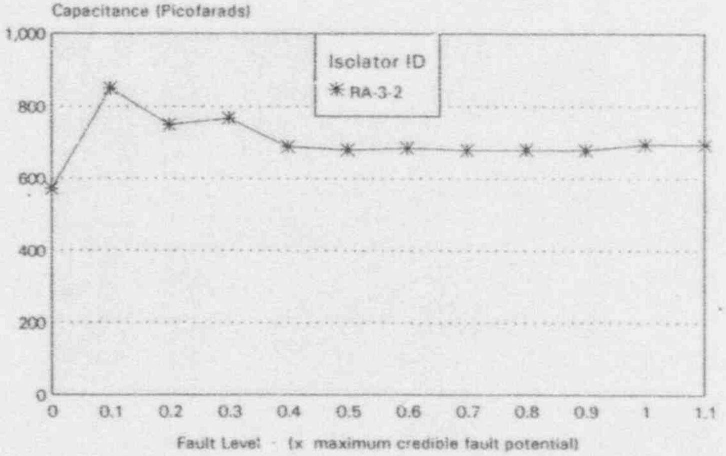


Figure D.11 Barrier Resistance vs Fault Level
Isolator RA-3-2



Resistance as measured after application of indicated fault level.

Figure D.12 Barrier Capacitance vs Fault Level
Isolator RA-3-2



Capacitance as measured after application of indicated fault level.

1

Figure D.13 Reach-Through Energy vs Fault Level
Isolator VD-3-1

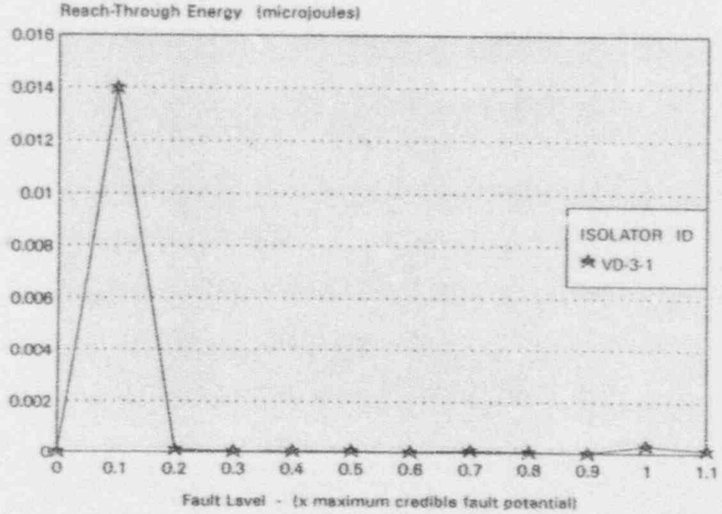
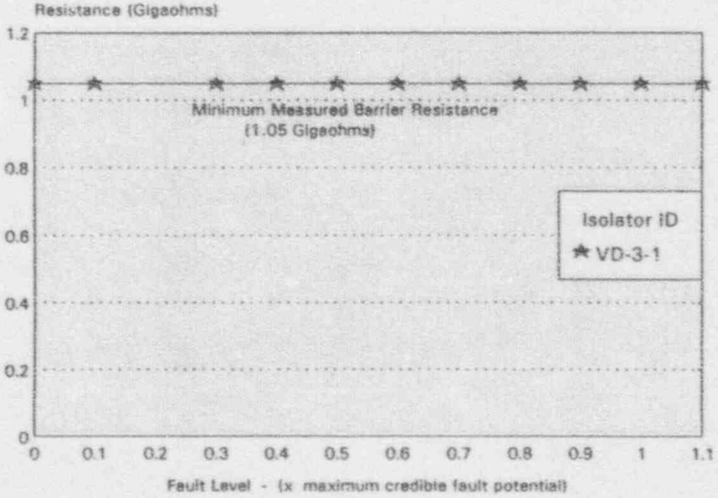
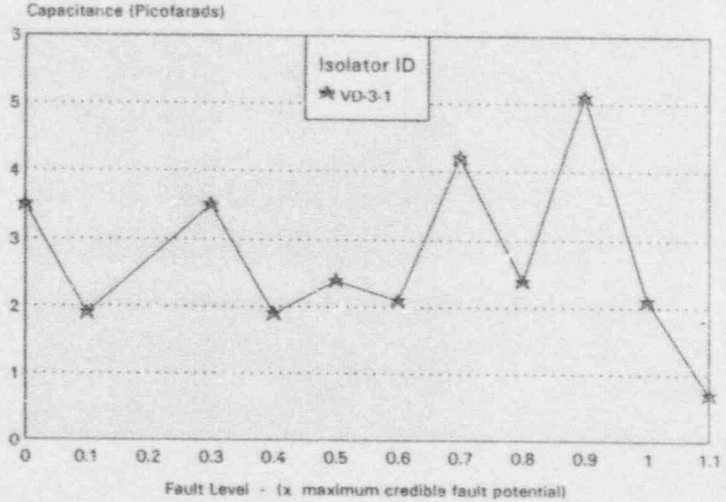


Figure D.14 Barrier Resistance vs Fault Level
Isolator VD-3-1



Resistance as measured after application of indicated fault level.

Figure D.15 Barrier Capacitance vs Fault Level
Isolator VD-3-1



Capacitance as measured after application of indicated fault level.

Figure D.16 Reach-Through Energy vs Fault Level
Isolator WA-3-1

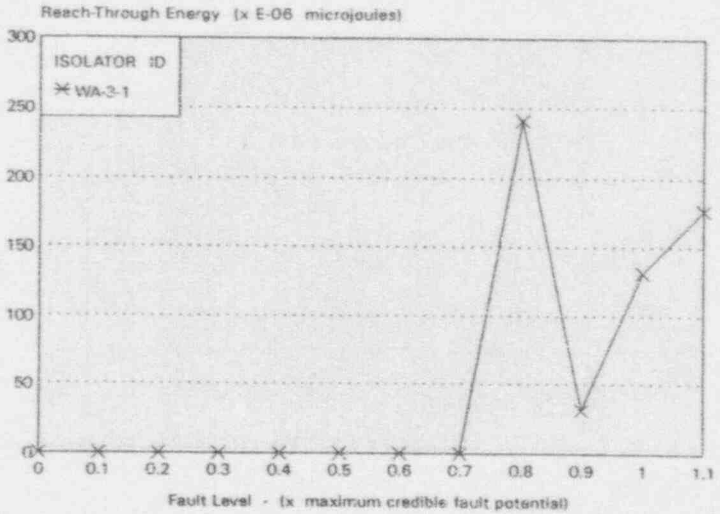
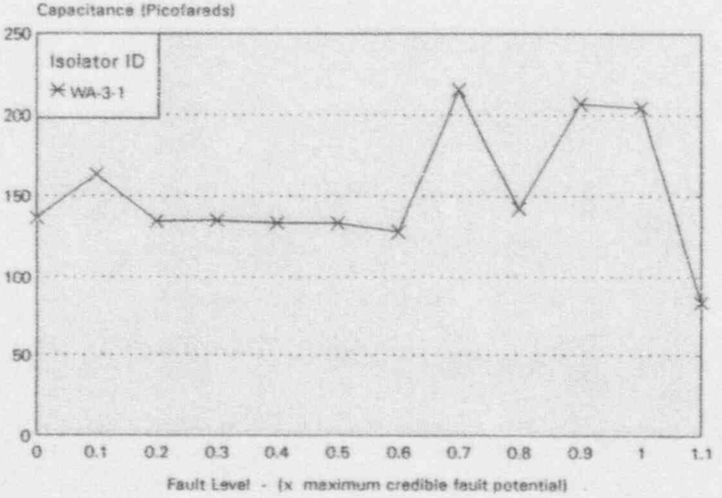
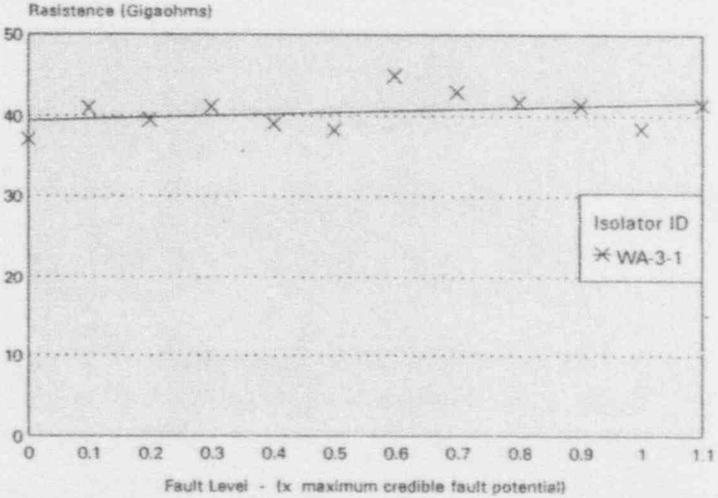


Figure D.18 Barrier Capacitance vs Fault Level
Isolator WA-3-1



Capacitance as measured after application of indicated fault level.

Figure D.17 Barrier Resistance vs Fault Level
Isolator WA-3-1



Resistance as measured after application of indicated fault level.

Figure D.19 Reach-Through Energy vs Fault Level
Isolator DA-2-3

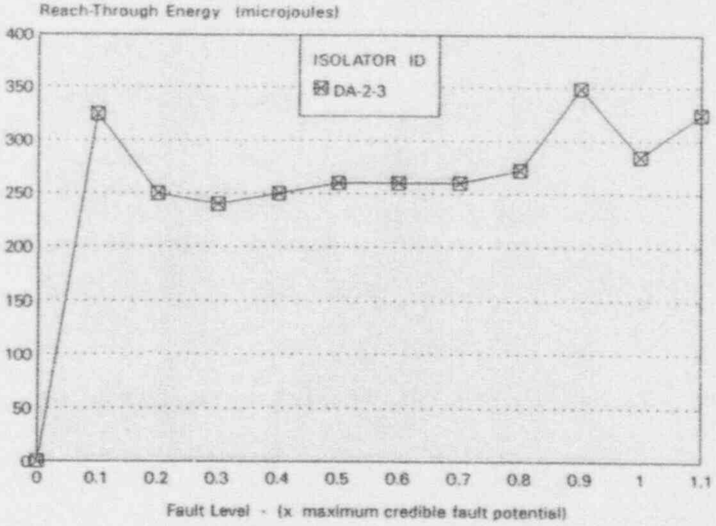
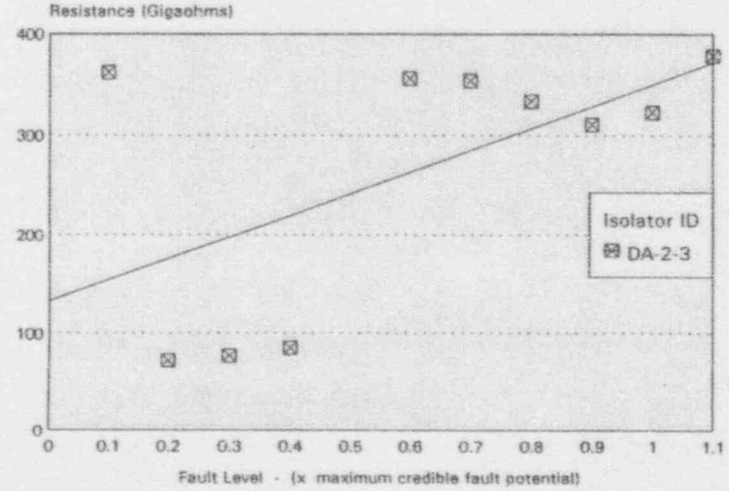
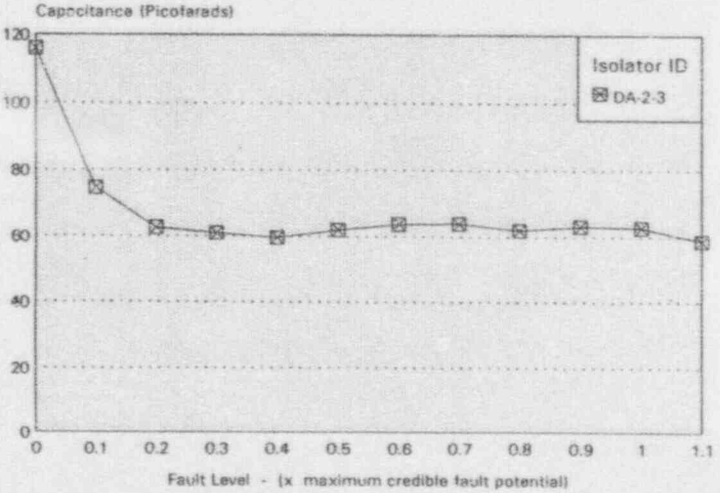


Figure D.20 Barrier Resistance vs Fault Level
Isolator DA-2-3



Resistance as measured after application of indicated fault level.

Figure D.21 Barrier Capacitance vs Fault Level
Isolator DA-2-3



Capacitance as measured after application of indicated fault level.

Figure D.22 Reach-Through Energy vs Fault Level
Isolator HNA-2-1

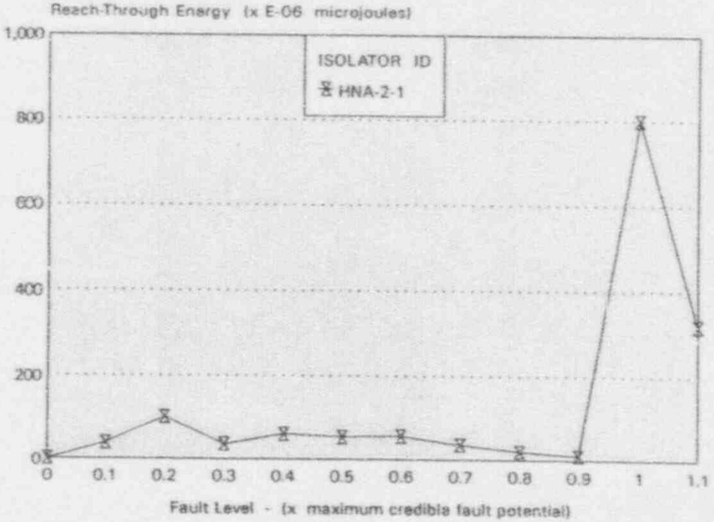
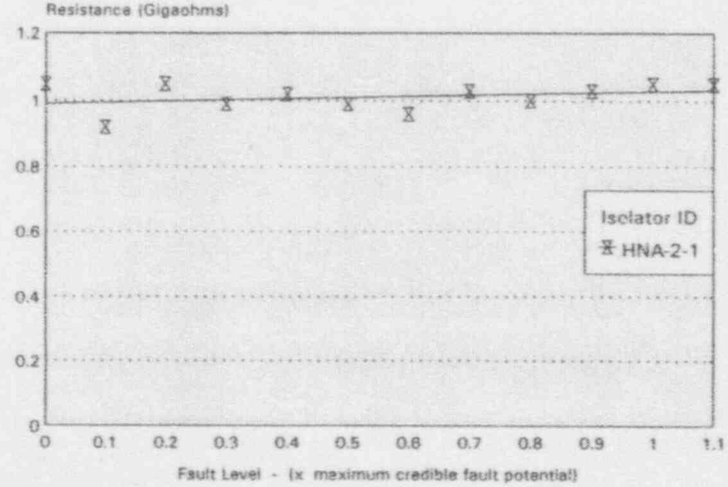
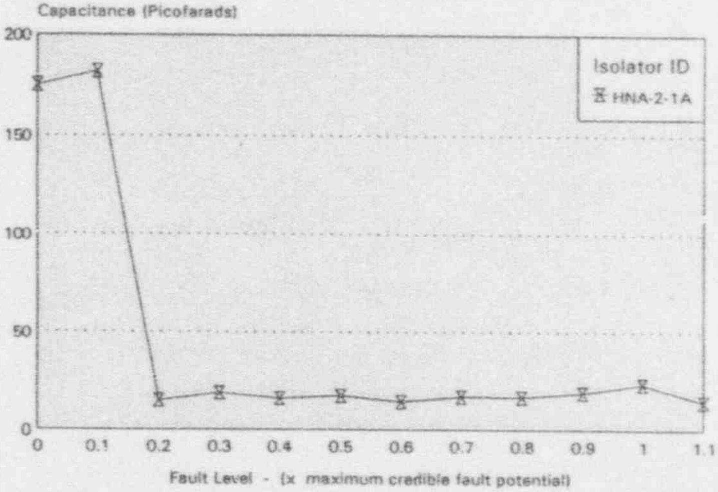


Figure D.23 Barrier Resistance vs Fault Level
Isolator HNA-2-1



Resistance as measured after application of indicated fault level.

Figure D.24 Barrier Capacitance vs Fault Level
Isolator HNA-2-1



Capacitance as measured after application of indicated fault level.

Figure D.25 Reach-Through Energy vs Fault Level
Isolator TRA-2-2

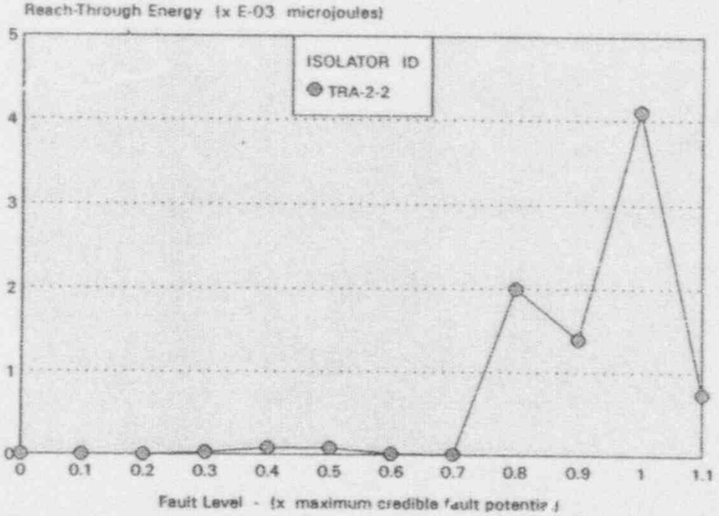
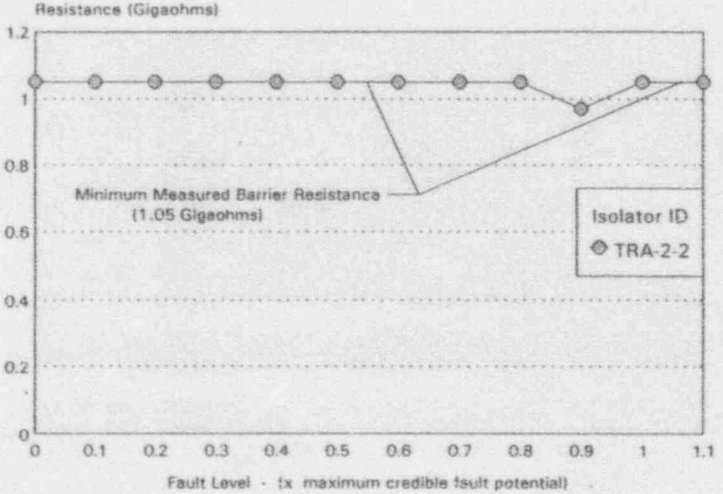
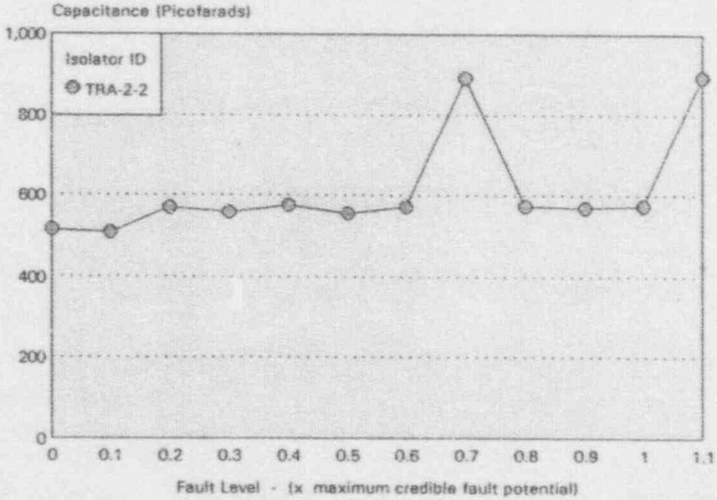


Figure D.26 Barrier Resistance vs Fault Level
Isolator TRA-2-2



Resistance as measured after application of indicated fault level.

Figure D.27 Barrier Capacitance vs Fault Level
Isolator TRA-2-2



Capacitance as measured after application of indicated fault level.

Figure D.28 Reach-Through Energy vs Fault Level
Isolator HND-4-2A

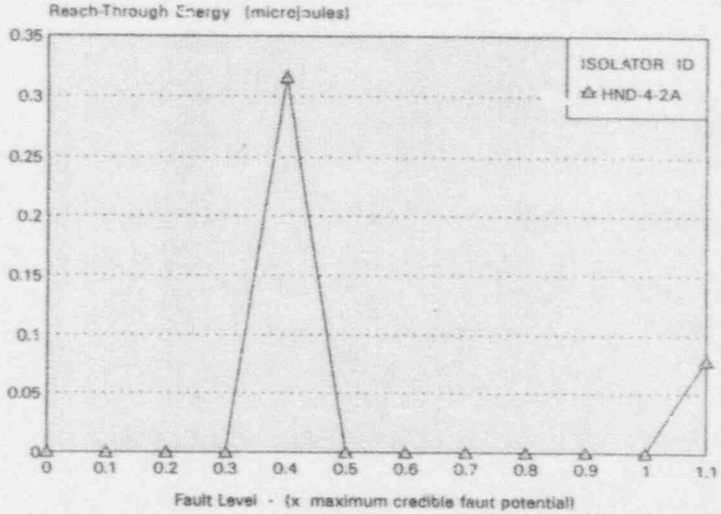
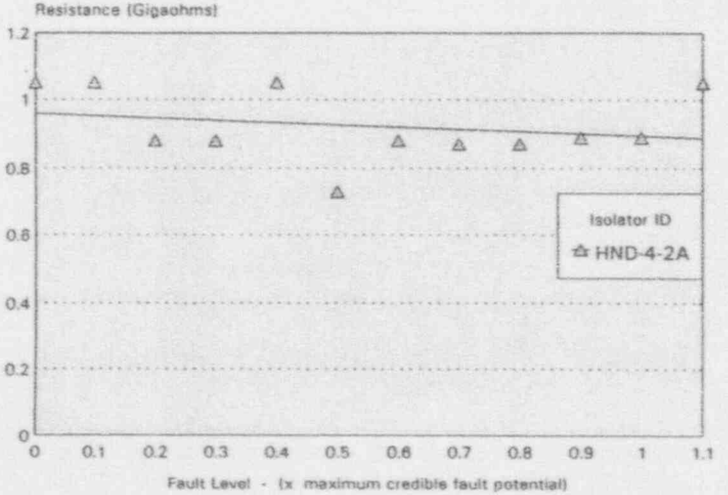
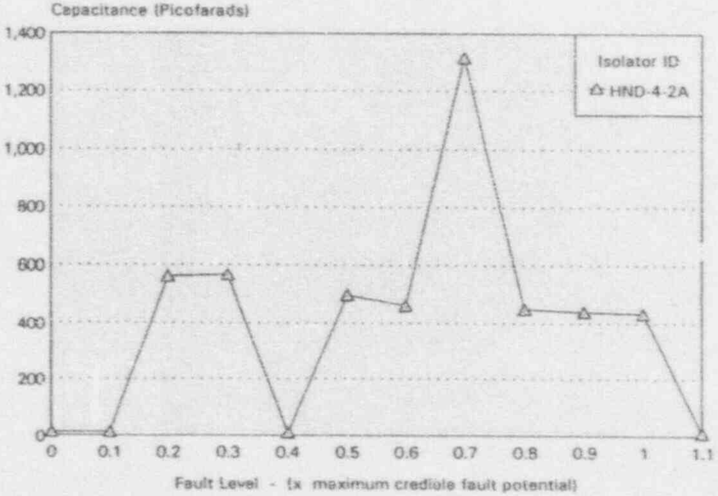


Figure D.29 Barrier Resistance vs Fault Level
Isolator HND-4-2A



Resistance as measured after application of indicated fault level.

Figure D.30 Barrier Capacitance vs Fault Level
Isolator HND-4-2A



Capacitance as measured after application of indicated fault level.

Figure D.31 Reach-Through Energy vs Fault Level
Isolator TD-4-1

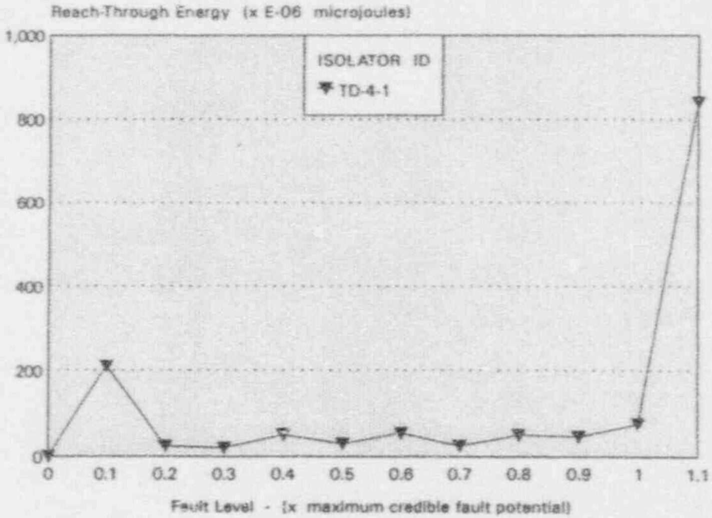
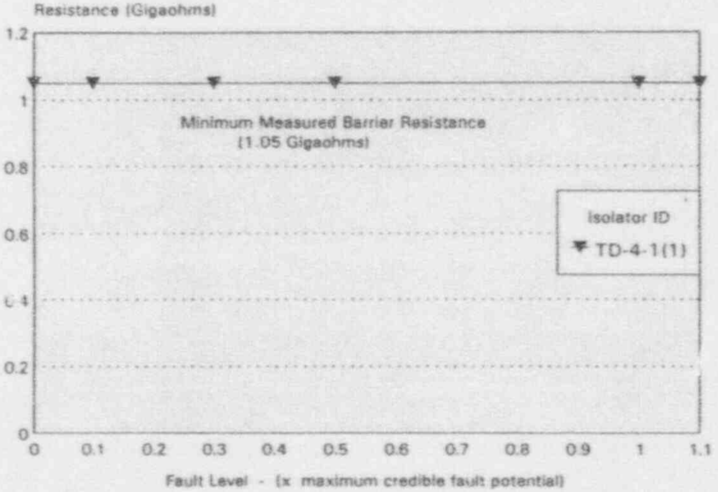
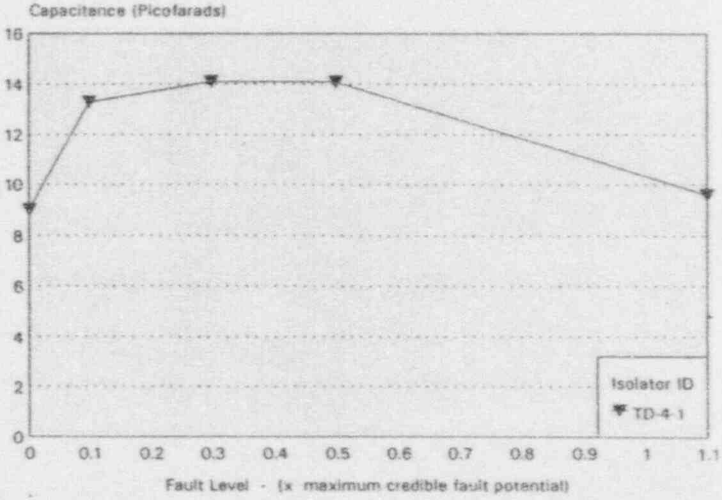


Figure D.32 Barrier Resistance vs Fault Level
Isolator TD-4-1



Resistance as measured after application of indicated fault level.

Figure D.33 Barrier Capacitance vs Fault Level
Isolator TD-4-1



Capacitance as measured after application of indicated fault level.

Figure D.34 Reach-Through Energy vs Fault Level
Isolator TD-4-3A

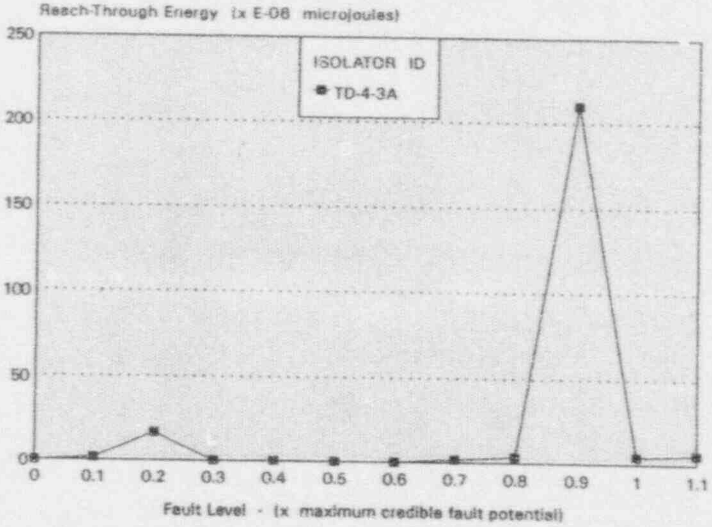
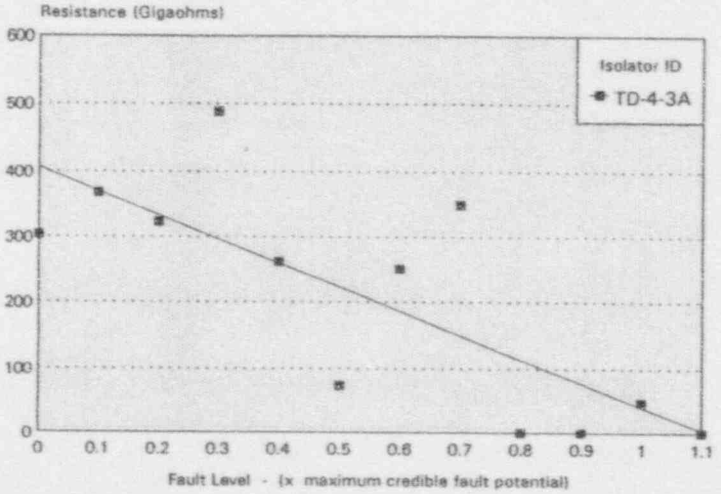
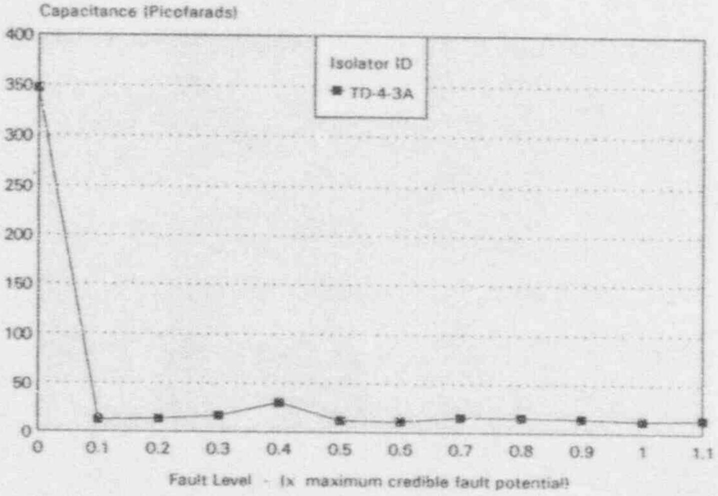


Figure D.35 Barrier Resistance vs Fault Level
Isolator TD-4-3A



Resistance as measured after application of indicated fault level.

Figure D.36 Barrier Capacitance vs Fault Level
Isolator TD-4-3A



Capacitance as measured after application of indicated fault level.

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11. ABSTRACT *(200 words or less)*

Electronic isolation devices are used in nuclear power plants to provide electrical separation between safety and non-safety circuits and systems. Major fault testing in an earlier program indicated that some energy may pass through an isolation device when a fault at the maximum credible potential is applied in the transverse mode to its output terminals. During subsequent field qualification testing of isolators, concerns were raised that the worst case fault, that is, the maximum credible fault (MCF), may not occur with a fault at the maximum credible potential, but rather at some lower potential. The present test program investigates whether problems can arise when fault levels up to the MCF potential are applied to the output terminals of an isolator. The fault energy passed through an isolated device during a fault was measured to determine whether the levels are great enough to potentially damage or degrade performance of equipment on the input (Class 1E) side of the isolator.

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Electronic circuits - performance testing
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Nuclear power plants - engineered safety systems, reliability, electrical equipment, electric currents, benchmarks, testing

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