EEIP Electrical Safety Design Reference Handbook

Version 1

SLAC-I-730-0A11F-001-R000

Forward

Section 1 provides guidance on how to achieve compliant, accepted and AHJ approved electrical equipment. Sections 2 through 7 are references on how to achieve these goals. These references have been taken from various sources and are identified in the Table of Contents. For additional information refer to document “Stanford Linear Accelerator Center Electrical Equipment Inspection Program” number SLAC-I-730-0A11A-001-R000 or contact the SLAC Electrical Safety Officer

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SLAC Design Electrical Safety Guidance

SLAC-I-730-0A11F-001-R000

All equipment not listed by a National Recognized Testing Laboratory (NRTL) should be constructed according to applicable standards, such as UL, ISA, ANSI, and IEEE. Equipment for which specific standards are unavailable should be constructed according to the principles of established standards, as determined by the AHJ.

Equipment should be examined for safety as extensively as possible. Areas of consideration include but are not limited to:

1. Failure modes
2. Heat effects
3. Magnetic effects
4. Grounding and bonding
5. Guarding of live parts
6. Leakage currents
7. Dielectric testing
8. Access to serviceable parts
9. Overcurrent and overtemperature protection
10. Clearances and spacing
11. Interlocks
12. Design and procedural documentation
13. Signage, labels, and administrative controls
14. Mechanical motion
15. Stored energy.

Documentation should be developed to substantiate the acceptance of any equipment. Documentation should include but not be limited to:

1. Tests performed
2. Conditions of acceptability
3. Applicable standards to which the equipment was evaluated
4. Limitations of approved use, if any.

Designing and Fabricating Safe Electrical Equipment

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11.1 Designing and Fabricating Safe Electrical Equipment

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Revision History

Date	Author	Revision
February 2002	Fred Coffield	Revision 0: Original release.

11.1.1 Introduction

The design and fabrication requirements in this document are derived from many sources, including American National Standards Institute (ANSI) standards, National Fire Protection Association (NFPA) standards, the Occupational Safety & Health Administration (OSHA), the National Electrical Code (NEC), LLNL Electronics Engineering Department Standards and Specifications, and best engineering practices. These design and fabrication requirements are intended to cover most electrical equipment but cannot be expected to comprehensively cover all equipment and all existing standards. Underwriters Laboratories (UL) standards are cited in many places. They are not part of the Laboratory's Work Smart Standards but have been chosen to serve as best engineering practices because of their appropriateness and UL's status as an NRTL accepted by OSHA.

11.1.2 Purpose

The purpose of these requirements is to identify a broad set of general design elements and principles that incorporate safe electrical design—that is, reduce the risk of electric shock and fire. These requirements are a consensus set of requirements that come from the sources listed above. They were chosen by the Authority Having Jurisdiction (AHJ) Working Group and approved by the Electronics Engineering Division Leaders and Department Head. Following these requirements should enable the resulting electrical equipment to pass AHJ inspection. A designer may deviate from many of these requirements provided that safety is assured by appropriate analysis. The analysis that is used to justify deviating from these requirements shall be documented in a Safety Note for the equipment.

The requirements in this document cover many aspects of electrical design and fabrication, including:

- Guarding of live parts
- Adequate wire size
- Grounding and bonding
- Component selection and mounting
- Equipment installation

These requirements are conservative in order to assure safety throughout the lifetime of the equipment, under varying conditions, and during fault conditions.

Design issues that are not covered adequately by the requirements in this document shall be resolved by applying good engineering processes. In other words, the design shall be reviewed with the appropriate level of formality graded by the risk in the system. Safety issues shall be documented in a Safety Note. Guidance on the engineering design process and the conduct of design reviews is contained in the *Engineering Policies and Procedures Manual*, Section 7, "Design." Guidance on when Engineering Directorate Safety Notes (EDSNs) are required and how they are developed is contained in the *Engineering Design Safety Standards Manual*, Part I, Chapter D, "ME, EE, and Engineering Directorate Safety Notes." The cognizant Engineering Division Leader has the authority to set the review and documentation requirements for any design task.

11.1.3 Terms and Definitions

Authority Having Jurisdiction (AHJ)	A general term identifying the entity that has legal authority over something.
AHJ Program	A program for examining and approving electrical equipment and installations at LLNL. For more information, see the *LLNL ES&H Manual*, Vol. II, Part 16, Document 16.3, "LLNL AHJ Requirements for Approving Electrical Equipment, Installations, and Work"
AHJ Working Group	A group working under the auspices of the AHJ to develop the AHJ Program at LLNL.
Conditions of use	Documented requirements for use of electrical equipment and components that must be met for the listing to be valid.
Listed	An approved electrical component or piece of equipment. Approval is contingent upon the component or equipment being used according to the conditions of use identified in its documentation.
Live part	A part that can be energized to 50 V or greater during any phase of equipment operation.

NRTL	Nationally Recognized Testing Laboratory. One of 17 organizations accepted by OSHA to inspect and approve electrical equipment. UL is the largest of the NRTLs.
Recognized	An electrical component or piece of equipment that has been determined by UL to be acceptable provided it is used in accordance with conditions of acceptability.
Risk	The quantitative or qualitative expression of possible loss that considers both the probability that a hazard will cause harm and the consequences of that event.
Shock hazard	Exposure during any phase of operations, normal and off-normal, to 50 V or greater.

11.1.4 Design and Fabrication Requirements

11.1.4.1 Components

Whenever possible, components should be NRTL-listed. Recognized components are acceptable also. Recognized components must be used in accordance with the conditions identified in the listing. Conditions of usage include factors such as temperature, environment, available fault current, and so forth. These conditions will be included in the documentation for the component.

Components that are not listed or recognized shall be evaluated for their safety and suitability. If the application involves a significant safety hazard or function, then the suitability of the component shall be documented in a Safety Note.

11.1.4.2 General Construction

Enclosures must be of substantial construction so as to avoid the likelihood of damage during normal use. Guidance on case thickness is found in UL Standard 508, Table 6.1 for steel and Table 6.2 for aluminum. In addition, the following criteria should be considered, as appropriate:

- Provide adequate conductivity to minimize shock hazard for maximum credible ground fault current. Alternatively, enclosures can be insulated to eliminate the shock hazard.

- Contain explosive concussion and shrapnel resulting from arc blast or structural failure of electrical components. A capacitor failure is an example.
- Provide the appropriate protection for the environment where the equipment will be used, e.g., outdoors, with explosive gases, in a corrosive atmosphere, etc.

Enclosures must not have open knockouts or holes that allow workers to contact energized parts. Holes that are 3/8-in. diameter or smaller provide adequate protection from energized parts.

Enclosures must be free of sharp edges. No parts that can be contacted by the user should be sharp enough to cause injury. No parts that are in areas likely to be serviced and are easily contacted by service persons should be sharp enough to cause injury. No sharp edges, burrs, threads, etc. should be in contact with conductors. Additional protection may be applied to conductors to protect insulation [1].

11.1.4.3 Mechanical Assembly

All components must be securely fastened. Observe the following fastening guidelines:

- Do not depend on gravity or friction to keep components in place.
- Fastening hardware should be of the locking/captive type.
- Ceramic and ceramic-coated parts shall be mounted with nylon or fiber washers in contact with the ceramic surfaces. Resilient washers are used whenever brittle materials are bolted in an assembly.
- There should be at least one thread visible beyond the front of a nut when threaded hardware is used.
- Split or internal-tooth lock washers should be used when self-locking screws or nuts are not available.

Corrosion protection must be considered in all environments to maintain electrical integrity. Examples of environmental conditions where corrosion protection must be considered include high humidity and presence of corrosive vapors.

Switches, lamp holders, and the like shall be securely mounted. All keyed devices shall be correctly seated in keyways. Devices shall not easily loosen by hand. Devices that are position-dependent, such as toggle and rotary switches, must not rotate out of position.

11.1.4.4 Bonding/Grounding

"Equipment grounding" generally refers to the connection of the equipment to the electrical system equipment-grounding conductor. "Bonding" generally refers to the practice of establishing electrical continuity between all exposed metal surfaces such that there is no potential between any two surfaces.

Bonding wires must be securely terminated. All grounding and bonding wires shall be attached by dedicated means. The hardware used for grounding or bonding shall not have any other purpose. A grounding conductor that enters the equipment shall be terminated in a pressure wire connector that is clearly marked as a grounding connection. Only one conductor may be terminated in the connector. Solder connections or sheet metal screws shall not be used for grounding or bonding purposes.

All metal not carrying a current must be properly bonded. All exposed metal parts must be positively bonded to one another. Surface contact of anodized aluminum is not acceptable for grounding and bonding. The anodizing must be stripped away to allow adequate electrical contact, or a bonding wire must be installed between anodized surfaces. Metal surfaces that are securely bolted together are considered bonded if:

- Sufficient area between the surfaces is clean of paint and other coatings to ensure good metal-to-metal contact
- Bolt heads and nuts/washers are fully in contact with clean, uncoated metal surfaces

Any enclosure intended for access by the user shall have an internal copper bonding wire installed between the access panel and a bonded surface. A hinge does not constitute bonding unless it is listed by an NRTL or recognized for this purpose. Connections that depend on friction are not acceptable for grounding or bonding.

Equipment ground must be run with circuit conductors. All grounded equipment shall have the equipment ground conductor contained in the same raceway or cable as the ac circuit supplying the equipment.

It is permissible to have additional grounding electrode connections to equipment as long as all conditions listed in this subsection are met. It is not permissible to ground equipment only to a driven rod or other electrode and disconnect the ground from the ac branch circuit.

11.1.4.5 Accessibility of Live Parts

No parts intended to be accessible to unauthorized employees shall be energized to >50 V and >5 mA or 10 J stored energy. This applies to holes in a chassis, connectors where conductors are not sufficiently recessed, and panels that may be opened without tools. Shrink tubing cannot be used as a primary barrier for exposed voltages >50 V unless it has been listed for that purpose.

Electrical equipment should be designed so that routine maintenance can be done without having workers exposed to live parts. It is especially important to consider whether people not qualified as electrical workers will perform the maintenance operation. If routine maintenance requires exposure to live parts, then the maintenance operations must be planned and documented with the level of formality and rigor appropriate to the level of electrical hazard in the equipment. Examples of such documented procedures are the Lock Out/Tag Out (LOTO) procedure, safing procedure, or Safety Note.

If an enclosure employs a cover that can only be removed with a tool, and if live parts are accessible when the cover is removed—that is, when the cover is not interlocked—then the cover shall be so marked.

Enclosures accessible without using tools shall either be interlocked so that live parts are de-energized when the enclosure is opened or there must be no exposed live parts. Interlocks may be implemented in software provided failsafe design principles are followed. Failsafe means that loss of power, power supply failure, broken or disconnected wires, communications failure, CPU failure, and so forth should all be interpreted as unsafe conditions and the hazardous conditions eliminated. Communications and CPU failure often require specific design features such as watchdog timers. The methods used to assure failsafe performance are examples of topics that

should be included in a Safety Note. Further information on interlock design is available in Section 12.1, "Designing Engineered Controls."

Front panels shall be electrically dead, including during fault conditions.

11.1.4.6 Internal Wiring

11.1.4.6.1 AC Power Connections

If ac power conductors are field-wired (conduit, flex conduit), they must terminate in approved pressure terminals. If power supply conductors are in flexible cable or cord, they must either enter the assembly in an approved strain relief fitting or plug into a power inlet that is mounted flush with the enclosure. In assemblies that are likely to be accessed by the user, the power supply terminals must be substantially guarded against accidental contact. Shrink tubing is not acceptable as a primary barrier for live parts above 50 V unless listed or recognized for use as an insulation material at the higher voltage.

11.1.4.6.2 Polarity

Color coding, as shown in Table 11.1-1, should be used to indicate terminal and power cord polarity.

Table 11.1-1. Color coding used to indicate polarity.

NEC Convention	Power Line Terminal	AC Connector Terminal Pin	Power Cord Wire	
			US	European
Engergized	"Hot"	Brass	Black	Brown
Grounded	"Neutral"	Silver/Nickel	White	Blue
Grounding	"Ground"	Green (round or U-shaped pin	Green	Green with stripe

All output terminals or devices identified as neutral must be continuous with the input neutral (except for devices with isolated or floating outputs). On items designed for intermittent exposure—for example, lamp holders—the most accessible parts (the shell) must be connected to the neutral. There is no circumstance where only the neutral conductor is switched or fused, leaving a continuous "hot" wire connected to a load. All devices such as receptacles and connectors are to be connected according to the

applicable standard (e.g., National Electrical Manufacturers Association [NEMA] standards and manufacturer's recommendations).

11.1.4.6.3 Power Circuit Separation

Terminal blocks for power circuits shall be grouped separately from control circuits [2]. Internal ac power conductors are to be segregated from other conductors.

11.1.4.6.4 Wiring Terminals and Leads

All internal wiring must be either Listed or Machine Tool Wiring (MTW). All internal wiring must be copper, except thermocouple or special-purpose wire. Insulation must be rated for the highest voltage on any adjacent (bundled) wire.

Connectors must be sized correctly for wire. Crimp terminals shall be used with stranded wire only, unless the product is specifically designated for solid wire. Solid wire must be wrapped three-quarters to seven-eighths of a turn around wire binding screws in the direction of the tightening screw. Stranded wire may be wrapped around wire binding screws only if the wire is tinned or soldered, or terminals have cupped washers, upturned edges, or other means of capturing all the strands. Only one wire is to be used per terminal connector (ring, fork, and spade) unless the connector is designed for more than one wire. Two wires are allowed in pressure connectors if the connectors are designed for two. No more than three terminal lugs shall be attached to a bolt or screw. If wire nuts are used, they must be the correct size, with no loose wires and no exposed strands.

11.1.4.6.5 Clearance/Creepage Distances

Table 11.1-2 summarizes the general clearance and creepage distances in several standards. For more detailed specifications, see Reference [3]. For voltages greater than 600 V, distances may be determined using engineering calculations.

Table 11.1-2. Summary of clearance/creepage distances.

From	To	Via	Minimum Spacings, in. (mm) Rating, V			
			51–150	151–300	301–600	Reference
Uninsulated live part	Uninsulated live part of opposite polarity or different circuit, or grounded part (not enclosure), or exposed metal part.	Through air	1/8 (3.2)	1/4 (6.4)	3/8 (9.6)	UL 508A, Table E
		Over surface	1/4 (6.4)	3/8 (9.6)	1/2 (12.7)	UL 508A, Table E
Uninsulated live part	Walls or fittings of metal enclosure	Shortest distance	1/2 (12.7)	1/2 (12.7)	1 (25.4)	UL 508A, Table E; NEC 373; NFPA79; 12.5.2, NEC Art. 373
Uninsulated live part	Any uninsulated part of the enclosure door	Shortest distance	1 (25.4)	1 (25.4)	1 (25.4)	NEC 373
Edge of any mounted device	Between the device and the enclosure walls	Shortest distance	1/16 (1.6)	1/16 (1.6)	1/16 (1.6)	NEC 373

11.1.4.6.6 High Temperatures

Any assembly subject to internal temperatures exceeding 60 °C in normal use must have wiring and components rated for the highest possible temperature to which they will be exposed.

11.1.4.6.7 Correct Use of Components

All components must be used in accordance with the manufacturer's intent and instructions and in accordance with NRTL specifications. All components must be rated for the voltage and current range for which they are used. Assemblies subject to high fault currents (>10,000 A) must either be rated to withstand the fault or appropriately protected with fast-acting fuses. Recognized components must be evaluated within the context of their component category.

11.1.4.6.8 Mechanical Bracing of Conductors

Conductors used in high-current applications (>100 A) must be supported against movement that can be induced by magnetic forces. This bracing can be achieved by using locking plastic ties or other means that will not damage the conductors or present a fire hazard.

11.1.4.6.9 Overcurrent Protection

Fuse holders with fuses intended to be replaceable by an operator must not present a shock hazard during fuse replacement. If line voltage fuses are provided, they must interrupt power to all components in the circuit path except for the power switch. Combination switch/fuse assemblies are acceptable.

See NEC Article 430 for motor overcurrent protection [4]. Some general rules are:

- Motors generally must be protected to no more than 125% of the full load rating.
- Integral thermal protectors are adequate.
- Impedance protection is adequate on motors under 1 hp.

Internal components must be protected at not more than their input current rating. Internal wiring must be protected as shown in Table 11.1-3.

Table 11.1-3. Wire sizes and associated protective device ratings [5].

Control-circuit wire size		Maximum protective device rating
AWG	mm^2	Amperes
22	0.32	3
20	0.52	5
18	0.82	7
16	1.3	10
14	2.1	20
12	3.3	25

11.1.4.7 Strain Relief

There must be no tension on terminals or connectors. Any cable entering an enclosure must be able to be pulled by hand without imposing any stress on the corresponding electrical termination point.

Correct fittings should be used. The strain relief fitting must be designed for the application. Only one cable is to be used per fitting unless the fitting is specifically designed for multiple cables. On chassis that are cord-connected to an external terminal strip, the cord can be restrained to the chassis by an adequate clamp at a point near the terminal strip. The terminal strip must be substantially guarded against unintentional contact to live parts.

11.1.4.8 Switches and Controls

Switches and controls are defined as those circuit elements that provide operator input to the device being operated. If these elements are switching electrical circuitry, they must be rated for the applied voltage and current. If higher voltages (>50 V dc) are being switched, then the switch must be guarded and appropriately rated. If the switch is being used without reference to the ground potential of the chassis, then it must be rated for the common-mode voltage that is being applied.

As an example, assume that the element is a potentiometer that controls a 0-to-5-V signal. If the signal is referenced to chassis ground, then the potentiometer needs to be rated at 5 V and no special precautions are necessary. If on the other hand the same 0-to-5-V signal is floating on a 600 V dc voltage with respect to the chassis ground, then the potentiometer must have a voltage rating for continuous duty at 605 V dc.

Electromagnetic loads such as motors, inductors, and transformers have large inrush currents. For the motor industry, control elements are given horsepower ratings. This rating must be used to evaluate the load. The motor's locked rotor current must be less than the rating of the switch. In general, switches must be rated for both the type and size of the load.

If switches and control elements are to be used by an operator, they must not require the use of a tool (screwdriver or wrench) to gain access. The switch must be located on the perimeter surface of the device.

A control system must be configured so that the electrical drive is not automatically reapplied to a motor load whenever there is power resumption following a power outage. There must be a positive action by an operator to reapply power to a motor. This same principle must be applied to high-voltage power supplies (V >600 V dc) and to interlocked devices. If interlocked, the device must be de-energized when the interlock permissive is removed and must remain in that condition—even if the permissive is re-applied—until positive action by an operator.

All switches and controls must be identified with their function and their state. For example, a switch could be labeled "Power" for function and "ON" and "OFF" for state. If the switch is energized by its load circuit, it must be labeled as follows:

WARNING
The load side of this switch may be energized
by the backfeed when in the open position

Switches shall be physically located so that gravity will not cause a switch to close and energize the load. The switch shall be wired in such a manner that the controlled device is energized with the actuation handle in the "UP" position. A knife switch shall be connected so that the blade is connected to the load circuit. For power switches used with overcurrent protection, see Subsection 11.1.4.6.9, "Overcurrent Protection." Separate power switches and fuses shall be connected so that the fuse is de-energized by the switch to allow the operator to change the fuse safely [6].

11.1.4.9 External Wiring

Conductors shall be the correct size for the current to be carried. See NEC ampacity Table 310-16 for guidance [7]. The conductor insulation must have the correct rating for the voltage to be applied.

Wire insulation must be correct for the application and the environment. Some examples are: tray-rated cable, plenum-rated cable, UV resistant cable for outside applications, oil or chemical resistant cable, temperature-rated cable, or cable rated for direct burial. The

cable used must be rated for the intended application. See NEC Tables 310-61 through 310–64 for further guidance [8].

Connectors must be properly rated for the application. Proper voltage and current rating are required. Materials must be compatible with the environment: watertight or sealed connectors for outdoor applications, sealed for underwater applications. There shall not be a shock hazard while connectors are not made up.

Strain relief must be provided at the connectors to prevent cable damage resulting from use, connecting, or disconnecting [9].

Wiring must be located where the potential for damage is minimized. Cables must be protected from damage from sharp corners or edges, from being walked on, or from being run over. Cables should be separated from external heat sources [10].

Cable shields should be grounded. For EMI shielding purposes, cable shields may be grounded at only one end. Cable shields shall not be used as equipment grounding conductors. Cable shields shall not be used to carry voltages greater than 50 V. Cable trays and wire ways shall be properly installed and grounded [11].

11.1.4.10 Cords and Plugs

Cords must have the correct voltage and current rating for the application [7]. The outer jacket material must be appropriate for the application (e.g., UV resistant for outdoor applications, oil or chemical resistant, and so forth). The cord shall be provided with strain relief where it enters the equipment [9].

Power cords must have a grounding conductor of suitable size for the application.

Note: Two-conductor cords may be used for some applications, such as double-insulated tools and equipment.

AC power connections shall not be exposed (connected to the male pins of a connector). Male pins shall be used on input connections and sockets on output connections. AC power connections and HV connections should use ring lugs rather than spade lugs.

11.1.4.11 Extension Cords and Power Strips

Cords must have the correct voltage and current rating for the application [12]. The material of the outer jacket must be appropriate for the application (e.g., UV resistant for outdoor applications, oil or chemical resistant, and so forth). Extension cords shall not be used in series.

Cords must have a grounding conductor of suitable size for the application. The ground pin on a plug must still be present and in good condition.

Note: Two-conductor extension cords may be used for some applications, such as small lamps, provided that the NRTL-listed load is equipped with a two-conductor cord.

Cord and plug strips must be placed in locations that minimize or eliminate tripping hazards. A cord may not be placed across a doorway or walkway unless it is covered with an approved cord cover. Cords may not run through doorways or through walls [10].

11.1.4.12 High Voltage (>600 Volts)

11.1.4.12.1 General Requirements

This section applies to individual chassis or large distributed systems. The following elements may describe a single component (in the case of a chassis) or many components of a large system.

From a human electrical shock perspective, any voltage exceeding 50 V is sometimes defined as being high voltage. For this section, the NEC use of voltages greater than 600 V is employed. The principle hazard in this case is energy storage in capacitors and cables.

At voltages over 15 kV dc, evaluation of the system's ability to generate nonionizing radiation must be performed. Corona discharge will create chemical byproducts; the most notable is ozone when operating in an air environment. Ozone will degrade most materials and, in sufficient concentrations, becomes a health concern.

11.1.4.12.2 Correct Connectors

Special care must be taken in the choice of connectors for high-voltage applications (>600 volts). In the commercial sector, there exists a small coaxial connector called the MHV. This connector may be easily forced to mate with the standard BNC connector. This mating produces a dangerous exposed voltage hazard, since the BNC is an unguarded connector (that is, it provides ready access to its center conductor).

An acceptable connector for use in the low-current regime is the SHV. This connector is guarded and is rated for 5 kV dc. The Reynolds family of high-voltage connectors is also acceptable. If the voltages being used are ac or have a significant ac component, then the connector must be rated by the manufacturer for this service. In general, the capacitive losses associated with many dc-rated connectors make them unsuitable for ac applications.

11.1.4.12.3 Safing

Safing is the act of making a high-voltage system safe to work on. This is accomplished by discharging all energy storage elements and placing devices such as grounding hooks into the circuit to prevent the accidental recharge of the elements.

The system must be constructed so that the worker may safely access locations for the insertion of grounding and measuring devices.

11.1.4.12.4 Discharge Circuit

The circuit design must have passive discharge circuits that ensure all capacitors storing more than 10 J are discharged. This passive circuit may require a parallel active circuit to ensure that the energy discharge process is accomplished before the worker can access the hazard area. The active circuit usually uses a resistor and a switch. The switch is usually a high-voltage relay or contactor. Both must be rated by the manufacturer for their circuit voltage and discharge energy. The flashover voltage must be at least twice the circuit voltage. The energy rating depends on the repetition rate expected. A minimum derating of twice energy is recommended.

11.1.4.12.5 Drop Switch

A drop switch is a circuit element that automatically discharges a high-voltage circuit. It is actuated by opening an access panel or door that gives entrance or access to the

hazardous area. The term "drop" refers to the fact that gravity is typically used to close the switch. The switch must be capable of repeatedly sustaining the discharge energy and current without damage. The worker must be able to easily verify the status of the drop switch before entering the high-voltage environment. This is generally accomplished by mounting the drop switch behind a transparent panel. A drop switch does not eliminate the requirement to provide a means for safing.

11.1.4.12.6 Insulation

Insulation refers to discrete material engineered into a system to prevent voltage breakdown. Standard electrical tape shall not be used as high-voltage insulation. High-voltage splicing tape is permitted if rated by the manufacturer as permanent. Some classes of insulating materials, such as Teflon and thermoplastics, have a property known as "cold-flowing." This means that after a long duration of applied pressure, the material will change its dimensions to decrease the applied pressure. Hence, a Teflon-insulated wire pulled tightly across a grounded sharp edge will eventually cause the insulation to fail.

11.1.4.12.7 Associated Dielectrics

The most common dielectric used is atmospheric air. The voltage breakdown of air is strongly influenced by barometric pressure and humidity. If a system is used in various environments, it must be evaluated for the highest altitude and humidity to which it will be exposed.

Geometry of parts in a high-voltage design greatly affects the breakdown of the dielectric systems. It is important to verify that all test data presented with the system under investigation is generated without any modification to the hardware. This also applies to parts that may be at ground potential.

Aging of dielectric, caused by accumulation of dirt and alteration from chemical and radiation exposure, must be considered in the design of systems that experience these effects.

The manufacturer usually performs a dielectric-withstand test. Typical voltages used are twice the rated voltage plus 1 kV [13]. This is for a 1-minute duration. If the test results are available, they may be used to verify the dielectric implementation.

11.1.4.13 High Current, Low Voltage

Circuits that operate below 50 V do not represent a shock hazard, but when they have high current capability, this creates unique hazards. If the circuit exceeds 1000 V · A, additional design considerations are necessary. The principle hazard is arcing and/or vaporization of conductive materials that short the circuit.

Appropriate overcurrent protective devices, capable of interrupting fault currents that may occur, must be present.

Terminal spacing must be adequate for the voltage to be applied, including inductive voltages that may appear under fault conditions. The terminals must be insulated or guarded from foreign objects, especially conductive materials or tools.

Conductors should be braced so that they are secure and can withstand the forces that will be applied during both normal and fault conditions. If these conductors are to be used to power magnets, the added magnetic forces must be considered in the bracing design.

11.1.4.14 Failure Modes

Failure modes are an important consideration for equipment that performs a safety function, such as interlock chassis. In this case failure mode relates to whether the equipment performs its proper function reliably. Another aspect of failure mode analysis is whether the failure of components in the electrical equipment will create an unsafe condition such as a shock or fire hazard. It is the latter aspect that is specifically addressed in the context of this document.

The equipment must failsafe; the failure of a single component must not create an unsafe condition.

The equipment shall be protected in an overload condition. Overtemperature or overcurrent interlocks shall be provided.

Ground faults in a piece of electrical equipment must result in a trip of a ground fault circuit interrupter that is installed in the electrical service. In other words, the equipment must be designed and installed so that the ground fault circuit interrupter will operate correctly.

Controls and interfaces shall not create unsafe conditions. For example, output cables should be able to withstand the full voltage and current of a power supply even if the application does not require the full output capability of the supply.

11.1.4.15 Marking Requirements

The following items are clearly and permanently labeled, as applicable. The label should be clearly visible and located adjacent to the item it refers to, when appropriate.

11.1.4.15.1 Identification and Product Information

- Manufacturer's name or mark
- Model number or name of product
- Title, drawing number, and serial number (S/N), if applicable
- Rated supply voltage and ac frequency or dc, as applicable
- Maximum rated power in watts or volt-amperes, or maximum rated input amperes
- Fuse size
- Fuse type
- Power switch
- All controls
- All indicator lamps and gauges
- Input terminals: voltage
- Output terminals: voltage, maximum current
- Grounding: equipment, auxiliary, and signal reference
- Batteries: size, voltage, rechargeability
- Maximum ambient temperature rating
- Type of environment for which equipment is intended, e.g., indoor or outdoor
- Field wiring instructions, e.g., "Connect to 208 V, 3-phase, 50 amp circuit. Minimum conductor size #6 CU THHN"
- Any restrictions of personnel, location, duty, and so forth

11.1.4.15.2 Safety Markings

- Assemblies with multiple power sources must have a "CAUTION – Dual ac voltage Source" or other appropriate warning label.
- The primary energy-isolating device—for example, a switch or circuit breaker—is labeled "Lockout Point." This point is not a control switch for a relay or other electromechanical device. This requirement does not apply to equipment that can be disconnected entirely by cord-and-plug.
- Any parts that are exposed and hazardous when live are marked with "DANGER", plus any other appropriate information.
- Enclosures containing greater than 600 V are marked "DANGER HIGH VOLTAGE."
- Hot surfaces are marked "DANGER HOT" or similar words. This does not apply if hot surfaces are self-evident.

11.1.4.16 Modifications

Modifications to commercial electrical equipment must be done with care. There can be many unintended consequences, especially when voltage, current, or power limits are changed. Modifications that have significant safety implications shall be documented in a Safety Note.

Safety features that are changed—such as interlocks, over-range limits, and so forth—must be reviewed and documented consistent with the risk associated with failure of the equipment or system. Changes to safety features shall be documented in a Safety Note.

Changes that affect the cooling of electrical equipment must be evaluated or tested. Active cooling features such as fans should not be defeated unless an adequate alternative is provided. Mounting or location must not compromise cooling. Equipment mounted in close proximity to walls or other equipment can result in blocked cooling vents in the chassis.

Wiring changes must be evaluated against a number of criteria. Wires must be routed to maintain separation between signal and power wires. Wires must be insulated to the maximum voltage level of other wiring or separated by barriers or adequate spacing.

Insulation must be temperature-rated for the environment. Wires must be rated for any solvents or other chemicals they might be exposed to, such as oil in machine tools.

Any conditions of use that are part of the NRTL listing of the equipment must be evaluated before modification. Replacement parts that are installed during maintenance must be chosen with care to make sure that they are equivalent to original parts.

11.1.4.17 Foreign-Manufactured Power Supplies and Equipment

Electrical equipment manufactured for use outside the United States may have electrical operating ratings that do not comply with standard US domestic electrical supply lines. In addition, foreign equipment marks or standards (i.e., the CE Mark) generally cannot be assumed to equate to acceptable NRTL criteria. All such equipment must be inspected. Note that foreign-made equipment that conforms to standard US electrical operating ratings and that is listed/labeled by an NRTL is acceptable. Also note that the inverse problem can arise when LLNL (or other US equipment) is sent abroad for operation in a foreign country.

Adapters (or converters) listed or labeled by an NRTL are acceptable when their rating is sufficient for the loads associated with the foreign equipment. Non-NRTL adapters (or converters) must be inspected. Foreign equipment having removable line cord/connector sets with ratings greater than 110 V–120 V nominal (such as those nominally rated 250 V) must use connector locks fixed to the equipment.

Common US voltage and frequency supplies (such as 120 V, 60 Hz) must be considered before connecting foreign equipment (often 220 V, 50 Hz). While step-up or step-down transformers (converters) can correct for differences in equipment or supply voltage levels, differences in operating frequency can cause overheating of equipment, speed changes in motors, or improper function of the foreign equipment. Some equipment is designed to operate in the range of 50 Hz – 60 Hz; other equipment designed to operate at 50 Hz may not be operated at 60 Hz. The magnetic saturation design parameters (V/Hz ratio) for US equipment is 120 V/60 Hz or 2.0, while the ratio for foreign equipment is often 220 V/50 Hz or 4.4. If more guidance on this topic is required, bring it to the attention of the AHJ.

Ampacity and insulation characteristics of wiring used in foreign equipment must have capabilities consistent with the LLNL application. In assessing ampacity, the cross-sectional area of the original wire and an alternate must be compared.

11.1.5 References

[1] National Fire Protection Association, *NFPA 79 Electrical Standard for Industrial Machinery, 1997 Ed.*, Section 17.1.1, National Fire Protection Association, Quincy, MA (1997).

[2] National Fire Protection Association, *NFPA 79 Electrical Standard for Industrial Machinery, 1997 Ed.*, Section 12.2.2, National Fire Protection Association, Quincy, MA (1997).

[3] Underwriters Laboratories, *Standard for Safety for Electrical Equipment for Laboratory Use; Part 1: General Requirements*, UL 3101-1, Annex D, Underwriters Laboratories, Northbrook, IL.

[4] National Fire Protection Association, *NFPA 70 National Electrical Code*, Article 430, National Fire Protection Association, Quincy, MA.

[5] Underwriters Laboratories, *Standard for Safety, Industrial Control Equipment*, UL 508, Table 18.1,Underwriters Laboratories, Northbrook, IL (1994).

[6] Underwriters Laboratories, *Standard for Safety, Industrial Control Equipment*, UL508, section 20.4,Underwriters Laboratories, Northbrook, IL (1994).

[7] National Fire Protection Association, *NFPA 70 National Electrical Code*, Table 310-16, National Fire Protection Association, Quincy, MA.

[8] National Fire Protection Association, *NFPA 70 National Electrical Code*, Tables 310-61 through 310–64, National Fire Protection Association, Quincy, MA.

[9] Underwriters Laboratories, *Standard for Safety for Electrical Equipment for Laboratory Use; Part 1: General Requirements*, UL 3101-1, Section 6.10.2, Underwriters Laboratories, Northbrook, IL.

[10] National Fire Protection Association, *NFPA 70 National Electrical Code*, Sections 400-7 and 400-8, National Fire Protection Association, Quincy, MA.

[11] National Fire Protection Association, *NFPA 70 National Electrical Code*, Article 318, National Fire Protection Association, Quincy, MA.

[12] National Fire Protection Association, *NFPA 70 National Electrical Code*, Section 240.3(d) and Table 310-16, National Fire Protection Association, Quincy, MA.

[13] Underwriters Laboratories, *Standard for Safety, Industrial Control Equipment*, UL508, section 49,Underwriters Laboratories, Northbrook, IL (1994).

Additional Reference

Lawrence Livermore National Laboratory, *LLNL ES&H Manual*, Vol. II, Part 16, "Electrical," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-MA-133867 (2001).

Fabrication, Electronic Equipment, General Specification

SLAC-I-730-0A11F-001-R000

SPECIFICATION

LED 21871 B

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE NATIONAL LABORATORY
ELECTRONICS ENGINEERING DEPARTMENT, LIVERMORE

Date January, 2000

NIF-5004082-OA

TITLE	APPROVED
FABRICATION, ELECTRONIC EQUIPMENT, GENERAL SPECIFICATION	CHECKED
	ORIGINATED R.J. Hersey

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5.0 Quality Assurance

REV	BY	APPROVED	DATE	DESCRIPTION OF REVISION
B	R. Kimble/J. Maestas/ T. Hauck/J. Mar		1/3/00	Major Revision – See History Copy
A	L. Henneman	L. Henneman	9/18/99	General Revision – See History Copy

1.0 General

1.1 Scope

This specification sets forth the minimum requirements for the fabrication of electronic equipment for Lawrence Livermore National Laboratory (LLNL).

1.2 Quality

It is the intent of LLNL to obtain the highest quality of materials and workmanship found in the best custom electronic equipment fabrication. Constructive suggestions for the improvement of quality are welcome and will be given prompt consideration.

1.3 Materials

1.3.1 Only new parts of current manufacture shall be used.

1.3.2 The manufacturer shall advise LLNL of the discontinuance or renumbering, by the part manufacturer, of any parts.

1.3.3 No substitutions may be made without the approval of LLNL.

1.4 Information Feedback

1.4.1 All changes agreed to between the manufacturer and LLNL shall be marked on one set of documentation, dated, and initialed. The preferred colors are red for deletions and green for corrections and/or additions.

1.4.2 The marked-up set of documents shall be returned to LLNL with the first "equipment" shipment (partial or complete).

1.5 Applicable Specifications

The latest revisions of the following documents form a part of this specification, to the extent stated herein:

ANSI/IPC-A-610	"Acceptability of Electronic Assemblies"
ANSI/IPC-RB-276	"Printed Wiring Board Production"
ANSI/J-STD-001	"Requirements for Soldered Electrical and Electronic Assemblies"

ANSI Y14.5M 1994	"Dimensioning & Tolerancing"
ANSI Y32.16	"Reference Designation for Electrical and Electronics Parts and Equipment"
EIA RS-336	"Color Coding of Chassis Wiring" (Electronics Industries Association)
IPC-CM-770	"Guidelines for Printed Board Component Mounting"
LED 21872	"Cable Assemblies"
LED 43-01-15-A1	"Electronics Engineering Drafting and Design Manual"
MIL-C-5541	"Chemical Treatment for Aluminum Alloys- General Purpose Coating"
MIL-STD-681	"Identification, Coding, and Application of Hook-Up and Lead Wire"
MIL-W-16878	"Wire, Electrical, Insulated, General Specification for"

1.6 Order Precedence

In case of conflict, the fabrication "package" documents shall take precedence in the following descending order:

1. Purchase Order
2. Equipment performance specification
3. Schematic circuit diagram
4. Parts list
5. Other drawings
6. This and other specifications referenced herein
7. Prototype or sample unit
8. Photographs

2.0 Marking

2.1 General

2.1.1 All markings shall be positioned for maximum readability.

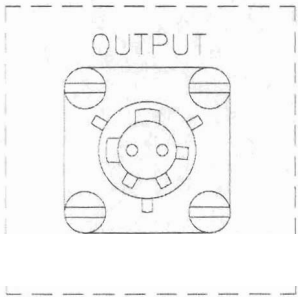
2.1.2 Marking shall be legible and neat in appearance regarding uniformity of size, spacing and alignment of characters. Unless otherwise specified, all markings will be a minimum of 2.54 mm [.100 inch] and a maximum of 4.0 mm [.156 inch].

2.1.3 Black ink shall be used on light background and white ink on dark background.

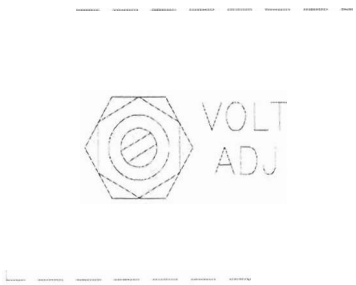
2.1.4 Function titles (shown in blocks on schematic) shall be marked above a component as follows:

2.1.4.1 Front Panel: Front

2.1.4.2 Rear Panel: Outside

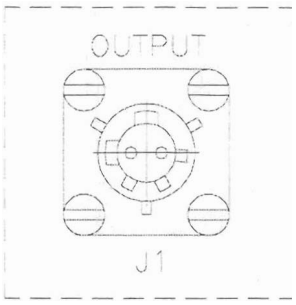


2.1.4.3 Chassis Plates: On the surface where adjustment is made.



2.1.5 Preferred location of component designation marking is below the mounted component. When component goes through the chassis plate, component designation should be marked on both sides of panel.

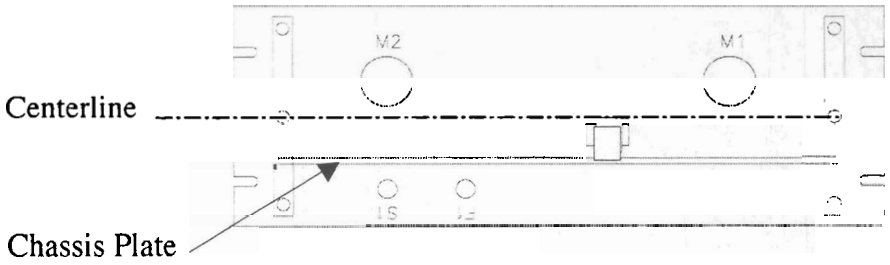
2.1.5.1 Rear Panel: Outside, below component



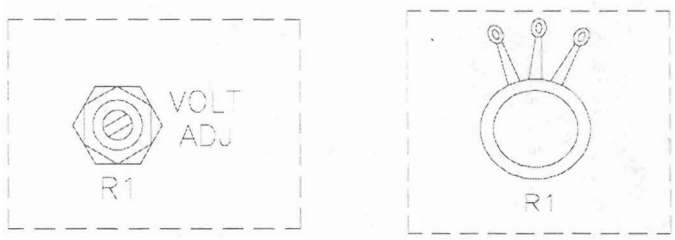
2.1.5.2 Front and rear panels: Inside

2.1.5.2.1 Markings above the chassis plate or panel centerline shall be located above the component.

2.1.5.2.2 Markings below the chassis plate (printed board assembly, shield, or other item that is mounted perpendicular to the front and rear panels) shall be located below the component and shall read right-side-up when the chassis is upside down. When there is no chassis plate, the panel centerline should be used as reference for marking orientation.

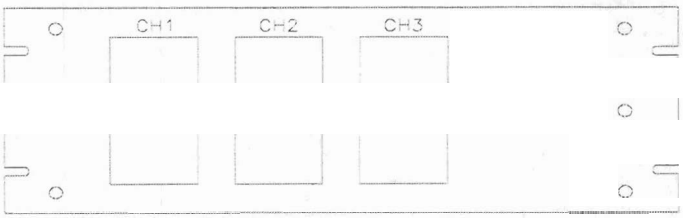


2.1.5.3 Component designation should be marked below the mounted component. When component goes through a panel, marking shall appear on both sides. When marking can not be placed below component, marking may be adjacent to component.

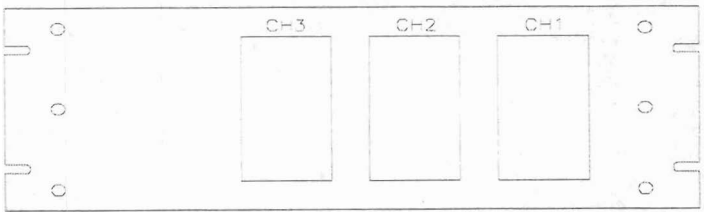


2.1.6 Multi-channel circuits within the same chassis shall be marked to read left to right from the operating face, as shown below.

2.1.6.1 Front Panel-Front View



2.1.6.2 Front Panel-Rear View



2.2 Front Panel

2.2.1 Markings on the front of the front panel shall be silk-screened.

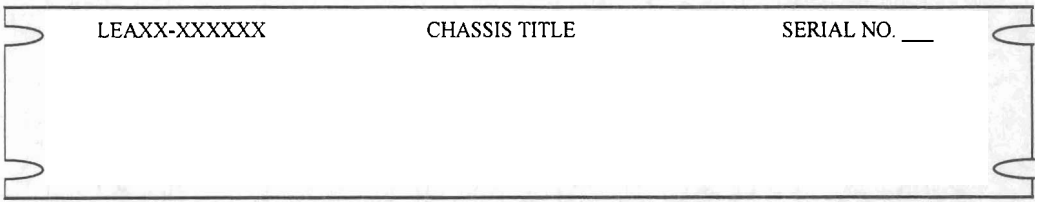
2.2.2 The title of the chassis unit shall be as shown in the title block of the schematic.

2.2.3 The drawing number of the chassis unit shall be as follows:

2.2.3.1 For LEA numbers, the number will be composed of the letters "LEA" followed by the drawing number (8 digits) as shown on the assembly, if one exists. Otherwise the schematic number will be used. NOTE: Revision level is omitted.

2.2.4 The title, drawing number, and serial number (S/N) shall be positioned as follows for a standard 19 inches rack mounted chassis:

1. Top of lettering shall be 1.59 mm [0.06 inch] from top edge of panel.
2. Drawing number is 50.8 mm [2.00 inch] from left edge of panel
3. Serial number is 50.80 mm [2.00 inch] from right edge of panel
4. Chassis title is centered on panel



2.3 Chassis Plates and Other Panels

2.3.1 Markings on other than the front of the front panel may be applied with silk-screen, rubber stamp, or labels, and covered with protective coating if necessary.

2.3.2 Multi-channel circuits within the same chassis shall be marked to read from right to left on the outside of the rear panel. (see 2.1.6.2)

2.3.3 All schematic reference designations shall be marked immediately below or adjacent to the referenced component. Reference designation shall be per ANSI Y32.16. The marking shall be readable after assembly of components and wiring.

2.3.4 All markings on the top of chassis plates or top covers shall be readable from the front of the chassis.

2.3.5 All markings on the bottom of chassis plates or bottom covers shall be readable from the rear of the chassis.

2.4 Component Marking

2.4.1 Circuit Breaker current rating shall be marked on the back of the panel and be visible after chassis assembly.

2.4.2 Plug-In components shall be marked with component designation on the plug-in side and with the socket designation "X" preceding the component designation on the wiring side.

2.4.3 Terminal Strips shall have the first and last contacts, and every fifth contact in between marked on the panel. If terminal strip is mounted through the chassis marking shall appear on both sides.

2.4.4 Fanning Strips, when used with a terminal strip, shall be marked in the same manner as the terminal strip.

2.4.5 Variable Transformer swinger fuses shall be marked with transformer component number and fuse rating.

2.4.6 All fuses shall have their amperage value and the words SLO BLO, if applicable, marked adjacent to the fuse holder.

2.4.7 Chassis with 250V or more shall have a "CAUTION" or "DANGER" label attached or marked with the appropriate multi-colored legend. See LED 43-01-15-A1 for more details.

2.4.8 Chassis with dual 117 VAC power sources shall have a "CAUTION – Dual AC Voltage Source" label attached or marked.

2.4.9 All components mounted through a panel with leads or connections extending through the panel shall have their reference designations marked on both sides of panel.

2.4.10 All components used for operating and maintaining equipment shall have their descriptive function: e.g., ON, OFF, Start, Stop, Voltage Adj., etc., marked on the front (operating) side of the panel and the reference designation marked on the opposite side of the panel.

3.0 Assembly

3.1 General

3.1.1 Components marked with values and ratings shall be mounted so that they can be easily read. When it is not possible to mount a small component (such as a diode) to show both the part identification and polarity, the unit shall be mounted so the part identification marking is visible.

3.1.2 Components with a mounting key slot shall be positioned with the slot on the bottom.

3.1.3 All fastening hardware shall be locking/captive type.

3.1.4 No more than three terminal lugs shall be attached to a bolt or screw.

3.1.5 Bolted or screwed electrical connections shall not depend on any insulating material to maintain contact pressure.

3.1.6 Ceramic and ceramic-coated parts shall be mounted with nylon or fiber washers in contact with the ceramic surfaces. As a general rule, resilient washers shall be used whenever brittle materials are bolted in assembly.

3.1.7 When using threaded hardware, there shall be one to three threads visible beyond the front of the nut.

3.1.8 A flat washer shall be placed between the head of the screw and any non-metallic materials and over a slotted hole.

3.1.9 Split or internal tooth lock washers should be used when self-locking screws or nuts are not available.

3.2 Component Mounting

3.2.1 Chassis receptacles shall be mounted so that the key-way and/or first numbered or lettered terminal will be on the 12 o'clock position.

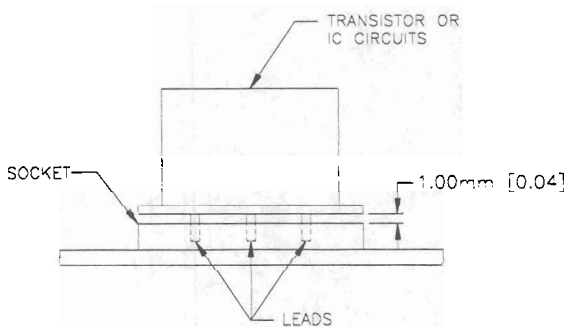
3.2.2 Preferably the ground pin of an AC receptacle should be oriented in the "up" position when mounted.

3.2.3 When heatsinks are specified for components, thermal heatsink compound or silpad should be used unless otherwise specified.

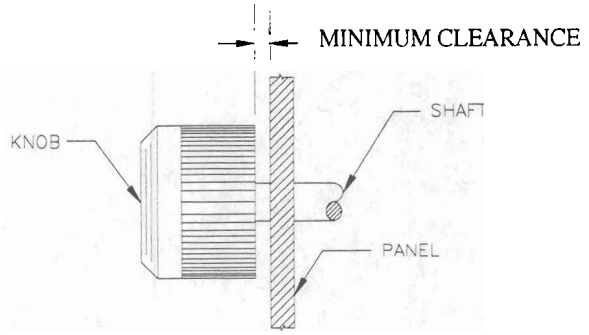
3.2.4 Control knobs and shaft couplings shall have metal inserts and be secured with two Allen-head set screws that are set at 90 degrees to each other.

3.2.5 When mounting an open-backed terminal strip on a metal surface, an insulating sheet, 1 mm [.04 inch] to 2mm [.08 inch] thick, shall be used between the terminal strip and metal surface.

3.2.6 Semiconductors requiring lead trimming shall be sheared to required length, not clipped with diagonal-jaw cutting pliers. Lead lengths shall be such that, when the device is fully inserted in the socket, there will be approximately 1mm of space between the body of the device and its socket. (See Illustration)



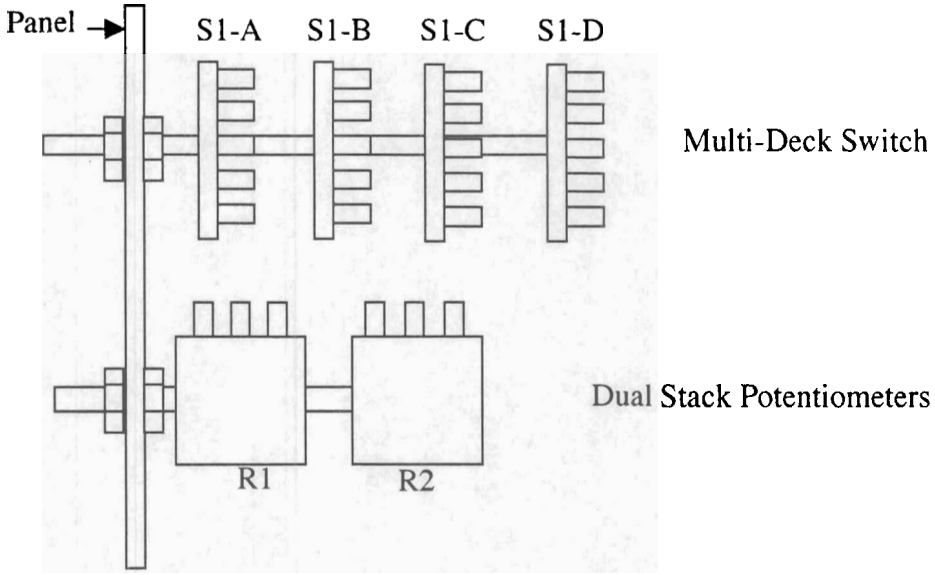
3.2.7 Knobs shall be positioned on shaft in accordance with manufacturer 's specifications, or as follows:



3.2.8 Fuseholders require a rubber washer be used between the fuseholder body and the panel.

3.2.9 Fan Assemblies shall have finger guards installed on the inside and outside of the chassis.

3.2.10 Multi-Deck Switches or Potentiometers should have the "A" section of the switch or the lower "R" number closest to the mounting surface.



3.2.11 Component leads shall extend out from component body at least 2 mm [.08 inch] before any bend is made. There shall be at least 4 mm [.156 inch] length between the component and the soldered connection.

4.0 Wiring

4.1 General

4.1.1 Tools used to shape leads shall not damage the leads. The use of round-nosed pliers or automatic lead forming machines is recommended.

4.1.2 Interconnection leads should be provided with a service loop at the wiring termination unless identified by "Δ" on line of schematic, which shall be as short as possible, but not taut.

4.1.3 Wires shall be arranged to prevent abrasion of the insulation. Long runs of wire shall be secured with ties or clamps.

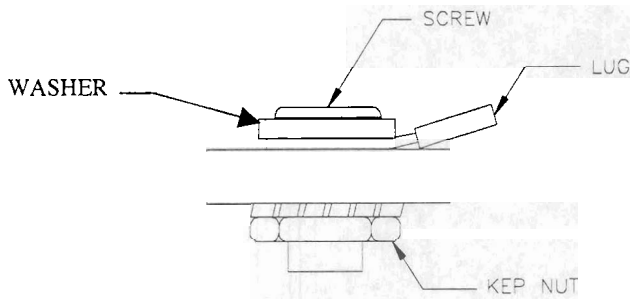
4.1.4 All wiring connections should be accessible for maintenance.

4.1.5 Transparent tubing or shrink tubing shall be used over wiring connections for inspection purposes.

4.1.6 An electronically interlocked safety device shall be provided when voltages of 250V or more are present.

4.1.7 Circuits greater than 1000 volts shall be wired with a minimum clearance to ground or to adjacent components of 25 mm [1.00 inch] per 10 kV, or 6.0 mm [0.24 inch], whichever is greater, after allowing for the voltage rating of any separating insulation.

4.1.8 There shall be a ground screw assembly located and labeled "⏚ " or "EG" on the chassis plate. The sole purpose of this assembly is to establish an earth ground. Note: For electrical connections see 4.1.9.9.



4.1.9 Wire Termination

4.1.9.1 Terminal lugs shall be closed ring and of the proper stud size and wire gauge. The barrel of the lug shall be filled with solder or crimped.

4.1.9.2 Wires shall not be spliced. The insulation on a wire shall be continuous between terminations.

4.1.9.3 Unused component wire leads, such as transformer center tap, shall be terminated at tie points.

4.1.9.4 A tie point shall be used for the junction of two or more wires and /or the termination of single component leads. (See 4.1.9.3)

4.1.9.5 Unused terminals on any component shall not be used as tie points.

4.1.9.6 When solid wire is specified, the wire may be terminated with a lug or soldered to a terminal.

4.1.9.7 Where there are removable or hinged portions of a box and/or chassis with components, a separate wire is required to ensure a good ground between the removable or hinged portion and the box and/or chassis.

4.1.9.8 Thermocouple wire that terminate at a screw may be terminated by looping wire around screw in a direction that will tighten the loop when screw is tightened.

4.1.9.9 Ground connections shall be connected to "⏚" or "EG". Ground connections shall be free of paint or insulating materials.

4.1.9.10 A tight mechanical connection of all wires to a terminal point should be made before applying solder.

4.1.10 Wire Routing

4.1.10.1 Grommets shall be used to protect wires passing through metal surfaces.

4.1.10.2 Wires within a wire harness should be parallel with a minimum of crossover. The harness shall be routed to eliminate interference with components, contact with heat dissipating items or abrasion of sharp or rough edges.

4.1.10.3 Special consideration should be given to routing wire harnesses within a chassis that contains a combination of: digital signal, relay control power, AC voltage, and High Voltage.

4.1.10.4 Tie-wraps or nylon lacing will be used for bundling wires. Ties at breakouts should be made as close as possible to each side of breakout and as close to each side of bend without placing the tie in the bend itself. Sufficient tie down clamps must be used to secure all wiring harnesses to chassis.

4.2 Wire Type and Sizes

4.2.1 Hook-up wire shall be per MIL-W-16878, Type C and D for vinyl and Type EE for Teflon. Wire wrap wire shall be Kynar (polyvinylidene fluoride) insulated.

4.2.2 117 VAC shall be No. 18 AWG minimum per MIL-W-16878, Type C, or No. 20 AWG Teflon (5 Amps max.).

4.2.3 All chassis hook-up wire shall be of a size selected from the following table:

Maximum Current "Amps"	Wire AWG Vinyl	Wire AWG Teflon
3	22	24
4	20	22
5	18	20
7	16	18
10	14	16
15	12	-
20	10	-
30	8	-

4.3 Color Code

4.3.1 Color values shall be within the limits defined in EIA Standard RS-336.

4.3.2 Chassis Hook-up Wire shall be coded as in the table below:

Black	Grounds, grounded elements
Brown	Heaters, Filaments, transformer secondary lead
Red	Primary Power Supply - Positive Voltage
Orange	Secondary Power Supply – Positive Voltage, Screen grids in tubes
Yellow	Cathode, transistor emitters
Green	Control grids, transistor bases, signal leads
Blue	Anodes (plates), transistor collectors (that are not tied directly to power supply – Positive Voltage)
Violet	Primary Power Supply – Minus Voltage, below ground returns (not tied to ground)
Gray	AC Primary Hot leg - power and interlock wiring
White	AC Neutrals

4.3.3 Polarities and color codes listed in the table below shall be carefully followed for the safety of equipment users:

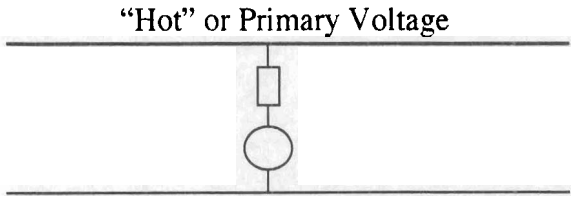
Power Line Terminal	AC Connector Terminal Pin	Power Cord Wire	European Power Cord	Chassis Wire
"Hot"	Brass	Black	Brown	Gray
"Neutral"	Silver/Nickel	White	Blue	White
"Ground"	Green (Round or U-Shaped Pin)	Green	Green w/stripe	Black (or Grounding Terminal)

4.4 Miscellaneous

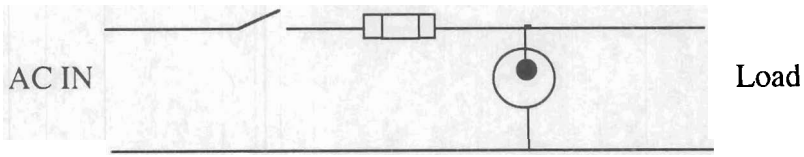
4.4.1 AC wiring shall be twisted unless otherwise specified. Preferably, AC wiring will be routed on the underside of the chassis plate and/or routed separately from other wires.

4.4.2 Potentiometers and variable resistors shall be wired so that "CW" or an arrow designates clockwise rotation as viewed from the shaft end.

4.4.3 Any voltage-dropping resistance used with an indicating light shall be connected between the light and the "Hot" or Primary voltage source.



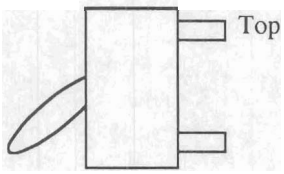
4.4.4 The power switch, the fuse and the "power on" light shall be connected to the "Hot" side of the 117V AC power line. The wiring sequence should be switch, fuse, light, unless otherwise specified.



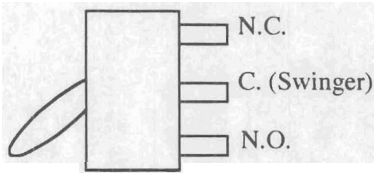
4.4.5 Incoming or "Line Side" AC wiring shall be connected to components as follows:

Components	Connection
Switch, single-throw, terminals on each end.	Top terminal
Switch, double-throw (used as single-throw).	Swinger side

Single-throw



Double-throw



4.4.6 All exposed AC voltage wiring shall be covered for safety in an appropriate manner such as with a non-conductive material lucite or shrink tubing.

4.4.7 Verify that chassis is free of sharp burrs, metal shavings, wire clippings, solder splatter and other foreign material which could cause electrical shorts.

5.0 Quality Assurance

5.1 The manufacturer shall perform all specified tests and inspection requirements, and shall verify that the materials, dimensions, markings, and workmanship meet requirements.

5.2 Manufacturers' test equipment, inspection methods, and test data shall be acceptable to LLNL.

5.3 Certificate of conformance shall accompany each shipment of product when specified.

Acquiring Electrical Equipment & Components

11.5 Acquiring Electrical Equipment & Components

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Revision History

Date	Author	Revision
May 2002	Chuck Pomernacki	Revision 0: Original release.

11.5.1 Introduction

Electrical safety (as it relates to electrical equipment) is concerned with assuring that potentially hazardous, electrically energized equipment is free from reasonably foreseeable risks of fire, electrical shock, and related hazards. Hence, by implication, such equipment is reasonably safe for its intended use.

The National Nuclear Security Administration (NNSA) of the U.S. Department of Energy (DOE) requires all National Laboratories, including those operated by the University of California, to comply with federal regulations regarding the safety of electrical equipment. This obligation is consistent with quality design practices, a good safety program, and with what is already practiced in the electrical equipment industry. It is therefore incumbent upon the PI/RI to use due diligence to ensure compliance with this obligation.

The *LLNL ES&H Manual,* Vol. II, Part 16, "Electrical," governs the requirements for electrical equipment at LLNL. Two Work Smart Standards govern the safety of our electrical equipment: WSS B56 and WSS B57. WSS B56 is 29 CFR 1910 (Subpart S, Electrical), also known as the Occupational Safety and Health Administration (OSHA) standards. WSS B57 is NFPA 70 (1999), also known as the National Electrical Code (NEC). The Work Smart Standards are specified in Appendix G of Contract 48.

11.5.2 Terms and Definitions

Authority Having Jurisdiction (AHJ) (electrical)	A person who interprets the requirements of electrical codes and standards, approves electrical equipment for use, and coordinates the activities of staff.
AHJ-approved	Non-NRTL electrical equipment that has been examined by an AHJ field representative and found acceptable in accordance with the criteria defined in LLNL's AHJ Program. AHJ-approved equipment will have a label affixed identifying it as such.
Due diligence	The diligence reasonably expected from, and ordinarily exercised by, a person who seeks to satisfy a legal requirement or to discharge an obligation. Alternately called "reasonable diligence."
Electrical component	An electrical element that is embedded in a larger assembly (chassis or rack) of elements and is not, by itself, usable by an operator.
Electrical equipment	Electrically-powered technology that is field installable as stand-alone or rack-mounted and ready to be electrically energized and used by an operator.
Examination	A process performed by a person qualified to evaluate whether or not electrical equipment is free from recognized hazards and meets code requirements.
Intended use	NRTL products or services are labeled or listed for a specific environment or installation application. For example, electrical enclosures may be labeled or listed according to consensus standards such as the National Electrical Manufacturers Association (NEMA) as Type 1, 3, 3R, or 12.

Non-NRTL	A product (or assembly) that has not been evaluated by an NRTL, is therefore neither listed nor labeled, and is required to be submitted to LLNL AHJ evaluation and acceptance prior to being used at LLNL. Non-NRTL equipment may include custom-built apparatus, NRTL-listed or labeled products that have been altered, equipment that has not been inspected or that has been inspected by a test facility not recognized by OSHA as an NRTL, or unique electrical equipment received from another DOE lab.
NRTL	Nationally Recognized Testing Laboratory. An organization that is recognized by OSHA as an acceptable laboratory for product evaluation and maintains records of periodic examinations of equipment and materials. The NRTL ensures that equipment and materials comply with designated standards or are tested to determine their suitability for use.
NRTL-listed	Equipment or materials ("products") or services included in a list published by an NRTL. The Listing Mark on a product is the manufacturer's representation that samples of that complete product have been tested by the NRTL to nationally recognized safety standards and found to be free from reasonably foreseeable risk of fire, electric shock, and related hazards. Alternately called "NRTL-certified."
Potentially hazardous electrically energized equipment	Equipment that is electrically energized to 50 V potential or greater AND 5.0 mA current, OR 10 J or more of stored energy. Note that all equipment powered by 120 V (nominal) and employing a standard cord and plug meet these criteria and might be potentially hazardous.
Reasonably safe (electrical equipment)	Electrical equipment that is NRTL-listed or AHJ-approved.

Recognized component (RC) A UL term identifying component products that have been tested and evaluated by UL's Component Recognition Service, but that are incomplete or restricted in performance capabilities. These components may be used in an assembly as a complete end-product or system that is listed by UL (see *NRTL-listed*). The UL RC Mark (RU) means that the component is electrically safe provided it is installed and used as documented by the manufacturer. An assembly consisting entirely of RC components is not assumed to be the equivalent of a listed product; the finished assembly must still be evaluated.

11.5.3 Ascertaining the Safety of Electrical Equipment

The *LLNL ES&H Manual,* Vol. II, Part 16, Document 16.1, "Electrical Safety," documents the conditions of approval and use for all electrical equipment at LLNL. In accordance with these conditions, all potentially hazardous equipment connected or plugged in to the Laboratory's electrical system must be either listed by a Nationally Recognized Testing Laboratory (NRTL) or approved by the electrical Authority Having Jurisdiction (AHJ).

Note: No equipment is "guaranteed safe" by either the NRTL or AHJ mechanisms. It is only (by testing and/or visual inspection) "found to be free from reasonably foreseeable risk of fire, electric shock and related hazards..."[1]

11.5.3.1 NRTL Listing

Commercially-available electrical equipment that is certified (i.e., listed) by a third-party, nongovernmental, independent agency known as a Nationally Recognized Testing Laboratory (NRTL) is automatically approved for use at LLNL. This is true so long as such equipment is used in accordance with the NRTL's approved listing conditions. OSHA grants NRTL certification to an organization, and 19 organizations currently are recognized as NRTLs. Each NRTL is a laboratory qualified for product evaluation. An NRTL tests samples of complete products to nationally recognized safety standards. An equipment manufacturer is certified by an NRTL to apply the NRTL certification mark to

[1] Excerpted from *The Code Authority*, vol. 6, no.1, Underwriters Laboratories Inc. (1997), http://www.ul.com/auth/tca/v6n1/difference.htm.

specific products. These products are listed in the NRTL data base. Much of the electrical equipment manufactured for use by the general public bears certification labels from NRTLs. Quite often, such certification comes from the industry-leading Underwriters Laboratories Inc. (UL).

While our main concern is the custom and one-of-kind R&D equipment built at LLNL or built elsewhere for us, we are also concerned with special, commercial scientific equipment that often does not have NRTL certification. RIs who conduct R&D experiments can be especially affected. NRTL labeling may or may not appear on potentially hazardous, electrically energized scientific equipment. Any potentially hazardous, non-NRTL electrical equipment the Lab buys or builds must be examined by an Authority Having Jurisdiction (AHJ).

If commercially-available electrical equipment is not NRTL-listed, and if the equipment cannot be obtained as NRTL-listed through alternate sources of supply, it must be AHJ-approved before it can be connected to the LLNL electrical system.

11.5.3.2 AHJ Approval

The Authority Having Jurisdiction (AHJ) program at LLNL provides a mechanism for accepting non-NRTL equipment for use at LLNL. The program is described in the *LLNL ES&H Manual*, Vol. II, Part 16, Document 16.3, "LLNL AHJ Requirements for Approving Electrical Equipment, Installations, and Work." The AHJ program is also an implementation vehicle for a portion of the *Engineering Policies and Procedures Manual,* Section 3, "Directorate Quality Assurance Plan." The subsection on nuclear facilities addresses important requirements of the Price-Anderson Amendments Act of 1988 (PAAA) relating to Safety Class and Safety Significant equipment in nuclear facilities.

Coleaders of the Electrical AHJ program come from the Engineering and Laboratory Services directorates. The Program AHJ, from Engineering, is responsible for approval of programmatic electrical equipment. The Building AHJ, from Laboratory Services, has primary oversight concerning NEC compliance and electrical equipment approval related to construction and infrastructure (i.e., premises wiring).

A number of AHJ field representatives have been trained to examine and approve or reject electrical equipment that is non-NRTL.[2] The AHJ field representative will conduct a visual examination of any potentially hazardous, non-NRTL equipment. An AHJ visual (or "level-one") inspection of non-NRTL electrical equipment establishes a defined threshold of electrical equipment safety for that specific equipment item. If the equipment is deemed acceptable, the representative will affix an approval label. If the equipment fails the examination, the representative will affix a rejection label. The AHJ field representative generates a report documenting the results in the LiveLink data base, which is available to all LLNL AHJ field representatives. A copy of the field report is available to the RI.

As an example, most battery-powered equipment will not need NRTL certification or AHJ approval. Examples include flashlights, pagers, and portable radios. However, NRTL labels are needed for the chargers of such equipment.

11.5.4 Verifying NRTL Status

Before ordering NRTL-listed equipment from a supplier, it might be necessary to verify that the equipment is in fact NRTL-listed. Unfortunately, it is common to hear or read a claim that equipment is NRTL-listed and later discover that it is not. A given manufacturer might have some equipment models NRTL-listed, but also have other equipment models that are non-NRTL. Sales representatives are often enthusiastic about their product and might not actually know its NRTL status. Sales brochures and web sites often show UL, CSA, or other NRTL marks, but the marks might apply to certain models and not to others. The marks might refer to a corporate capability to do NRTL certification if requested (for a fee). Or, the marks might refer to the fact that UL certifies the supplier as ISO 9000 (which is a QA certification, not electrical safety certification). Statements might be made by the manufacturer that their equipment is "designed," "built to," or "compliant with" UL standards—which may well be true. However, none of these claims equate to actually being NRTL-listed. The only way to know the listing status of a product is to verify it with the NRTL certifying organization (UL, CSA, etc.).

European common-market electrical safety mechanisms are different from OSHA third-party certification. In Europe, the equipment manufacturer, not an independent third-

[2] Training is available through Lab course HS5290/HS5290-C, Electrical Program Authority Having Jurisdiction Field Representative Training Program Qualification & Certification.

party, bases their Conformité Européen (CE) Declaration Of Conformity (DOC) on a self-certification mechanism. Certificates of conformity may be useful as part of an AHJ investigation, but they are not, by themselves, an alternative for NRTL certification. CE-marked electrical equipment may indeed be of high quality in its design, fabrication, and safety characteristics, but that alone does not relieve the requirement for NRTL certification of equipment used at LLNL. CE marking is not acceptable to OSHA.

11.5.4.1 Equipment

If you actually know—through prior experience and confirmation—that the electrical equipment you want to purchase is NRTL-listed and labeled, then proceed with the order. If the NRTL certification status is not known, the equipment manufacturer can be a source of information about the status of electrical equipment that is being considered for purchase. Ask if the equipment (product) has an NRTL label. If it is not NRTL-listed, you might wish to find another source of equipment. If there are no alternate sources of NRTL-listed equipment for your application and the decision is made to purchase a non-NRTL product, then the product must be approved by an LLNL AHJ field representative before it is used or connected to the LLNL electrical system. If a seller informs you that the equipment you intend to purchase is NRTL-listed, you might want to confirm the NRTL status independently. Ask the seller for the NRTL File Number (UL example: E162647) and a copy of the "Listing Page." This information, along with the manufacturer's name (e.g., Tektronix) and model number, can be verified by the NRTL. NRTL web sites—for example, the UL Certifications web site (http://www.ul.com; click on "Certifications") and the CSA Certifications web site (http://www.csa-international.org; click on "CSA Certified Product Listings")—are also useful resources. Other NRTLs might not have web site data bases, making a telephone call necessary. Appendix A provides an example UL Listing Page and verification information. The OSHA web site http://www.osha.gov/dts/otpca/nrtl/index.html lists all 19 NRTLs and contains a link to a page showing their various Marks.

11.5.4.2 Components

It is recommended that Recognized Components be selected and used in the design of electrical equipment that may affect electrical safety.

Manufacturers of RC products have technical reports about product descriptions, engineering considerations, and "Conditions of Acceptability" for specific components. The manufacturer will supply the report for a given UL File number (example: E94081)

on request. The UL file number for the component can be verified at the UL Certifications web site (http:// www.ul.com; click on "Certifications"). Appendix B provides an example report and verification.

The equipment designer should ensure that the Conditions of Acceptability associated with use of a specific component are addressed in the design phase. Failure to address such conditions risks rejection of the equipment in the subsequent AHJ examination.

11.5.5 Methods for Acquiring Electrical Equipment

There are various means for acquiring electrical equipment for the Laboratory:

1. It may be purchased (as COTS or built for LLNL) or rented through several mechanisms (see Figure 11.5-1 for additional detail):
   a. Unicard transaction
   b. Material transaction
   c. Blanket Order Release
   d. Requisition
2. It may be borrowed from an outside organization.
3. It may be obtained as "excessed" equipment from another government agency.
4. It may be built at LLNL. (This subject is treated in Section 11.1).[3]

[3] Equipment built by or for the Laboratory needs to incorporate AHJ design standards at the beginning of the design cycle so that subsequent AHJ examination of the equipment results in AHJ approval. Section 11.1, "Designing and Fabricating Safe Electrical Equipment," addresses this subject.

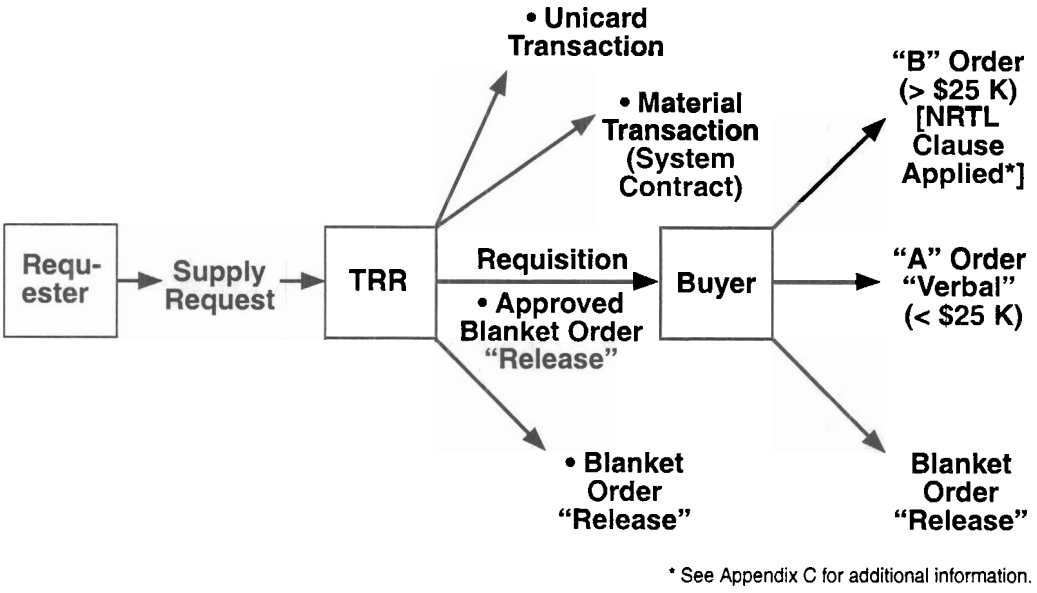

Figure 11.5-1. Procurement and Material purchasing mechanism.

Regardless of how the electrical equipment is acquired, it must be NRTL-listed or AHJ-approved before connection to the LLNL electrical system.

11.5.5.1 Safety As a Factor In Supplier Selection

In purchasing electrical equipment to fulfill an application requirement based on technical performance specifications, it is often possible to select among several commercial suppliers. Given several suppliers whose products meet the needed technical performance specifications for the application requirement, a selection decision is generally driven by price considerations. This seems reasonable—among a set of equals, choose the one that has the lowest price. However, one of our specifications is that the equipment we acquire for the Lab be *reasonably safe*. That is, it must be NRTL-listed or AHJ-approved before connection to the LLNL electrical system. If the selection is among suppliers that all offer NRTL-listed equipment, then the choice is simplified. However, if some suppliers are offering NRTL-listed equipment and others are offering non-NRTL equipment—at lower prices (curiously)—then selection is no longer among a set of like choices. If a lower-priced, non-NRTL equipment item is selected, then it must be examined by an AHJ and the AHJ examination effort charged against the requesting

account. Given the total cost (equipment price plus examination charge), it might be advisable to acquire a somewhat higher-priced equipment item that is NRTL-listed and avoid the AHJ examination charge. Additionally, there is a risk in purchasing non-NRTL electrical equipment, as it might not pass an AHJ examination. If it fails the examination, the equipment could require expensive modifications, or might be unusable at LLNL.

In general, NRTL-listed electrical equipment should always be selected unless programmatic performance requirements can only be met from a manufacturer of non-NRTL electrical equipment. Even then, it may be preferable to ask that manufacturer if they offer an NRTL listing service for that equipment item at an additional fee. The fee may be lower than the cost of an LLNL AHJ examination for complex equipment. In some situations, it may even be worthwhile to consider having an NRTL perform a field evaluation on LLNL-built equipment.

11.5.5.2 Responsibilities

There are two individuals in the procurement path for purchasing new electrical equipment. The first is the PI/RI (likely equipment owner) as the requester. The second is the Technical Release Representative (TRR). It is important that there is a conscious effort to address the NRTL/AHJ issue during the order generation process. The TRR can have a positive role in raising this issue if the NRTL/AHJ topic is not clearly defined in an order request. Nevertheless, the PI/RI is ultimately responsible for the electrical safety of all equipment procured and operated under their purview.

11.5.5.3 Equipment to Be Used Off-Site

Scientific, engineering, and technical work at LLNL may involve purchasing or building electrical equipment for others or for use at off-site locations (DOE or non-DOE). It is the AHJ and Engineering policy that such equipment is subject to the same rigor in electrical safety requirements (NRTL/AHJ) as that imposed on equipment used at LLNL. Generally, LLNL-built equipment is operated on-site in a test phase before it is transferred to others. Hence, it must conform to on-site electrical equipment safety and operational safety requirements during the test phase.

11.5.6 Summary

In summary, before potentially hazardous electrical equipment can be operated on-site or connected to the LLNL electrical system and used for its intended purpose, it must be

either NRTL-listed or AHJ-approved. A catch-phrase—"Buy NRTL or Go AHJ!"—has been coined as a reminder of this requirement. This requirement applies to:

- Equipment designed and built at LLNL
- Equipment built outside to LLNL design specifications
- Commercial equipment
- Equipment acquired by any other means

It is important to remember the two basic elements in the electrical safety equation: the equipment itself and how the equipment is used. NRTL certification or AHJ approval focuses on the equipment portion, while Operational Safety focuses on how it is used. This section emphasizes the NRTL/AHJ equipment function, but this is only a part of the complete picture of establishing overall electrical safety at LLNL.

Appendix A Example UL Listing Page and Verification Information

"LISTING PAGE"

Northbrook, Illinois • (847) 272-8800
Melville, New York • (631) 271-6200
Santa Clara, California • (408) 985-2400
Research Triangle Park, North Carolina • (919) 549-1400
Camas, Washington • (360) 817-5500

NRTL

Underwriters Laboratories Inc.®

RECEIVED TEKTRONIX, INC. JUN 8 2001 MBD PRODUCT SAFETY

TEKTRONIX INC
MR W THOMAS, M S 50-150
D/S 50-150
PO BOX 500
BEAVERTON OR 97077

Post-it™ Fax Note 7671	Date 13 Jul 01	# of pages ▶ 2
To Chuck Pomeranck:	From Don Hanson	
Co./Dept.	Co. Tektronix	
Phone #	Phone # 503 627 1922	
Fax # 9 422 1767		

RE: Project Number(s) - 01CA04220

Your most recent listing is shown below. Please review this information and report any inaccuracies to the UL Engineering staff member who handled your project.

For information on placing an order for UL Listing Cards in a 3 x 5 inch format, please refer to the enclosed ordering information.

CATEGORY CONTROL NUMBER (CCN)

PICQ

June 13, 2001

Measuring, Testing and Signal Generation Equipment

PRODUCT

MANUFACTURER

TEKTRONIX INC
D/S 50-150 PO BOX 500, BEAVERTON OR 97077

E162647

UL File Number

10 Amp, dual 1-wire switch matrix, Model VX4361.
10 Amp SPST switch module, Model VX4351.
120-Channel relay mux, Model VX4330.
256-Crosspoint relay matrix, Model VX4380.
Accessory cable, Model AF1DS.
AC current transformers, Models CT-1, -2.
AC/DC current clamp oscilloscope probes, Models A6212, A6302, A6302XL, P6312, TCP202.
Analog-to-digital nicam encoder, Model 728E.
Audio-video delay corrector,, Model AVDC100.
Broad wavelength optical to electrical converter, Model ORS20.
Communications signal analyzer, Model CSA8000.
Component TV generators, Models TSG300, TSG300E.
Component/composite generators, Models TSG370, TSG371.
Current probes, Models A6303, A6303XL, A6304XL.
Digital sampling oscilloscopes, Models 11801C, CSA803C, TDS8000.
Digital television generator, Model TSG170D.
Digital component generator, Model TSG422.
DMM/Counter VXI modules, Models VX4101, VX4101A.
External tracking generator, Model 2707.
GBIC test system units, Models GTS1063, GTS1250.
General purpose relay switching module, Model VX4350.
Differential oscilloscopeprobe, Model P5200.
Logic analyzer, color portable mainframes, Models TLA-601, -602, -603, -604, -611, -612, -613, -614, -621, -622, -623, -624, -704, -714.
Microprocessor Support Package , Models TMSSG1, TMSSGP1, TMSSKP1, TMSSK1, TMSSN1, TMSSNP1.
Nicam modulator, Model 728M.
Oscilloscopes, Models TDS210, -2[illegible], -324, -340, -340A, -360, -380, -420A, -430A, -460A, -510A, -520B, -520C, -520D, -540B, -540C, -540D, -580C, -580D, -620B, -620C, -640A, -644B, -654C, -680B, -680C, -684B, -684C, -694C, -714L, -724C, -724D, -754C, -754D, -784C, -784D, -820, -3012, -3014, -3032, -3034, -3052, -3054, -7054, -7104, -7204, -7404, TLS216.
Oscilloscope probes, Models P3010, P5[illegible], P5102, P5135, P5205, P5210, P6101B, P6103B, P6105A, P6106A, P6109B, P6111B, P6112, P6113B, P6114B, P6117, P6131, P6133, P6136, P6138A, P6139A, P6339A.
Oscilloscope/DMM, Models THS710, -710A, -720, -720A, -720P, -730A.
PAL TV generator, Model TSG271.
PAL sync generator, Model SPG271.
RF switching module, Model VX4320.
SDH/SONET line code converter, Model SC100A.
Signal conditioner, Model VX4780.Includes LP/LV options and accessories.
Sync changeover unit, Model EC170A.
Sync pulse generator, Model SPG170A.

MODEL NUMBER
(can search on: 654C)

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JUN 18 2001
MBD PRODUCT SAFETY

Underwriters Laboratories Inc.®

Digital mult-meter, Models TX1, TX3.
SO[illegible] test sets, Models CTS710, -750, -750I with and without rackmount kit option; Model CTS850, ST2400, ST2400A.
Test system, Model BT100.
Test pattern generator, Model TPG625.
Test signal generator, Model TSG170A.
TLA DSO modules, Models TLA7D1, -7D2, -7E1, -7E2.Includes limited options and accessories.
TVS waveform analyzers, Models TVS621, -621A, -623, -625, -625A, -641, -641A, -643, -645, -645A.
Video measurement set, Model VM700T.
VXI [illegible], Models TLA7XM, -711, -720, -721, VX1410, -1410A, -1411, -1411A, -1420A.

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UL HOME

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Ways to search:

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- UL File Number
- Appliance Wiring Material (AWM)
- Fire Resistance - Design or System Number
- Roofing Materials & Systems - Construction Number
- Building Materials - Assembly Number
- UL Category Control Number (CCN)/Guide Information
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- Search for Registered Firms (ISO, QS)

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TEKTRONIX INC	Measuring, Testing And Signal Generation Equipment - Component	*PICQ2.E162647*
TEKTRONIX INC	Measuring, Testing And Signal Generation Equipment Certified For Canada	*PICQ7.E162647*
TEKTRONIX INC	Measuring, Testing And Signal Generation Equipment Certified For Canada - Component	*PICQ8.E162647*

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Measuring, Testing and Signal Generation Equipment

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Measuring, Testing and Signal Generation Equipment

Guide Information

E162647

File Number

TEKTRONIX INC
/S 50-150

BEAVERTON, OR 97077 USA

10 Amp, dual 1-wire switch matrix, Model VX4381.

10 Amp SPST switch module, Model VX4351.

120-Channel relay mux, Model VX4330.

256-Crosspoint relay matrix, Model VX4380.

Accessory cable, Model AFTDS.

AC current transformers, Models CT-1, -2.

AC/DC current clamp oscilloscope probes, Models A6212, A6302, A6302XL, P6312, TCP202.

Analog-to-digital nicam encoder , Model 728E.

Audio-video delay corrector, , Model AVDC100.

Broad wavelength optical to electrical converter, Model ORS20.

Communications signal analyzer , Model CSA8000.

Component TV generators , Models TSG300, TSG300E.

Component/composite generators , Models TSG370, TSG371.

Current probes, Models A6303, A6303XL, A6304XL.

Digital sampling oscilloscopes, Models 11801C, CSA803C, TDS8000.

Digital television generator , Model TSG170D.

Digital component generator , Model TSG422.

DMM/Counter VXI modules, Models VX4101, VX4101A.

External tracking generator, Model 2707.

GBIC test system units, Models GTS1063, GTS1250.

General purpose relay switching module, Model VX4350.

High voltage differential oscilloscopeprobe, Model P5200.

Logic analyzer, color portable mainframes, Models TLA-601, -602, -603, -604, -611, -612, -613, -614, -621, -622, -623, -624, -704, -714, -715 .

Microprocessor Support Package, Models TMSSG1, TMSSGP1, TMSSKP1, TMSSK1, TMSSN1, TMSSNP1.

Nicam modulator , Model 728M.

Oscilloscopes, Models TDS210, -220, -224, -340, -340A, -360, -380, -420A, -430A, -460A, -510A, -520B, -520C, -520D, -540B, -540C, -540D, -580C, -580D, -620B, -620C, -640A, -644B, -654C, -680B, -680C, -684B, -684C, -694C, -714L, -724C, -724D, -754C, -754D, -784C, -784D, -820, -3012, -3014, -3032, -3034, -3052, -3054, -7054, -7104, -7304, -7404 , TLS216.

Model Number

Oscilloscope probes, Models P3010, P5100, P5102, P5135, P5205, P5210, P6101B, P6103B, P6105A, P6106A, P6109B, P6111B, P6112, P6113B, P6114B, P6117, P6131, P6133, P6136, P6138A, P6139A, P6339A.

Oscilloscope/DMM, Models THS710, -710A, -720, -720A, -720P, -730A.

PAL TV generator , Model TSG271.

PAL sync generator , Model SPG271.

RF switching module, Model VX4320.

SDH/SONET line code converter, Model SC100A.

Signal conditioner, Model VX4780.Includes LP/LV options and accessories

Sync changeover unit , Model EC170A.

Sync pulse generator , Model SPG170A.

Digital mult-meter, Models TX1, TX3.

SONET/SDH test sets, Models CTS710, -750, -750I with and without rackmount kit option; Model CTS850, ST2400, ST2400A.

Test system , Model BT100.

Test pattern generator , Model TPG625.

Test signal generator , Model TSG170A.

TLA DSO modules, Models TLA7D1, -7D2, -7E1, -7E2.Includes limited options and accessories.

TVS waveform analyzers, Models TVS621, -621A, -623, -625, -625A, -641, -641A, -643, -645, -645A.

Video measurement set, Model VM700T.

VXI mainframes, Models TLA7XM, -711, -720, -721 , VX1410, -1410A, -1411, -1411A, -1420A.

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UL Listed and Classified Products UL Recognized Components Products Certified for Canada

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The appearance of a company's name or product in this database does not in itself assure that products so identified have been manufactured under UL's Follow-Up Service. Only those products bearing the UL Mark should be considered to be Listed and covered under UL's Follow-Up Service. Always look for the Mark on the product.

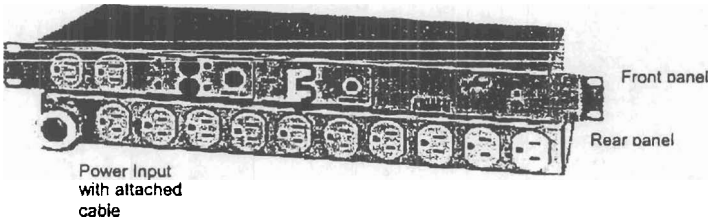
Appendix B Example RC Report and Verification Information

The following pages contain examples of a manufacturer's product data sheet, information about the manufacturer's products (as listed on UL's web site), engineering considerations, and conditions of acceptability. Important information, such as product name and model number, the UL RC mark, and UL file number, are identified on the various examples to act as guides on what to look for when verifying a component's NRTL status.

PULIZZI ENGINEERING INC.

3200 S. Susan Street, Santa Ana, CA 92704-6865 (714) 540-4229 FAX: (714) 641-9062
E-MAIL#: sales@pulizzi.com HOMEPAGE (URL): http://www.pulizzi.com
SALES: (800) 870-2248 FAX: (605) 334-4999 or (605) 334-2611

TPC 981: 120V~ and 240V~, 1Ø, 50/60 Hz, 15A, 20A and 30A



File #: E94081 UL/CUL 1950
Models A, A2, B are 3rd Edition
Models C, D, F are 2nd Edition

RACK MOUNTED

- EIA standard for 19" racks
- Hole spacing to IEC 297
- Height 1.75" (1U) x Depth 7.0"
- 16 GA. Steel, Zinc Plated
- Approximate shipping weight 7 lbs. for models A and B. 8 lbs. for models C, D and F.
- Pulizzi recommends chassis support brackets, from your cabinet supplier, should be utilized.

12 NEMA OUTLETS

- 2 on front and 10 on rear panel.
- Other NEMA outlets are optional.

EMI/RFI FILTERING

Common Mode Line to Ground

- Differential Mode Line to Line

SPIKE/SURGE SUPPRESSION

- Line to Neutral
- Line to Ground
- Neutral to Ground

POWER INPUT

- Power cable with plug is attached to unit through the rear panel cable grip.
- Model B does not come standard with a plug but is available as an option.

INDICATOR LIGHT

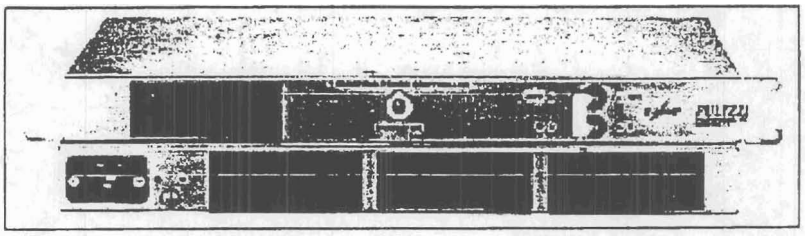
- One neon indicator light illuminates when the circuit breaker is in the "on" position.

OVERLOAD CIRCUIT PROTECTION

- Precision electromagnetic breakers, with a long time delay curve, provide both manual on/off switching and open (trip) automatically with an overload condition.
- When the front duplex is wired as unswitched, a 15A or 20A thermal resettable breaker is provided.
- Kick Guards provided.

Models: TPC 981	-A	-A2	-B	-C	-D	-F	-E
Agency Approval:	UL/CSA	UL/CSA	UL/CSA	UL/CSA	UL/CSA	UL/CSA	
Voltage Input/Output (50/60Hz):	120V~	120V~	240V~	120V~	120V~	240V~	240V~
Current Input:	15A	20A	15A	30A	30A	30A	30A
Current Output De-rated:	12A	16A	12A	24A	24A	24A	24A
Full Load Volt/AMP De-rated:	1440VA	1920VA	2840VA	2880VA	2880VA	5760VA	5760VA
NEMA Outlets (2F/6R):	5-15R	5-20R	6-15R	5-15R	5-20R	6-15R	6-20R
Circuit Breaker with Kick Guard:	15A	20A	15/15A	15/15A	15/15A	(2) 15/15A	(2) 20/20A
EMI/RFI Filter:	20A	20A	20A	30A	30A	30A	30A
Power Cord/Length (rear panel):	14/3, 9'	12/3, 9'	14/3, 9'	10/3, 15'	10/3, 15'	10/3, 15'	10/3, 15'
NEMA Power Input Plug:	5-15P	5-20P	N/A	L5-30P	L5-30P	L6-30P	L6-30P

NOTE: 120V/30A units utilize a 2pole breaker with four outlets per pole and the HOT line is separated into two HOT lines, one through each pole.



The TPC 2104 is the international IEC version of the TPC 981 systems.

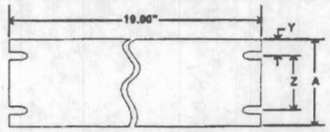
Please reference the product specifications for the TPC 2104 for further details.

MULTI-STAGE SPIKE AND SURGE SUPPRESSION

Response time is approximately 50 nanoseconds. Exceeds recommended specifications for High Exposure Areas per ANSI/IEEE C62.41-1980, Class B.

CAUTION: If the ground M.O.V.'s are exposed to an improper voltage level, they will fail. Please verify that the power source is wired correctly prior to connecting the PDU.

MAXIMUM RATINGS (85°C)				CHARACTERISTICS (25°C)					
CONTINUOUS		TRANSIENT		VARISTOR			MAXIMUM		
RMS VOLTAGE	DC VOLTAGE	ENERGY (10/100µS)	PEAK CURRENT (8/20µS)	VOLTAGE @1 mA DC TEST CURRENT			CLAMPING VOLTAGE V_C @ TEST CURRENT (8/20µS)		TYPICAL CAPACITANCE
$V_{m(ac)}$	$V_{M(dc)}$	W_{tm}	I_{tm}	MIN.	$V_{N(de)}$	MAX.	V_C	I_P	f=0.1 - 1MHz
VOLTS	VOLTS	JOULES	AMPS	VOLTS	VOLTS	VOLTS	VOLTS	AMPS	PICOFARADS
120V~ systems: (1) 275V MOV Line/Neutral and (3) 150V's Line/Neutral, Line/Ground, Neutral/Ground									
275	369	140	6500	389	430	453	680	100	900
150	200	80	6500	212	240	243	360	100	1600
240V~ systems: (1) 320V MOV Line/Neutral and (3) 275V's Line/Neutral, Line/Ground, Neutral/Ground									
320	420	160	6500	462	510	540	810	100	750
275	369	140	6500	389	430	453	680	100	900



HOLE SPECIFICATION TABLES

A	Y	Z
1.750	.250	1.250

EMI/RFI FILTERING FOR 15A/20A Models:

Rated Voltage/Current: 120V~/20A or 250V~/16A
Operating Frequency: 50/60 Hz.
Hi-pot rating one minute: 2250 VDC Line to Ground, 1450 VDC Line to Line
Maximum Leakage Current (each line to ground): .5 mA @ 120V~ 60 Hz, 1.0mA @ 250V~ 50Hz
UL #E48570, CSA Class 2221 #LR46870, VDE #7064-4730, SEV #J1.21/257.

COMMON MODE INSERTION LOSS
Line to Ground in 50 ohm circuit

MHz.	.15	.50	1.0	5.0	10.0	30.0
dB.	6	19	28	42	45	50

DIFFERENTIAL MODE INSERTION LOSS
Line to Line in 50 ohm circuit

MHz.	.15	.50	1.0	5.0	10.0	30.0
dB.			30	50	30	30

EMI/RFI FILTERING FOR 30A Models:

Rated Voltage/Current: 120V~/30A or 250V~/25A
Operating Frequency: 50/60 Hz.
Hi-pot rating one minute: 2250 VDC Line to Ground, 1450 VDC Line to Line
Maximum Leakage Current (each line to ground): .5 mA @ 120V~ 60 Hz, 1.0mA @ 250V~ 50Hz
UL #E48570, CSA Class 2221 #LR46870, VDE #7064-4730, SEV #J1.21/257.

COMMON MODE INSERTION LOSS
Line to Ground in 50 ohm circuit

MHz.	.15	.50	1.0	5.0	10.0	30.0
dB.	6	19	28	42	45	50

DIFFERENTIAL MODE INSERTION LOSS
Line to Line in 50 ohm circuit

MHz.	.15	.50	1.0	5.0	10.0	30.0
dB.			30	50	30	30

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Federal ID: 95-3411351, Dun & Bradstreet: 09-273-5521, Cage/Supply Code & FSCM: 70513, SIC: 3612,
ANSI/ISO/ASQC Q9004-1-1994 and ANSI/NCSL 2540-1 (Calibration)

NWGQ2.E94081

Information Technology Equipment Including Electrical Business Equipment - Component

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Information Technology Equipment Including Electrical Business Equipment - Component

Guide Information

PULIZZI ENGINEERING INC
SUITE 6B
5009 W 12TH ST
SIOUX FALLS, SD 57106 USA

E94081

Model PC874-BX, -EX, -FX.

Model PC874-AX, -CX, -DX.

Models PC420-AX, -A2, -BX, -CX, -DX, -EX, -FX.

Models PC125-AX, -A2, -BX, -CX, -DX, -EX, -FX, PC125-377X.

Models 110-AX, -A2, -BX, -CX, -DX, -EX, -FX , where X is any letter or number.

Models TPC981-A, -A2, -B.

Models TPC981-C, -C-3061, -D, -F.

Models PC874-F-2496, PC874-F-2496-1 and PC874-F-2496-2.

Models PC300-F/MTD, PC300-D/MTDX, PC300-DX, PC300-CX, PC300-C/MTDX, PC1938, where X may be any three or four digits, number or alphanumeric designation.

Models PC726-C(X), PC726-C/MTD(X), PC726-D(X) and PC726-D/MTD(X), where X can be any three or four digit number or alphanumeric designation.

Model PC1924.

Models TPC 12X-(Y), TPC 12F-X-(Y), TPC 12-A2(Y), TPC 12F-A2(Y), TPC 12-X-RCB(Y), TPC 12F-X-RCB(Y), TPC 12-X-CB(Y), TPC 12F-X-CB(Y), TPC 10-X-RCB(Y), TPC 10-X-CB(Y) and TPC12FACB-2499, where X is A or C and (Y) may be 3 or 4 alphanumeric characters.

Models PC-301-X, PC-301, PC-301/MTD, PC-301-I/XXXX, where X may be any alphanumeric character.

Models PC2034-X, PC2034-E-X and PC2034-F-X.

Model PC-2060.

Models TPC-2364-XXXX, /XXXX, where X may be any alphanumeric character.

Models T9092A, T9092A-CB, T9092A-CBSF, T9092B, T9092B-CB, T9092B-CBSF and T9092B-CB-3045.

Models IPC3X00, IPC IPC3X01, IPC IPC3X02, where X is 1, 2 or 3, may be followed by "F" and/or "S".

Models PC5585-AB, PC 5585-AB1/MTD, PC5585-AB/MTD, PC5585-CF, PC 5585-CF1/MTD, PC5585-CF/MTD, PC 5585-CF/2368.

Models TPC 2234-A, TPC 2234-A-F, TPC 2234AF-3041, TPC 2234-A2, TPC 2234-A2-F, TPC 2234-B, TPC 2234-B-F.

Models PC975, PC975-LT, PC975-1969, PC975-2109.

Models PC585-C, PC585-C1/MTD, PC585-C/MTD, PC585-D, PC585-D1/MTD, PC585-D/MTD, PC585-F, PC585-F1/MTD, PC585-F/MTD.

Model PC302-I/XXXX, where X may be any 2 or 4 alphanumeric characters .

Note: Suffix X may be any three or four digit number or alphanumeric designation.

Models TPC 115-8-A, TPC 115-8-A2, TPC 115-8-B.

Models TPC 115-8-C, TPC 115-8-D.

Models TPC 115-10A, TPC 115-10-A-LT, TPC 115-10A/MTD, TPC 115-10A/LT, TPC 115-10A2, TPC 115-10A2-LT, TPC 115-10A2/MTD, TPC 115-10A2/LT, TPC 115-10B, TPC 115-10B-LT, TPC 115-10B/MTD, TPC 115-10B/LT.

Models TPC 115-10-C, TPC 115-10-C-LT, TPC 115-10C/MTD, TPC 115-10C/LT, TPC 115-10D, TPC 115-10-D-LT, TPC 115-10D/MTD, TPC 115-10D/LT, TPC

NWGQ2.GuideInfo

Information Technology Equipment Including Electrical Business Equipment - Component

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Information Technology Equipment Including Electrical Business Equipment - Component

The devices covered under this category are incomplete in certain constructional features or restricted in performance capabilities and are intended for use as components of complete equipment submitted for investigation rather than for direct separate installation in the field. THE FINAL ACCEPTANCE OF THE COMPONENT IS DEPENDENT UPON ITS INSTALLATION AND USE IN COMPLETE EQUIPMENT SUBMITTED TO UNDERWRITERS LABORATORIES INC.

Recognitions in this category cover components. Consideration should be given to the conditions under which the components are actually employed as compared with the test conditions used for the investigation of the component.

Devices covered under this category may have the following features indicated in the individual Recognitions:

Feature	
Rated Input Volts	—Rated input voltage and frequency or dc of component.
Load Amps	—Maximum current loading of component during normal operation.
F/R	—Flame rating of fire enclosure (V-1, V-0 or 5V). or decorative bezel (DEC/HB or DEC/V-2). [V-2 represents either V-2 material or material tested per UL 1950/60950, Annex A.2. V-1 represents either V-1 material or material tested per UL 1950, Annex A.2. 5V represents either 5V material or material tested per UL 1950/60950, Annex A.1.]
Laser Class	—Component's laser class in accordance with FDA 21CFR, Sub-part J. (I, II, IIa, IIIa, IIIb)

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UL Listed and Classified Products UL Recognized Components Products Certified for Canada

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The appearance of a company's name or product in this database does not in itself assure that products so identified have been manufactured under UL's Follow-Up Service. Only those products bearing the UL Mark should be considered to be Listed and covered under UL's Follow-Up Service. Always look for the Mark on the product.

DESCRIPTION

PRODUCT COVERED:

USR/CNR Power Controller, Models TPC 981-C, TPC 981-C-3061, TPC 981-D and TPC 981-F.

ELECTRICAL RATING:

Model	Voltage (ac)	Input/Output (A)	Frequency (Hz)
TPC 981-C	120	24	50/60
TPC 981-C-3061	120	24	50/60
TPC 981-D	120	24	50/60
TPC 981-F	240	24	50/60

ENGINEERING CONSIDERATIONS (NOT FOR FIELD REPRESENTATIVE'S USE):

Use - For use only in (or with) complete equipment where the acceptability of the combination is determined by Underwriters Laboratories Inc.

Special Considerations - The following items are considerations that were used when evaluating this product.

USR indicates investigation to the U.S. Standard for Safety of Information Technology Equipment, Including Electrical Business Equipment, UL 1950, Second Edition, dated February 26, 1993.

CNR indicates investigation to the Canadian Standard for the Safety of Information Technology Equipment, Including Electrical Business Equipment, CAN/CSA-C22.2 No. 950-93.

The equipment was submitted and tested for a maximum manufacturer's recommended ambient (Tmra) of 25°C.

The equipment is: For building in, rack mountable, Class I (earthed), pluggable Type A and B, uses non-detachable power cord, intended for use on a TN power system.

LL/AF:bd
SCDLS

Conditions of Acceptability - When installed in the end-product, consideration shall be given to the following:

1. This component has been judged on the basis of the required spacings in the Standard for Safety of Information Technology Equipment, Including Electrical Business Equipment, UL 1950, Second Edition, Sub-Clause 2.9, CAN/CSA C22.2 No. 950-93, Sub-Clause 2.11, CAN/CSA C22.2 No. 234-M90, which would cover the component itself if submitted for Listing.

2. The products were tested on a 30 A branch circuit. If used on a branch circuit greater than this, additional testing may be necessary.

3. The equipment has been evaluated for use in a Pollution Degree 2 environment.

4. This equipment is configured with standard supply outlets which are defined as not accessible to the operator.

5. Standard supply outlets must be provided with markings that are visible when the unit is installed in the end product, that state the maximum load total for all receptacles and maximum load per receptacle.

6. These units do not meet 20 A branch circuit protection requirements for the standard supply outlets if the outlets are operator accessible. Operator accessibility of these outlets should be evaluated in the end-use product.

7. The plug on the power supply cord must be rated not less than 30 A, per Subclause 3.2.1.

8.* These products are intended for use in North America when protective earthing lead insulation is solid green.

The following is a list of Supplement C, D3 deviations which are required for compliance with UL 1950, Second Edition: SC2.7.1.

Appendix C Procurement Safety Standards & Testing Provisions

When placing a "B" purchase order (in excess of $25,000) for commercial electrical equipment or components, the LLNL buyer attaches one of the following clauses to the terms of the purchase agreement.

Version where electrical materials or equipment are to be furnished or used and a University Technical Representative is designated:

Safety Standards and Testing
The Ordered Items shall meet nationally recognized safety standards or have been tested and found safe for use by the University in a manner specified by the Seller. All electrical equipment, components and conductors and other items of the type requiring testing by a Nationally Recognized Testing Laboratory (NRTL) recognized by the Occupational Safety and Health Administration (OSHA), shall be NRTL listed, labeled, or certified in accordance with Title 29, Part 1910, General Industry Standards, of the Code of Federal Regulations (29 CFR 1910). The Seller shall notify the University Procurement Representative and the University Technical Representative, in writing, of any Ordered Items to be furnished or used that do not meet these requirements, and shall not furnish or use such materials or supplies without written approval from the University Procurement Representative.

Version where electrical materials or equipment are to be furnished or used and NO University Technical Representative is designated:

Safety Standards and Testing
The Ordered Items shall meet nationally recognized safety standards or have been tested and found safe for use by the University in a manner specified by the Seller. All electrical equipment, components and conductors and other items of the type requiring testing by a Nationally Recognized Testing Laboratory (NRTL) recognized by the Occupational Safety and Health Administration (OSHA), shall be NRTL listed, labeled, or certified in accordance with Title 29, Part 1910, General Industry Standards, of the Code of Federal Regulations (29 CFR 1910). The Seller shall notify the University Procurement Representative, in writing, of any Ordered Items to be furnished or used that do not meet

these requirements, and shall not furnish or use such materials or supplies without written approval from the University Procurement Representative.

DOE Electrical Handbook Chapter 9

SLAC-I-730-0A11F-001-R000

9.0 ENCLOSED ELECTRICAL/ELECTRONIC EQUIPMENT

9.1 PURPOSE

This section provides guidelines to

1. complement existing electrical codes and recommend industry standards,

2. improve electrical safety in the work environment for personnel within the DOE complex.

3. eliminate the ambiguity and misunderstanding in design, construction and implementation requirements for electrical/electronic equipment, and

4. assist the AHJ in providing information for acceptance of equipment within the scope of this document.

9.2 SCOPE

This section addresses enclosed electrical/electronic equipment electrical safety guidelines which are not specifically addressed elsewhere in the *Electrical Safety Handbook.* These types of equipment include: instrumentation and test consoles; enclosed electrical/electronic equipment; other laboratory diagnostic electrical/electronic equipment (stationary or mobile) mounted in or on an enclosure, rack or chassis; and special electrical/electronic equipment facility requirements.

9.3 GROUNDING AND BONDING

Many ground system types exist within electrical equipment. All metal parts of electrical equipment enclosures and chassis shall be bonded and grounded as per the NEC. The methods chosen to avoid ground loops and reduce noise shall meet the requirements of the NEC 250.6.

9.3.1 OBJECTIONAL CURRENT OVER GROUNDING CONDUCTORS

Enclosed Electrical/Electronic equipment has both power and signal conductors entering and leaving these enclosures. Objectionable currents and noise may be the result of the design or installation of conductors and equipment and their grounding locations. NEC 250.6 addresses these objectionable currents and noise (See Section 10.9.2.1).

NEC 250.6 must be used with care because it seems to give blanket authority to do whatever is necessary to stop objectionable currents from flowing in the grounding system. This is not the intent. NEC 250.6D specifically indicates that the introduction of noise or data errors in electronic equipment shall not be considered objectionable currents, as addressed therein. Therefore, such objectionable currents must be handled in other ways. NEC Section 250.6 principally deals with objectionable currents that can flow over grounding conductors due to severely unbalanced loads or improper installation practices. NEC 250.96(B) provides requirements for isolation of grounding circuits to reduce electrical noise (EMI). Because of the complexity and number of interconnections of most grounding systems, the NEC allows modifications of the grounding system and connections in order to address such problems. Those permitted:

1) Arrangement to prevent objectionable current. Grounding of electrical systems, circuit conductors, surge arresters, and conductive noncurrent-carrying materials and equipment shall be installed and arranged in a manner that will prevent an objectionable current over the grounding conductors or grounding paths. Use of a single-point grounding system, as well as meeting the other requirements of NEC Article 250, will usually overcome problems.

2) Alterations to stop objectionable current. If the use of multiple grounding connections results in an objectionable current, one or more of the following alterations are permitted to be made, provided that the requirements of NEC 250.4(A)(5)(B)(4), are met. Such permitted alterations are:

    1. Discontinue one or more, but not all, of the grounding connections;

    2. Change the locations of the grounding connections;

    3. Interrupt the continuity of the conductor or conductive path interconnecting the grounding connections; and/or

    4. Take other suitable remedial action satisfactory to the authority having jurisdiction.

3) Temporary currents not classified as objectionable currents. Temporary currents resulting from accidental conditions, such as ground-fault currents, that occur only while the grounding conductors are performing their intended protective functions shall not be classified as objectionable. This does not prohibit changes in the system to correct excessive current during a fault condition.

4) Limitations to permissible alterations. The intent of NEC 250.6 is not to permit electronic equipment to be operated on AC systems or branch circuits that are not grounded as required by NEC Article 250. Currents that introduce noise or data errors in electronic equipment are not considered to be the objectionable currents addressed in this Section.

    Voltage differences and thus objectionable currents may exist because impedances to ground are not equal throughout a grounding system due to variations of the resistance of the earth, improper connections, or other problems.

    Even though voltage differences allow unwanted currents to flow in the grounding conductors, and induced noise may travel over this path, it is not to be used as a reason to disconnect all grounding connections to any system component. At least one grounding connection must remain.

9.3.2 EQUIPMENT GROUNDING CONDUCTOR

The equipment grounding conductor of a power-supply cord or interconnecting cable should be size in accordance with NEC 250.122 and the associated NEC Table 250.122. The minimum size equipment grounding conductor is based on the total rating of the enclosed equipments in amperes. Note that the minimum size equipment grounding conductor may be smaller than the size for the current-carrying conductors; i.e., the grounded (neutral) and ungrounded conductors, which are sized per NEC Article 310.15 – usually following NEC Table 310.16.

9.3.3 ENCLOSURE GROUNDING AND BONDING

Enclosure grounding and bonding should comply with the following requirements: (See Figs. 9-1 thru 9-3)

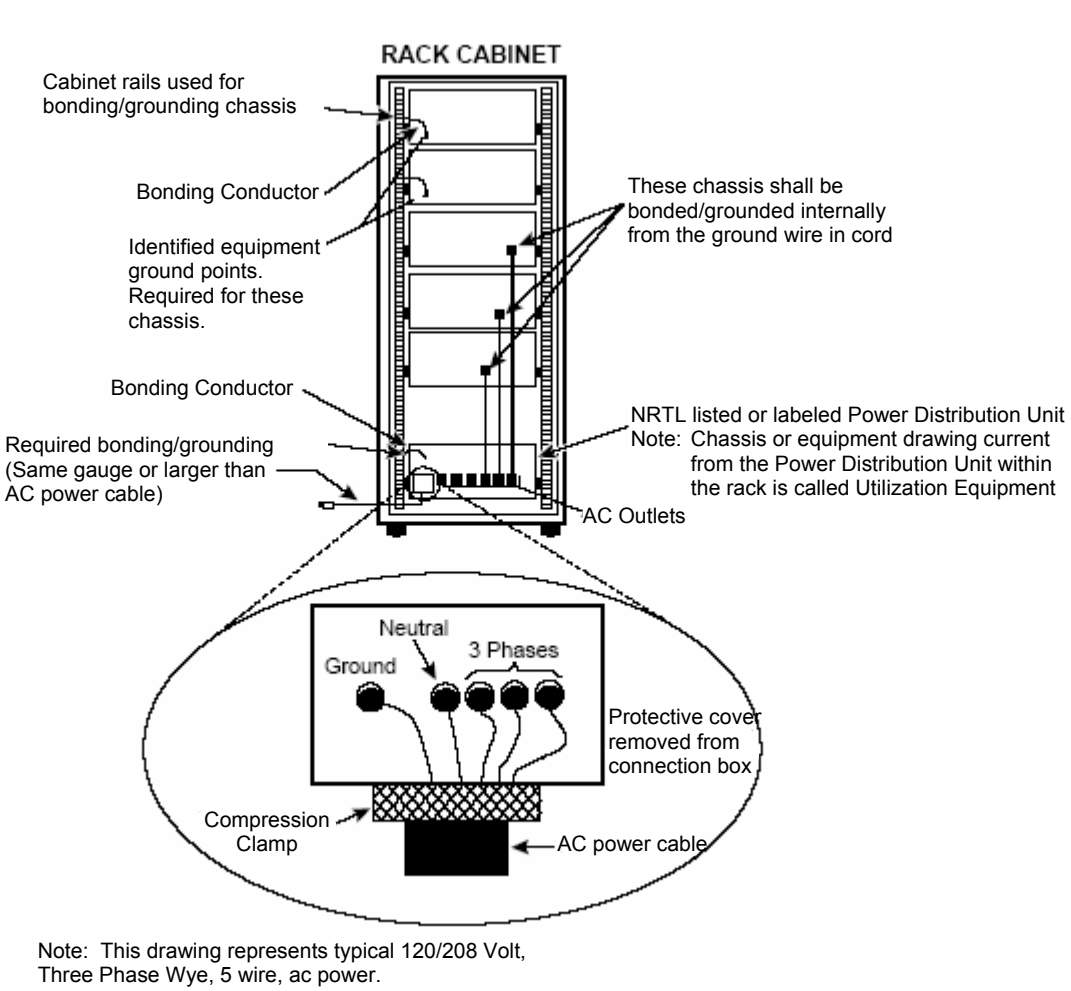


Figure 9-1

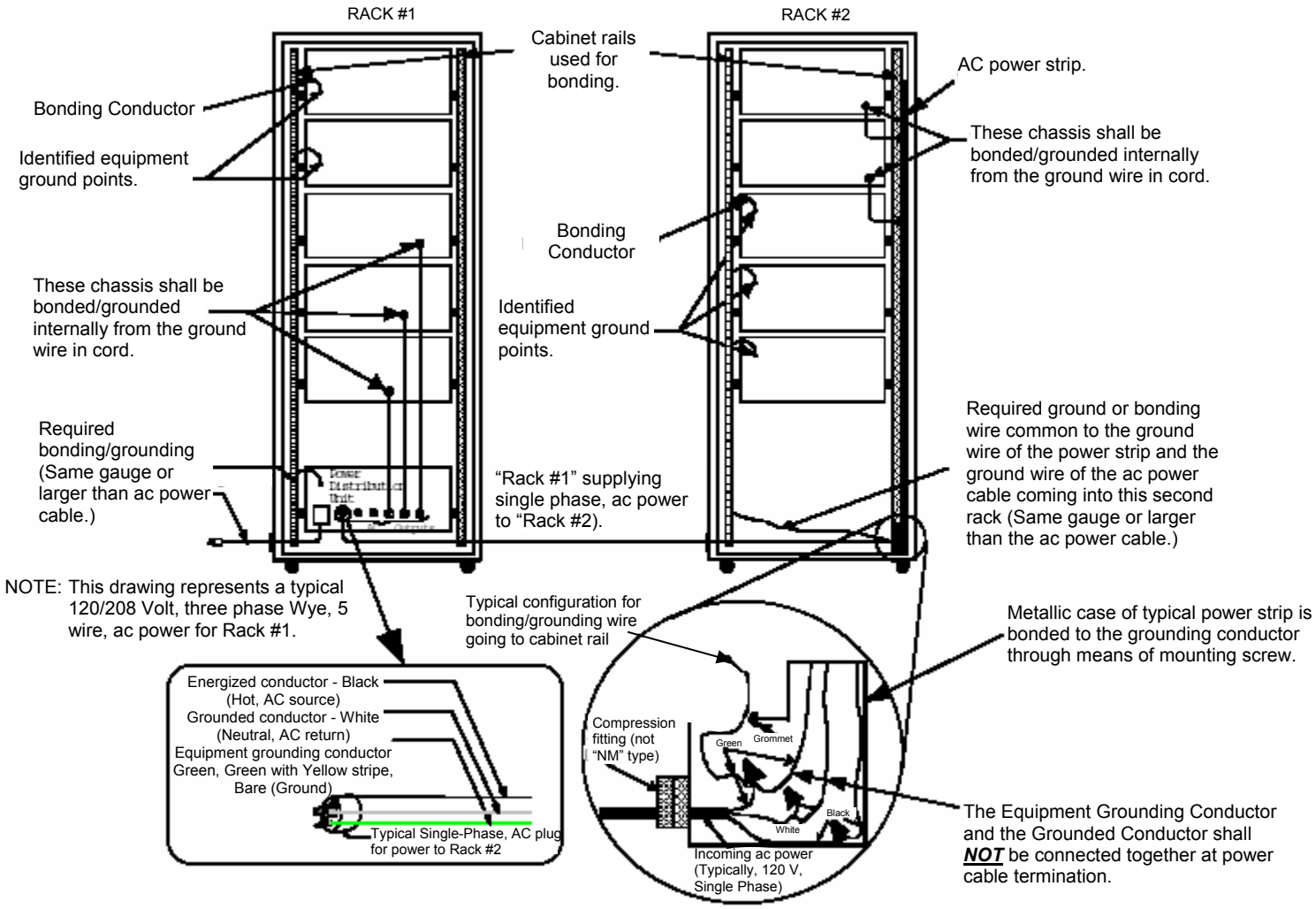


Figure 9-2

1) Have a common grounding or bonding bus (normally a cabinet rail).

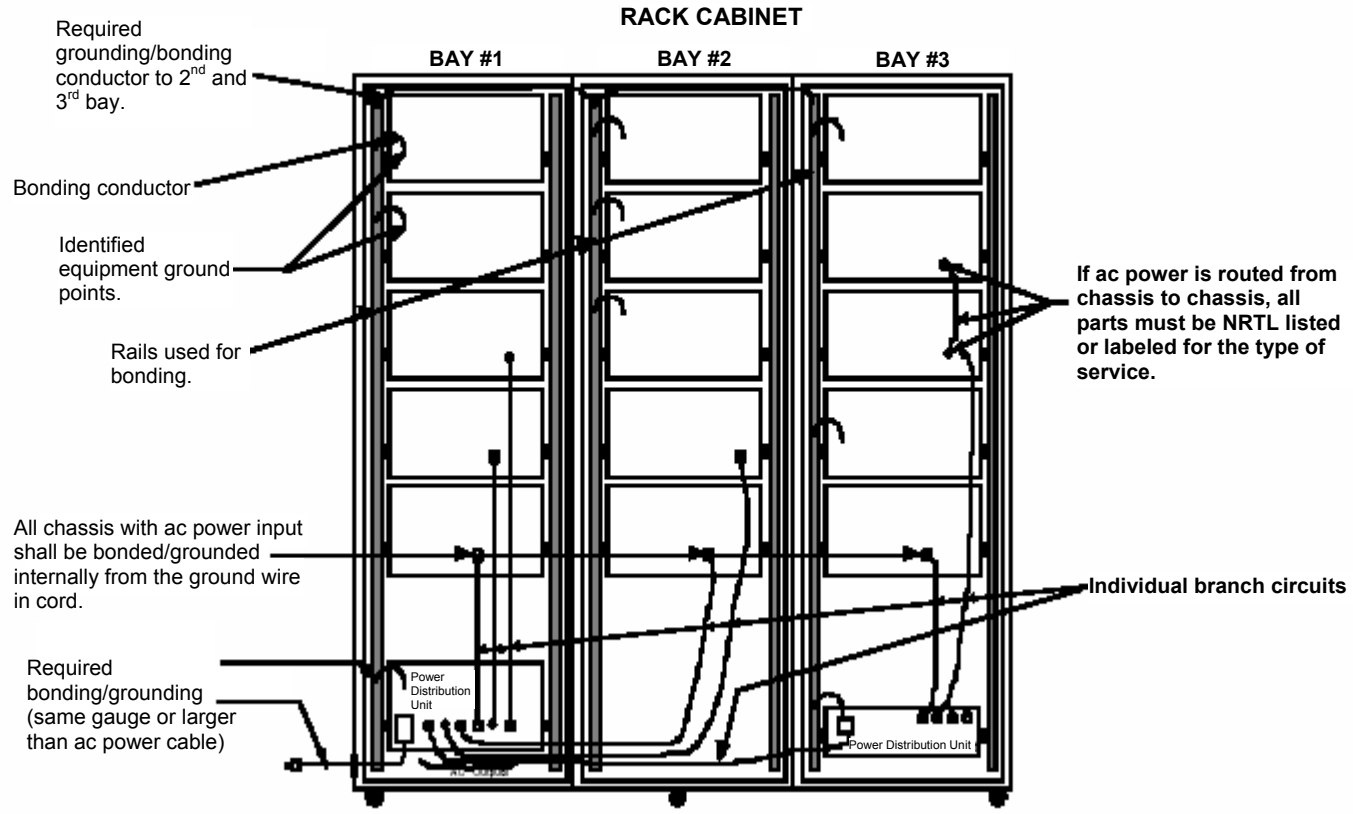
2) When the enclosure contains more than one bay, bond all grounding or bonding busses together.

3) All mounted chassis within rack cabinets shall have a grounding or bonding conductor attached to the common grounding or bonding bus when the chassis is not grounded or bonded through the power cord.

4) The grounding or bonding conductor shall be permanent and continuous.

5) Subassemblies mounted in other types of enclosures should be bonded by adequate preparation of the mounting surfaces or by the use of a bonding conductor.

6) To provide protection against grounding or bonding conductor breakage, conductors between the common grounding or bonding bus and moveable chassis should be braided cable or stranded wire.



NOTES: 1. This drawing represents typical 208/120-V, Three Phase Wye, 5 wire, ac power for Rack #1.
2. Multiple bays must be bonded together even if multiple Power Distribution Units are installed in separate bays.

Figure 9-3

All grounding or bonding points should be tight for good continuity, identified by green color, permanently labeled, and properly prepared by cleaning metal surfaces to bare metal or by the use of serrated bushings. Anodized aluminum must be cleaned to bare metal.

The resistance across the bonding point should be very low, so that heating stress effects due to power loss across the bonding point are minimized. If a measurement is required, the method of measurement is to be determined by the user. The user may determine a maximum resistance, e.g., 0.1 ohm.

9.3.4 SPECIAL CONSIDERATIONS

Systems feeding power isolation transformers must continue the equipment grounding conductor to the equipment or the ungrounded equipment must be guarded and labeled.

For two-wire cord connected equipment, an equipment grounding connector should be installed according to the manufacturer's instructions.

9.4 RACK POWER DISTRIBUTION

The following guidelines will provide the necessary information to correctly install power distribution equipment within instrumentation racks containing electrical and electronic equipment.

9.4.1 GENERAL REQUIREMENTS APPLYING TO ALL AC POWER EQUIPMENT WITHIN OR ATTACHED TO INSTRUMENT RACKS

9.4.1.1 LOADS

Knowledge of the loads that will be connected within a rack cabinet is necessary before starting design of a rack power distribution system. All components must be sized correctly for the loads and should provide for expansion.

Equipment enclosures may or may not contain a power distribution unit. A rack power distribution unit contains a main overcurrent protection device and multiple branch circuits that are individually protected against overcurrent. Without a power distribution unit, the power wiring is considered part of one branch circuit.

Branch circuit loading shall meet the requirements of NEC Article 210. (See NEC 210.21 through 210.23).

External convenience outlets should be connected to a separate circuit breaker.

Where three-phase, four-wire service is utilized, the loads should be evenly distributed on all phases and there should be consideration of sizing the neutral conductor for certain loads (such as computer equipment) due to the presence of harmonic currents. (See NEC 210.4 and 310.10).

9.4.1.2 OTHER GENERAL EQUIPMENT REQUIREMENTS

Rack power distribution components or assemblies must be listed by an NRTL, or have AHJ approval (See Section 2.5).

9.4.2 CONDUCTORS AND CABLES SPECIFIC REQUIREMENTS.

Each type of internal wiring for equipment or an accessory shall be acceptable for the particular application when considered with respect to (1) the current, ambient temperature, voltage, and other conditions of service to which the wiring can be subjected, and (2) exposure to oil or grease.

The term "cables" refers to groupings of wires typically used for control signals, data, or DC power. The term "cords" refers to AC power cords.

The basic insulation on each wire shall be rated for at least the maximum voltage to which the wire is connected, and for at least the temperature it attains. Additionally, the insulation should be rated for the maximum voltage of nearby conductors and wire to which each wire may be exposed. Insulating tubing, sleeving, and tape shall be rated for at least the maximum voltage against which it insulates, and for at least the temperature it attains. Power and signal wires should be routed separately within a chassis.

Wires shall be routed away from sharp edges, screw threads, burrs, moving parts, etc. Holes through which wires are routed shall have smooth, well-rounded surfaces, or shall have a bushing. Clamps for guides used for routing or wiring shall have smooth, well-rounded edges. Pressures exerted by such clamps should not cause cold-flow or otherwise deform the basic insulation.

9.4.2.1 FLEXIBLE CABLES

Flexible cables may be used:

1. Where flexible cables and attachment plugs are furnished by the manufacturer as part of the equipment to be mounted in the rack.

2. For connection of stationary equipment to facilitate their frequent interchange.

3. To prevent the transmission of mechanical vibration.

4. Where the fastening means and mechanical connections are specifically designed to permit ready removal for maintenance and repair.

5. For data processing cables approved as part of the data processing system.

6. For temporary wiring.

Where breaking or loosening of a circuit connection would render an electric shock or could result in a fire, such connection shall be made mechanically secure. Mechanical security of connections may be provided by crimped, closed ring or flanged lug, or a wrapping that forms at least an open U or by cable clamps, or by cable lacing, insulating tubing, or similar means.

9.4.2.2 STRAIN RELIEF

Wiring, cords, or cables shall be provided with strain relief as required to prevent damage.

Additional insulation may be required when the construction of the strain relief may damage the insulation. The use of type NM (Romex) cable clamps on flexible cords and cables is not permitted. Use listed or labeled clamps. The use of any metal clamp or other means that may cause undue stress on the cables within or external to instrument racks is not allowed. Cord and cable support for AC power cable or other heavy duty or large diameter cables must distribute the load over a large area of the outer covering of the cable.

9.4.2.3 SEPARATION OF VOLTAGES

Insulated conductors of different circuits shall be separated or segregated from uninsulated live parts connected to different circuits unless provided with insulation suitable for the highest voltage involved.

Segregation of insulated conductors may be accomplished by clamping, routing, or equivalent means that provide permanent separation from insulated or uninsulated live parts of a different circuit.

Loose strands of stranded internal wiring, connected to a wire-binding screw, shall be prevented from contacting other uninsulated live parts not always of the same potential and from

contacting noncurrent-carrying metal parts. This may be accomplished by use of pressure terminal connectors, soldering lugs, crimped eyelets, or soldering all strands of the wire together.

9.4.2.4 OTHER CONCERNS

Conductors shall not be bundled together in such a way that the temperature rating of the conductors is exceeded. Bundled conductors may require derating of their ampacities. For example, see NEC 310.15(B)(2) and Table 310.15(B)(2)(a)

Flexible cord should be listed or labeled and used only in continuous lengths without splice or tap when initially installed.

Repairs are permitted if the completed splice retains the insulation, outer sheath properties, and usage characteristics of the cord being spliced. In most instances, the entire length of flexible cord should be replaced, in order to assure integrity of the insulation and usage characteristics.

9.4.3 POWER SWITCHES AND INTERLOCK DEVICES SPECIFIC REQUIREMENTS

For all electrical/electronic enclosures utilizing power switches or interlocks, the following should apply:

1. Interlocks should be utilized where exposed voltages (50 volts or greater) are present in equipment and access to the exposed live parts is not controlled (See Section 9.6.4).

2. Ensure all line-side unprotected contacts are guarded on interlocking contactors or other switching equipment.

3. Be suitable for the conditions, use, and location.

4. Circuit breakers used for the equipment power switch will be rated for switching under load.

5. Provide provisions for lockout/tagout requirements.

9.5 CHASSIS POWER DISTRIBUTION

Manufacturers are responsible for determining the safety of such chassis and/or enclosures and for providing documentation showing how that determination was made. Listed equipment should be selected by design when available. Unlisted commercial equipment and in-house fabricated equipment shall be approved by the local AHJ.

9.5.1 AC POWER DISTRIBUTION

9.5.1.1 CHASSIS BONDING AND GROUNDING

Metal chassis shall be effectively bonded to a main grounding point in the rack cabinet where necessary to assure electrical continuity and shall have the capacity to conduct safely any fault current likely to be imposed on it. (NEC 250.96)

In a chassis with ac service connected to it, the grounding terminal of its receptacle shall be internally bonded to the chassis frame. (NEC 250.146)

If solder is used, the connection of the equipment grounding conductor shall not depend on solder alone. (NEC 250.8)

The leakage current of cord connected equipment should be very low.

9.5.1.2 CONNECTIONS, CONNECTORS, AND COUPLINGS

Input/output ac power connections to the chassis shall comply with NEC requirements.

The exposed, noncurrent-carrying, metal parts of panel mount connectors operating at 50 volts or greater shall be bonded to the chassis.

Plugs and sockets for connecting any AC power source shall be NRTL-listed for the application. (Ref. ISA-S82.01-1992, Section 6.10.3.a)

AC power plugs and sockets shall not be used for purposes other than the connection of AC power.

Connectors operating at 50 V or greater shall be listed, rated or recommended for their intended use.

Any connector used to provide power at 50 V or greater shall not allow personnel to make inadvertent contact with the power source.

If plug pins of cord-connected equipment receive a charge from an internal capacitor, the pins shall not be capable of rendering an electric shock or electric burn in the normal or the single fault condition 5 seconds after disconnection of the supply. Plug-in type connectors intended to be connected and disconnected by hand shall be designed so that the grounding conductor connection makes first and breaks last with respect to the other connections. [NEC 250.124(A)].

The following applies for all AC power connectors within or external to electrical/electronic enclosures:

1. There should be no exposed current-carrying parts except the prongs, blades, or pins.

2. The connector shall prohibit mating of different voltage or current rating than that for the device intended.

3. All connectors must be protected against overcurrent in accordance with their rated ampacity. (NEC 240.5)

4. Connectors must be NRTL-listed for the application.

5. Use of MS, PT, or other non-approved connectors is not permitted except when justified to and approved by the AHJ.

If conditions require the use of a non-NRTL listed or labeled connector, such as an "MS" (military standard pin and socket type) or "PT" (similar to "MS" but smaller) type, for input/output

ac power, a warning label should be affixed next to the connector stating: "WARNING - POWER MUST BE REMOVED BEFORE CONNECTING/DISCONNECTING."

9.5.1.3 TERMINALS/LIVE PARTS

All terminals/live parts with a potential of 50 volts or greater shall be guarded to protect from accidental contact or bringing conductive objects in contact with them (NEC 110.27). Consult ANSI/ISA-S82.01-1988, Table 9-1 for spacing information regarding live parts.

All energized switching and control parts shall be enclosed in effectively grounded metal enclosures and shall be secured so that only authorized and qualified persons can have access.

9.5.2 DC POWER DISTRIBUTION

Guidelines for dc power distribution include:

1. The metal chassis or cabinet should not be used as a return path.

2. High-current analog or switching do power supplies should use separate return paths from digital circuits.

3. All of the guidelines pertaining to ac power such as grounding, proper wire size, high voltage, etc. should apply to do circuits as well.

An accessible terminal charged by an internal capacitor should be below 50 volts within 5 seconds after interruption of the supply.

As with ac power, avoid contacting dc parts when working on a live chassis. The use of the appropriate class gloves should be considered when performing this type of work.

9.6 PROTECTIVE DEVICES FOR ENCLOSED ELECTRICAL/ ELECTRONIC EQUIPMENT

This section deals with the various protective devices commonly found in electrical/electronic equipment not discussed elsewhere.

9.6.1 SURGE ARRESTERS

The more common types of surge arresters used with electronic equipment are the metal oxide varistor (MOV), avalanche diodes, and spark gap arresters. The type and electrical rating of the surge arrester is generally determined by the requirements of the circuit being protected, and by the amplitude and duration of the expected surge. (See ANSI/IEEE C62.11-1987.)

Metal oxide varistors and avalanche diodes are voltage-dependent devices whose impedance changes from a near-open circuit to a highly conductive level when subjected to transient voltages above their rated voltages. An MOV is considered "sacrificial" in that a portion of its material is literally burned off each time such a surge is encountered. The response time of an MOV is limited to approximately 500 picoseconds while avalanche diodes can respond in approximately 50 picoseconds. Lead lengths can greatly increase the response times of these devices. The normal failure mode of both devices is a short circuit although sustained voltages well beyond the rating of the MOV can cause the device to rupture and result in an open circuit.

When used at a point on a circuit, a surge arrester should be connected between each ungrounded conductor and ground.

For power line applications, MOV manufacturers recommend a varistor be used with a fuse that limits the current below the level that MOV package damage could occur. In general, circuit breakers are not recommended for this application since circuit breaker tripping is too slow to prevent excessive fault energy.

Consult the manufacturer's application data sheets for more information.

9.6.2 FUSES

Fuses are temperature-sensitive, current-sensing elements that are generally used as short circuit protective devices in individual electrical chassis. The fusing characteristic, or opening time versus current, must be within the safe time/temperature characteristic of the device being protected.

Designers must carefully consider the load requirements in the fuse selection process, particularly when high surge currents may be encountered during initial turn-on. Operating time/current characteristics of the various types available can usually be found in fuse manufacturers catalogs. A fuse's interrupting current capacity must also be considered when connected to a power distribution system having a significant fault current capacity.

The voltage rating on a fuse shall be equal to or greater than the device's operating voltage.

In general, cartridge fuses should have a disconnecting means on the supply side, (NEC 240.40), and shall not be connected in parallel unless factory assembled and listed as a unit (NEC 240.8).

9.6.3 CIRCUIT BREAKERS

A chassis or cabinet shall not employ circuit breakers as “on/off” switches unless rated for the application by the manufacturer.

9.6.4 POWER INTERLOCK DEVICES

Cabinets and equipment having potentially dangerous currents and/or voltages present should have a means of controlling access, or a power interlock device designed to interrupt the power to the cabinet. Provisions should also be made to discharge any stored energy, such as in capacitors or inductors, to less than 50 volts within 5 seconds when the safety interlock is opened. Interlocks may not be used as a substitute for lockout/tagout. [29 CFR 1910.333(c)].

9.7 DISCONNECTING MEANS

All enclosed electrical/electronic equipment shall be provided with a means for disconnecting it from each external or internal operating energy source. This disconnecting means shall disconnect all current carrying conductors.

9.7.1 GENERAL

Interlock systems are not a recommended disconnecting means for cabinets and equipment having potentially dangerous currents and/or voltages present. (See Section 9.6.4)

Permanently connected equipment and multi-phase equipment should employ a listed switch or circuit breaker as means for disconnection.

All cord-connected equipment should have one of the following as a disconnecting device:

1. A switch or circuit breaker,

2. Plug that can be disconnected without the use of a tool, or

3. A separable plug, without a locking device, to mate with a socket-outlet in the building

Where equipment is connected to the source of supply by flexible cords having either an attachment or appliance plug, the attachment or appliance plug receptacle may serve as the disconnect (NEC 422.33).

Where a switch is not part of a motor, motor circuit or controller, the disconnecting means should be within 50 feet and in sight of the operator and marked as the disconnection device for the equipment.

Where a disconnecting means is not part of the equipment, the disconnecting means should be near the equipment, within easy reach of the operator during normal operation of the equipment, and marked as the disconnection device for the equipment.

If a disconnecting device is part of the equipment, locate it as close as practical to the input power source.

9.7.2 EMERGENCY SHUTDOWN

The emergency shutdown switch should be within arm's reach of the operator, be easily identifiable, deenergize all power to all equipment associated with the system, be separate from the routine on/ off switch, and be located to protect the employee from moving parts. However, the emergency shutdown switch should not disconnect auxiliary circuits necessary for safety (such as cooling).

9.7.3 SPECIAL CONSIDERATIONS

The disconnecting means should interrupt the source voltage for secondary or remote controlled equipment, such as those using thyristor controls. Do not rely on disconnecting the control voltage.

9.8 MARKING AND LABELING REQUIREMENTS

9.8.1 GENERAL MARKING REQUIREMENTS

For all chassis and rack cabinets (electrical, computer, power distribution, etc.), the manufacturer's name, trademark, or other descriptive marking of the organization responsible for the product should be identified.

Other markings for power requirements are:

1. Voltage
2. Maximum rated current in amperes
3. Wattage
4. Frequency
5. Duration
6. Duty cycle
7. Other ratings as specified in the NEC (NEC 110.21)

9.8.2 HAZARD MARKING REQUIREMENTS

All enclosures containing exposed energized circuits over 600 volts nominal should be marked "Danger High Voltage Keep Out" with a label that is permanent. These areas shall be accessible to authorized personnel only. The label shall be placed in a noticeable location on the access panel to the enclosure. Mark all other hazards that are associated with the equipment.

9.8.3 OTHER REQUIREMENTS

All equipment markings shall be of sufficient durability to withstand the environment involved and should be large enough to read.

To obtain the correct chassis load requirements for marking and labeling, monitor individual chassis while under load. Many chassis have components that are not energized except under certain conditions.

A normal current draw may be a few amperes, but when the chassis is sourcing current to a load, the current draw may be much higher. Individual loads, internal and external, may be tabulated and added to determine the chassis current labeling requirements.

For rack cabinets with power distribution units, the outside of the rack cabinet should be labeled with the input parameters of the power distribution system installed within it.

For rack cabinets without power distribution units the outside of the rack cabinet should be labeled with the total current on the combined systems installed within it.

9.9 WORKING CLEARANCES

Clear working space and headroom shall meet the NEC requirements (see Figs. 9-4 and 9-5). The clear working space and passageways to this space should not be used for storage. At least one entrance of sufficient area shall be provided to give access to working space above electrical equipment. For example, 24 inches may be sufficient in depth and 30 inches in width with 6 ½ foot height

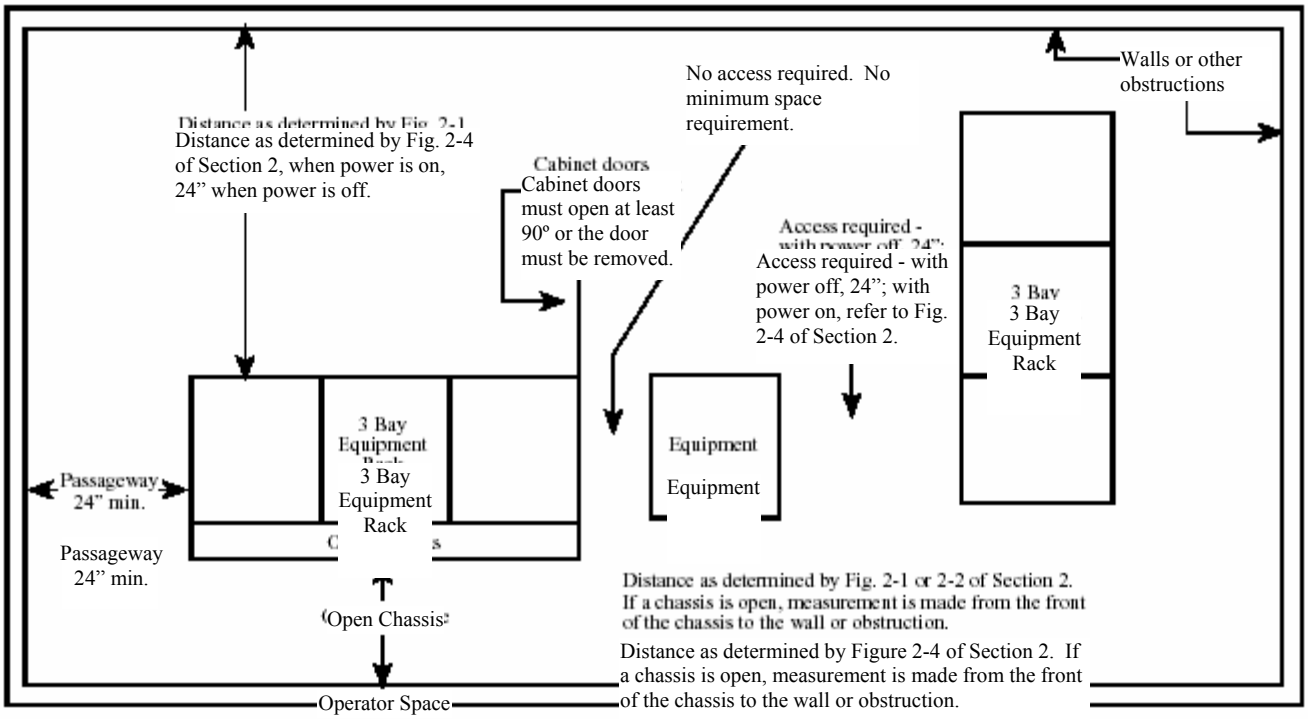


Fig. 9-4. Top View of Equipment Layout in a Room (Drawing is not to scale)

While maintenance, repair or calibration are being performed, personnel should identify clear working spaces via suitable means such as "Danger" or "Caution" barrier tape, or barricades to keep other personnel from entering the clear working spaces.

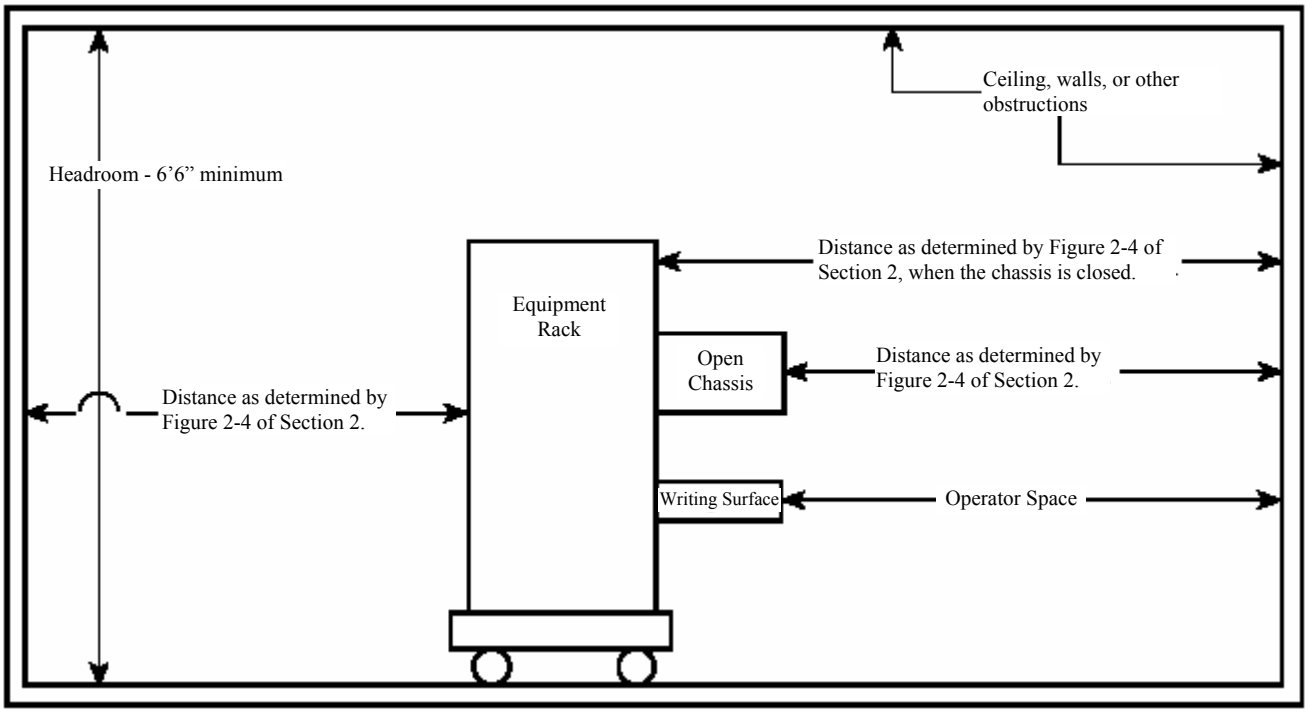


Fig. 9-5. Side View of Equipment Layout in a Room (Drawing is not to scale)

9.10 CABLE/UTILITY MANAGEMENT SYSTEM

9.10.1 USAGE WITH ENCLOSED ELECTRICAL/ELECTRONIC EQUIPMENT

In certain locations cable supports and/or enclosures are installed for dedicated usage with enclosed electrical/electronic equipment. For these situations it is acceptable for these cable/utility management systems to be utilized for the required purposes of the equipment. This may include a bundle of cables, hoses, and tubing that is required to be run from the equipment console to the unit under test. In these situations the use of a cable/utility management system is considered to be a part of custom-made equipment consisting of enclosed electrical/electronic equipment, cabling, cable/utility management system, and unit under test with associated equipment (See Figure 9-6).

In cable/utility management systems where cables other than those of the equipment exist, the decision should be documented that any risk posed by the situation is acceptable for the operation to be performed and to the functions of the existing cables.

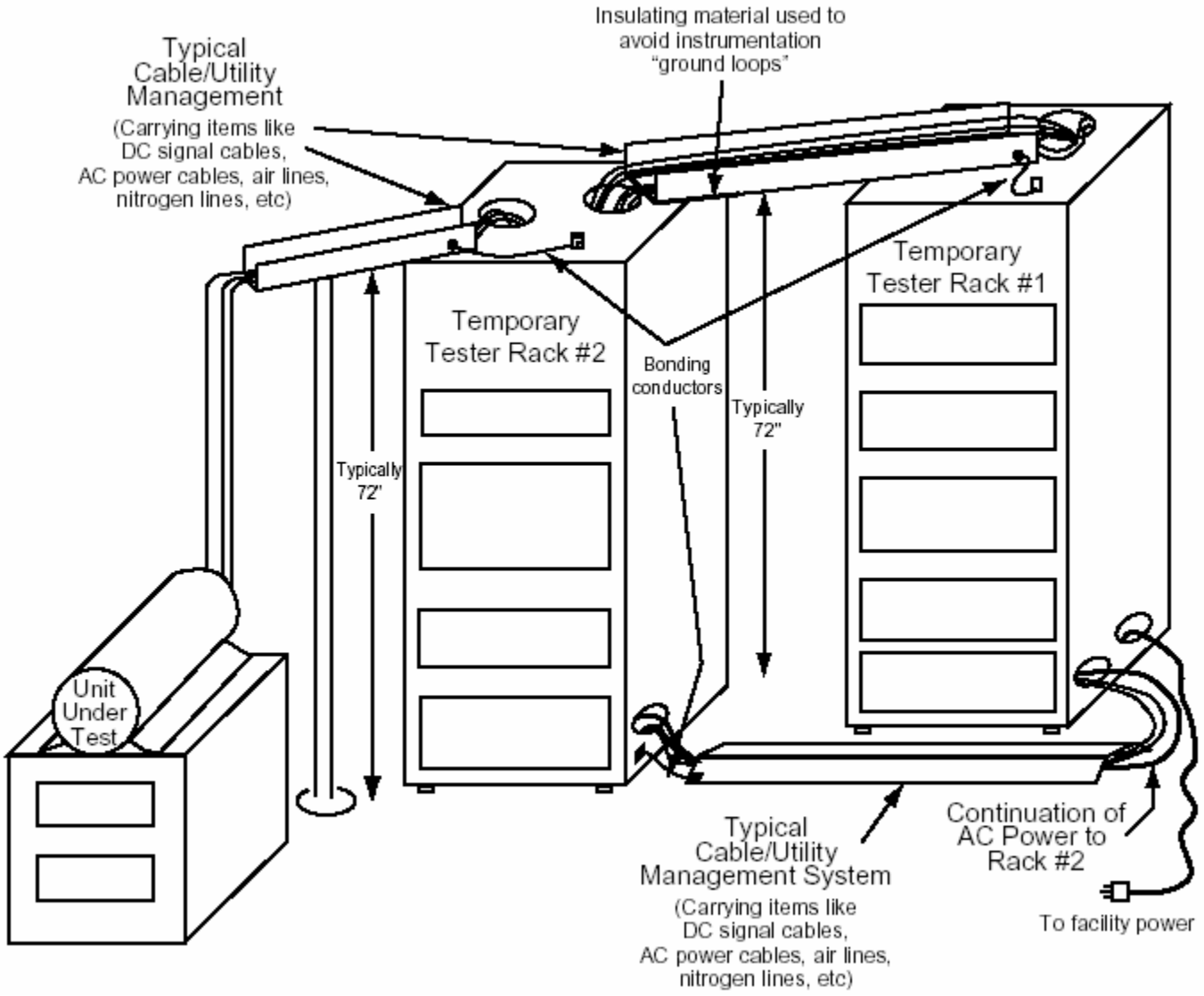


Figure 9-6

9.10.2 REQUIREMENTS

An assessment of any hazards identified with the equipment and the operation with which it is involved should be performed to assure safe operation of components in the cable/utility management system. Where any cable/utility runs include hazardous fluids or pressurized gases, the utilization of these utilities with the cables involved must be determined to be safe.

Metallic cable/utility management systems that support electrical conductors shall be grounded or bonded to the equipment. Grounding integrity should be checked by inspection by a qualified worker for all components with exposed metal parts. This inspection should be documented. Where cable/utility management systems are installed exclusively for electrical/electronic equipment usage and where these trays are metallic and not grounded or bonded, approved documentation shall exist stating the reason for not grounding or bonding the system (See Section 9.3.1).

Equipment cable/utility runs installed in cable/utility management systems should be visually inspected periodically. These inspections should be performed at the time of installation and any interval specified in the equipment documentation. Any inspection should, as a minimum, consist of:

1. A visual check for the integrity of cable jackets and visible shields;

2. A check for the integrity of all utility hoses by looking and listening for leaks;

3. A visual check on all securing devices used to hold the bundle on the tray to assure the bundle is positioned properly and no damage has occurred;

4. A visual inspection on all bends for signs of pinching, cutting, exceeding minimum cable bending radius, or other damage; and

5. Documentation of all results of any inspection.

Supports shall be provided to prevent stress and physical damage to cables where they enter or exit cable/utility management systems.

9.11 ELECTRICAL SAFETY REQUIREMENTS FOR TESTER FACILITIES

The following is not intended to encompass all of the electrical design requirements which must be considered in planning electrical systems for facilities intended to accommodate testers. The information provided should, however, provide a guide to understanding for personnel who would be tasked with specifying facility electrical safety necessary to the testing environment.

Provisions for an adequate number of receptacle outlets and associated branch circuits to accommodate cord and plug connected equipment, testers, etc., in a facility must also be considered in specifying the electrical requirements.

For equipment that cannot tolerate power interruption, consideration should be given to the use of a continuously operating or standby uninterruptible power supply (UPS) or a generator.

9.11.1 AMPACITY OF FACILITY WIRING AND DISTRIBUTION EQUIPMENT

Consideration must be given to accommodating the anticipated load demand which may occur as a result of power supplied to the various possible combinations of electrical equipment connected to a particular branch circuit (See Section 9.4).

9.11.2 FACILITY GROUNDING AT TEMPORARY OR REMOTE SITES

Proper grounding is considered crucial to providing the safest possible electrical installation, from the standpoint of maximizing the safety of facility occupants and minimizing property damage and loss.

Designs for equipment to be used at temporary or remote sites must take into consideration the same grounding issues which may not be accommodated in the same manner as for permanent facility power wiring (See Section 9.3 and NEC Article 527).

9.11.3 FACILITY LIGHTNING PROTECTION

Lightning protection is required for facilities which will house enclosed electrical/electronic equipment while such equipment is involved with radioactive, explosive, and similarly hazardous materials or for facilities that are considered valuable or house valuable contents.

9.11.4 SURGE PROTECTION

In addition to facility lightning protection, the effects of surges resulting from lightning strikes to power distribution systems may be lessened by the use of lightning arrestors and suppressors installed at strategic points in the supply system to the facility. An assessment is necessary, addressing the consequences of lightning-induced surges, in order to determine the degree to which protection should be provided.

For additional information see Section 9.6.1.

9.12 ENCLOSED POWER ELECTRONICS

Power electronics equipment is equipment that uses electronic components and subsystems to control significant amounts of electrical energy. Examples of power electronics systems include:

1. Power supplies and modulators for laser systems;

2. Accelerators, magnets, x-ray systems, and other research equipment;

3. Radio and radar transmitters;

4. Variable speed motor drives; and

5. Induction heating systems.

All applicable portions of this section should be addressed due to the hazards involved with this type of equipment.

9.12.1 ENCLOSURES

Power electronics equipment should be constructed in all-metal enclosures for containment of fire, high energy, and electromagnetic radiation hazards.

The enclosures should support the housed equipment, provide strength to brace conductors against short circuit forces, and protect housed equipment against physical damage.

It is usually easier to provide barriers to protect the electronics enclosure from collision and missile hazards rather than strengthening the enclosure itself.

9.12.2 COMPONENT CLEARANCES

Enclosures must provide adequate clearance from energized parts. The required clearances depend on the shape of the conductor, the surface characteristics of the conductor and enclosure, the voltage characteristics, environmental conditions, and creepage. The breakdown

strength along the surface of supporting insulators may require larger clearances than breakdown in air.

All power electronics enclosures shall provide adequate room for access to parts and subsystems for expected maintenance and modification. Consideration should be given to handling provisions for heavy parts and subsystems, access to test points and calibration adjustments, and work clearances for safe access to enclosure interiors.

Safe work on high-voltage equipment requires installation of manual grounding devices on exposed high-voltage conductors. Enclosure size shall provide adequate room to safely apply and remove grounding devices, and permit grounding devices to remain in place without interfering with expected work. (See Section 10.10.1.2)

Enclosures shall be sized to allow cables to be installed and routed without infringing on required clearances from high-voltage conductors.

Subassemblies, circuits, and related equipment should be segregated to the extent possible to minimize the possibility of a fault in one device damaging another.

9.12.3 INSTRUMENTATION

Power electronics systems can involve fast pulses, high frequencies and high currents and it is common for the voltage difference between ground in one circuit and ground in another circuit to differ substantially. This difference can be hundreds or thousands of volts. Wire and cable shall be insulated to withstand these potentials. Surge arrester and capacitor protection maybe used to control these potentials. DC circuits connected to coils, solenoid valves and other inductive components should be tested for induced voltages and appropriate protection for circuits should be provided.

9.12.4 GENERAL

Test points needed for adjustment and diagnosis should be installed on the front panel or other appropriate location of power electronic systems to facilitate their use without exposure hazard to employees in the area.

Currents generated only during fault conditions or those introducing noise or data errors shall not be considered objectionable currents. However, Bonding and grounding may be altered to reduce the noise or data errors, in accordance with provisions of NEC 250.96(B). Conductors, bus bars, and internal wiring should be insulated in the event objects are dropped into the equipment.

Automatic discharge devices are not a substitute for grounding devices used for personnel protection. Grounding points shall be located in the system and physically arranged to permit the attachment of adequate grounding devices for the protection of personnel working on the system.

These grounding points shall be capable of carrying the short-circuit current to which they may be subjected and applied using methods appropriate for the voltages or currents involved.

9.13 NON-IONIZING RADIATION

9.13.1 ELECTROMAGNETIC RADIATION

Human exposure to electromagnetic (EM) radiation at certain power-density levels can be hazardous. The hazards are generally regarded to be associated with the heating of biological tissue, which occurs when EM radiation is absorbed by a body. This heating is essentially similar to the cooking process in a microwave oven. Use caution where EM sources are being used with the shielding altered or removed.

When working with EM radiation, it is recommended that the emitted radiation levels be estimated by equations and measured by radiation hazard monitors.

EM radiation-safe levels have been established by the Institute of Electrical and Electronics Engineers and are documented in the IEEE standard - C95.1-1999. Also, see Section 10.8.4.

Exposure to hazardous levels of EM radiation can be lessened by maintaining as much distance as possible from the source. Power density is reduced by a factor the square of the distance from the source (e.g., a factor of 4 for 2 times the distance).

9.13.2 ELECTROMAGNETIC RADIATION THREAT TO ELECTROEXPLOSIVE DEVICES

Designers of enclosed electrical/electronic equipment must consider the possible effects on nearby EED of electromagnetic radiation (EMR); i.e., radio frequency (RF) energy, emitted by that equipment.

Energy induced into an EED by the electromagnetic field resulting from such emissions may be adequate to cause the device to initiate detonation.

Factors which should be taken into account in assessing concerns for possible EMR emissions are:

1. Wiring, shielding, and sensitivity

2. Proximity

3. Frequency of the emissions causing coupling of electrical energy

4. Power density

5. Type of emission modulation

Possible measures to mitigate the threat of EMR emissions include:

1. Enclosure and signal line shielding and grounding to prevent leakage of EMR from the equipment.

2. Designed-in physical separation or barrier that would ensure that the power density of the electromagnetic field is inadequate to cause detonation of an EED at the closest possible distance to the emission source within the equipment.

3. Filter, or provide ferrite beads for, signal lines from the equipment which may conduct EMR emissions into EED circuitry or secondarily radiate EMR in the proximity of an EED thus causing a threat of detonation.

4. Ensure that the minimal power necessary is used to operate circuitry capable of producing EMR.

5. Label the equipment capable of emitting EMR to indicate the minimum separation distance to be maintained between the equipment and an EED or EEDs.

6. Use a safety factor in design for EMR reduction; e.g., only 1/10 of the energy that would initiate an EED is allowed.

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SLAC-I-730-0A11F-001-R000

10.0 RESEARCH & DEVELOPMENT

The DOE complex engages in a variety of research & development (R&D) activities that often incorporate the design and use of special or unusual apparatus and equipment in its facilities.

10.1 PURPOSE

Requirements of existing electrical codes, recognized industry standards, and DOE Orders do not specifically address these types of apparatus. Even with these specialized R&D needs, the workplace must be maintained free of known hazards that cause, or are likely to cause, death or serious injury. Special efforts must therefore be made to ensure adequate electrical safety beginning with design and continuing through development, fabrication and construction, modification, installation, inspection, testing, operation, and maintenance of R&D electrical apparatus and facilities. This section provides guidelines to complement existing electrical codes and recognized industry standards in conformance with DOE Orders and OSHA requirements.

Because of the differences in R&D program requirements in the DOE complex and the unpredictability of R&D activities, it is impractical to establish a single set of electrical safety requirements to be applied uniformly. General electrical safety guidelines, however, apply across the DOE complex.

This section contains safety criteria for the DOE complex in the design, development, fabrication and construction, modification, installation, inspection, testing, operation, and maintenance of R&D electrical apparatus and facilities. Personnel safety shall be the primary consideration. When conflicts between electrical codes, recognized industry standards, DOE Orders, or regulations arise, the requirement that addresses the particular hazard and provides the greater personnel safety protection shall govern.

10.2 SCOPE

This section addresses R&D electrical systems which are not specifically addressed elsewhere in the *Electrical Safety Handbook.* The electrical environment of the DOE complex is extremely varied, ranging from low-voltage electronic circuits to common office and industrial electrical systems to large, high-voltage power distribution systems to high-voltage/low-current and low-voltage/highcurrent systems associated with R&D programs. Electrical systems of all types are an integral part of R&D operations and associated support work.

10.3 COMPLIANCE WITH OSHA

It is important to note that special types of work on R&D electrical systems (e.g., electronic circuits) are considered electrical work, and therefore the work shall follow electrical safety requirements.

Consistent with other sections of this document, electrical systems and equipment and all design, development, fabrication and construction, modification, installation, inspection, testing, operation, and maintenance shall be in accordance with applicable electrical requirements. Specific attention shall be focused on the electrical regulations of OSHA, including:

1. 29 CFR 1910.137

2. 29 CFR 1910.147

3. 29 CFR 1910.269

4. 29 CFR 1910.301-399

5. 29 CFR 1926.401-449.

10.4 STANDARDIZED SAFETY PRACTICES AND PROCEDURES

Standardized safety practices shall be developed for performing electrical work. These practices should be consistent with the other electrical safety-related work practices noted elsewhere in this document.

10.5 EQUIPMENT NOT LISTED BY A NATIONALLY RECOGNIZED TESTING LABORATORY

10.5.1 HAZARDS

Electrical equipment is considered to be acceptable either by being listed by an NRTL, designed, manufactured, and tested according to nationally recognized standards, or approved by AHJ-determined criteria. Refer to Section 2.5, *Approval of Electrical Equipmen*t.

Procurement and use of equipment not listed by an NRTL should be reviewed by the AHJ. The extensive testing involved in the listing process usually cannot be duplicated at the user facility, and many of the tests are destructive in nature. The AHJ should develop an examination acceptance process to ensure appropriate confidence in the safety of the product.

See Section 9.0, *Enclosed Electrical/Electronic Equipment*, for additional guidance. Also see UL 508 and applicable ANSI and IEEE documents.

10.5.2 DESIGN AND CONSTRUCTION

Equipment should be constructed such that:

1. There is adequate protection from fire, electric shock, or injury to personnel during normal use or servicing.

2. Normal use or servicing will not cause the components or materials to exceed electrical, mechanical, or temperature limits.

3. The components, wiring, and other internal parts are protected from being displaced or damaged.

NRTL-listed parts and UL-recognized components should be used wherever possible. An assembly of recognized components is not equal to a listed product, but more readily enables an independent evaluation of the assembly.

All equipment not listed by a NRTL should be constructed according to applicable standards, such as UL, ISA, ANSI, and IEEE. Equipment for which specific standards are unavailable should be constructed according to the principles of established standards, as determined by the AHJ.

Equipment should be examined for safety as extensively as possible. Areas of consideration include but are not limited to:

1. Failure modes
2. Heat effects
3. Magnetic effects
4. Grounding and bonding
5. Guarding of live parts
6. Leakage currents
7. Dielectric testing
8. Access to serviceable parts
9. Overcurrent and overtemperature protection
10. Clearances and spacing
11. Interlocks
12. Design and procedural documentation
13. Signage, labels, and administrative controls
14. Mechanical motion
15. Stored energy

Documentation should be developed to substantiate the acceptance of any equipment. Such documentation should include but not be limited to:

1. Tests performed
2. Conditions of acceptability
3. Applicable standards to which the equipment was evaluated
4. Limitations of approved use, if any.

10.6 OPERATION AND MAINTENANCE

Maintenance procedures and schedules should be developed for R&D equipment. Electrical equipment shall be checked, cleaned, and maintained on a schedule and in a manner based on its application and use. Additional information is referenced in Section 3.0, *Electrical Preventive Maintenance*.

10.7 EMPLOYEE QUALIFICATIONS

This section provides guidance for determining the qualification process for persons involved with specialized electrical equipment, configurations or work tasks associated with experiments. The guidance provided in this section is in addition to the minimum qualifications described in Section 2.8, *Training and Qualifications of Qualified Workers*.

10.7.1 HAZARDS

The hazards associated with R&D equipment are sometimes unique because the equipment itself is unique. These hazards are sometimes made worse because of an uncommon design or the fact that it may be one of a kind. Special efforts are thus necessary to identify all the potential hazards that may be present in a specific unique design. These hazards should be identified and a plan developed to mitigate the associated risk. Personnel working on R&D equipment shall be qualified to work on this equipment, depending on its unique safety problems.

10.7.2 ADDITIONAL QUALIFICATIONS

Personnel assigned to tasks involving R&D equipment shall be apprised of the hazards identified in Section 10.7.1. It is suggested that they participate in developing mitigation plans to reduce the risks associated with the hazards.

A list of additional experience qualifications should be developed by the appropriate personnel including the workers. This list should identify specific training requirements necessary for unusual equipment or tasks.

10.8 GENERIC R&D EQUIPMENT

There are many possible types of electrical ac and dc power source hazards in complex R&D systems and the various design philosophies preclude establishing hazard classifications based on voltage alone.

10.8.1 POWER SOURCES

10.8.1.1 HAZARDS

1. Internal component failure can cause excessive voltages. Internal component open-circuit failure in capacitor banks and Marx generators can result in full voltages across components that may not be appropriately discharged in the usual manner.

2. Internal component shorts in capacitor banks and Marx generators can result in excessive fault current, causing extreme heat, overpressurization of capacitor enclosures, and rupture.

3. Overloading or improper cooling of power supplies can cause excessive temperature rise.

4. Output circuits and components can remain energized after input power is interrupted.

5. Auxiliary and control power circuits can remain energized after the main power circuit is interrupted.

6. When power supplies serve more than one experiment, errors made when switching between experiments may create hazards to personnel.

7. R&D electrical apparatus may contain large amounts of stored energy, requiring fault analysis.

8. Liquid coolant leaking from R&D electrical equipment may pose an electrical hazard to personnel.

10.8.1.2 DESIGN AND CONSTRUCTION

In design and construction of R&D equipment, it is important to remember the following cautions:

1. Install only components essential to the power supply within the power-supply enclosure.

2. Provide appropriate separation between high-voltage components and low-voltage supply and/or control circuits.

3. Provide to personnel a visible indicator that the power supply is energized.

4. Minimize the number of control stations and provide an emergency shutdown switch where needed.

5. Where possible, avoid multiple-input power sources.

6. Apply a label containing emergency shutdown instructions to equipment that is remotely controlled or unattended while energized.

10.8.1.3 OPERATION AND MAINTENANCE

Before working in a power-supply enclosure or an associated equipment enclosure, see Sections 2 and 7. Personnel should take the following precautions:

1. Implement lockout/tagout.

2. Check for auxiliary power circuits that could still be energized.

3. Inspect automatic shorting devices to verify proper operation.

4. Short the power supply from terminal to terminal and terminal to ground with grounding hooks.

10.8.2 CONDITIONS OF LOW VOLTAGE AND HIGH CURRENT

10.8.2.1 HAZARDS

It is usual for R&D facilities to have equipment that operates at less than 50 V. Although this equipment is generally regarded as nonhazardous, it is considered hazardous when high currents are involved. Examples of such equipment are a power supply rated 3 kA at 25 V, a magnet power supply with rated output of 200 A at 40 V, and a bus bar carrying 1 kA at 5 V.

Though there is a low probability of electric shock at voltages less than 50 V (See Figure 10-1), there is a hazard due to arcing and heating in case of an accidental fault. For example, a tool could drop onto the terminals and initiate an arc, causing severe burns.

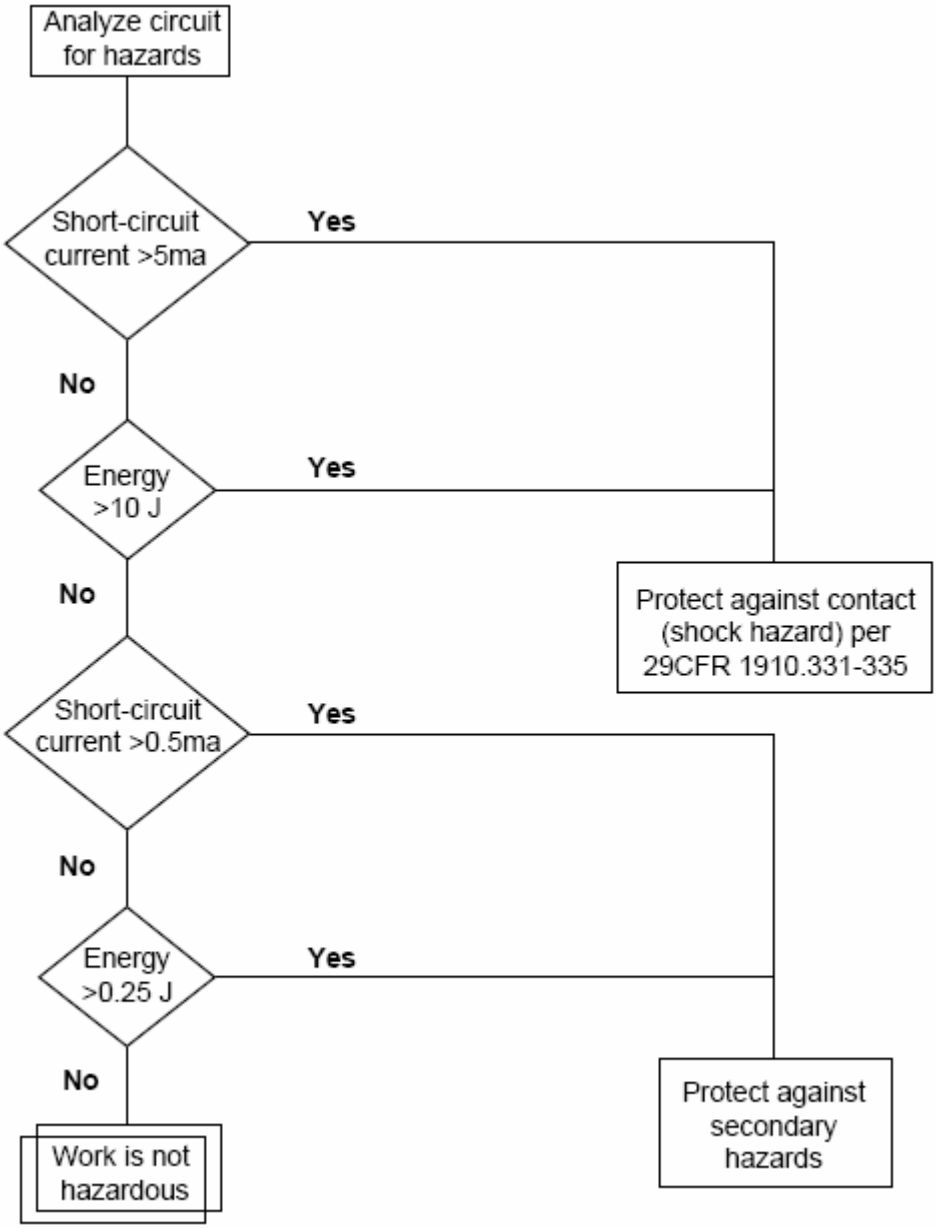

Figure 10-1. Process for the analysis of circuit hazards.

10.8.2.2 DESIGN AND CONSTRUCTION

A circuit operating at 50 V or less shall be treated as a hazardous circuit if the power in it can create electrical shocks, burns, or an explosion due to electric arcs. Observe all of the following rules for such circuits:

1. Provide protective covers and/or barriers over terminals and other live parts to protect personnel.

2. By suitable marking, identify the hazard at the power source and at appropriate places.

3. Consider magnetic forces in both normal-operation and short-circuit conditions. Use conductors that have appropriate physical strength and are adequately braced and supported to prevent hazardous movement.

4. Inductive circuits may create high-voltage hazards when interrupted. Careful circuit design will include a method to bleed off power safely should an interruption occur.

10.8.2.3 OPERATION AND MAINTENANCE

Follow these guidelines for working on circuits operating at 50 V or less that are treated as hazardous:

1. Work on such circuits when they are de-energized.

2. If it is essential to work on or near energized low-voltage, high-current circuits, observe the safety rules as if the circuits were operating at more than 50 V. Refer to Section 2.1.2, "Considerations for Working on Energized Systems and Equipment" and 2.13.4, "Safe Energized Work (Hot Work)."

10.8.3 CONDITIONS OF HIGH VOLTAGE AND LOW CURRENT

10.8.3.1 HAZARDS

When the output current of high-voltage supplies is below 5 mA, the shock hazard to personnel is low. Where combustible atmospheres or mixtures exists, the hazard of ignition from a spark may exist. High-voltage supplies (ac or dc) can present the following hazards:

1. Faults, lightning, or switching transients can cause voltage surges in excess of the normal ratings.

2. Internal component failure can cause excessive voltages on external metering circuits and low-voltage auxiliary control circuits.

3. Overcurrent protective devices such as fuses and circuit breakers for conventional applications may not adequately limit or interrupt the total inductive energy and fault currents in highly inductive dc systems.

4. Stored energy in long cable runs can be an unexpected hazard. Safety instructions should be in place to ensure proper discharge of this energy.

5. Secondary hazards such as startle or involuntary reactions from contact with high-voltage low-current systems may result in a fall or entanglement with equipment.

10.8.3.2 DESIGN CONSIDERATIONS

Personnel in R&D labs may encounter energized parts in a variety of configurations, locations, and under environmental conditions that are not usual for most electrical power personnel. Sometimes the equipment can be designed to incorporate mitigation of the hazards associated with working on such equipment. If not, then safe operating procedures must be developed and used.

10.8.3.3 SAFETY PRACTICES

An analysis of high-voltage circuits should be performed by a qualified person before work begins unless all exposed energized parts are guarded as required for high-voltage work. The analysis must include fault conditions where circuit current could rise above the nominal rated value as explained here and shown graphically in Figure 10-1. Depending on the results of the analysis, any of the following may apply:

1. If the analysis concludes that the current is above 5 mA or energy is above 10 joules, then the work is considered to be energized work and should be performed in accordance with Section 2, "General Requirements" and/or Section 7, "Work In Excess of 600 Volts."

2. If the analysis concludes that the current is between 0.5 mA and 5 mA and between 0.25 and 10 joules, then the worker may be exposed to a secondary hazard (e.g., startle reaction) that must be mitigated.

3. If the analysis concludes that the current is below 0.5 mA and below 0.25 joules, then the worker exposure is minimal and no special precautions are required.

High-voltage supplies that use rated connectors and cables where there are no exposed energized parts are not considered hazards. Connections shall not be made or broken with the power supply energized unless they are designed and rated for this type of duty (e.g., load-break elbows). Inspect cables and connectors for damage and do not use if they are damaged. Exposed high-voltage parts must be guarded to avoid accidental contact.

10.8.4 RADIO-FREQUENCY/ MICROWAVE RADIATION AND FIELDS

The DOE complex conducts R&D programs that involve sources of radio-frequency/microwave (RFMW) nonionizing electromagnetic radiation. Devices that may produce RFMW radiation include telecommunications and radar equipment, industrial equipment such as radio-frequency heaters, and scientific and medical equipment such as magnetic resonance imagers and klystron tubes. The nationally recognized consensus standard for personnel exposure to radio-frequency radiation is ANSI/IEEE C95.1(1999), *Electromagnetic Fields, Safety Levels with Respect to Human Exposure to Radio Frequency*.

10.8.4.1 HAZARDS

1. RF amplifiers frequently use dc high-voltage power sources.

2. There may be x-ray hazards (when supply voltage exceeds 10 kV and there are evacuated components).

3. Currents maybe induced in conductive objects or metal structures that are not part of the RF structure.

4. RF currents can cause severe burns.

5. Falls from towers may result from RF burns from antennas.

6. Electromagnetic interference may cause equipment to malfunction.

7. Electromagnetic fields may cause unintended ignition of explosives, fuel, and ordnance.

8. Grounding and bonding conductors that are adequate for dc and power frequencies may develop substantial voltage when fast pulses and radio frequency currents are present, due to inductance and skin effect.

10.8.4.2 DESIGN AND CONSTRUCTION

Engineering control in accordance with ANS/IEEE C95.1 (1999) should be the primary method used to restrict exposure whenever practical. If engineering controls are not practical, work-time limits, based on the averaging intervals and other work-practice and administrative controls, must be used.

1. Warning Signs. Signs commensurate with the RFMW level must be used to warn personnel of RFMW hazards. These signs must be posted on access panels of RFMW enclosures and at entrances to and inside regulated areas.

2. Access Limitation. Access can be limited by controls such as barriers, interlocks, administrative controls or other means. The operation supervisor controls access to regulated areas and must approve nonroutine entry of personnel into these places. When practical, sources of RFMW radiation should be switched off when not in use.

3. Shielding. Shielding that encloses the radiating equipment or provides a barrier between the equipment and the worker may be used to protect personnel; the shielding design must account for the frequency and strength of the field.

4. Interlocks. Chamber or oven-type equipment that uses microwave radiation must have interlocks designed to (1) prevent generation of the radiation unless the chamber is sealed and (2) shut off such equipment if the door is opened.

5. Lockout/Tagout. The design shall incorporate features that allow the equipment to be locked out and tagged out for servicing.

6. PPE. PPE such as eyewear is not readily available and is generally not a useful option as protection against RFMW radiation and fields. Protection must therefore be achieved by other means.

10.8.4.2.1 EXEMPTIONS FROM RFMW EXPOSURE LIMITS

The following items are exempt from the RFMW exposure limits; however, their manufacture is subject to Federal RFMW emission standards:

1. Cellular phones and two-way pagers and PDAs

2. Two-way, hand-held radios and walkie-talkies that broadcast between 10 kHz and 1 GHz and emit less than 7 W

3. Microwave ovens used for heating food

4. Video display terminals.

10.8.4.2.2 EXPOSURE CRITERIA FOR PULSED RFMW RADIATION

The basic considerations for peak-power exposure limits are consistent with ANSI/IEEE C95.1 (1999) as follows:

1. For more than five pulses in the averaging time and for pulse durations exceeding 100 milliseconds, normal time averaging applies and the time-averaged power densities should not exceed the Maximum Permissible Exposure (MPE) given in Table 10-1 for controlled and Table 10-2 for uncontrolled environments, per IEEE/ANSI C95.1 (1999).

2. For intermittent pulse sources with no more than five pulses during the averaging time, the peak power density for any of the pulses should not exceed the limit given by the following equation.

$$MPE_p = \frac{MPE_\alpha (t_\alpha)}{5(t_p)}$$

where:

MPE_p = Peak (power density)
MPE_α = Time-Average (power density)
t_α = Averaging time (seconds)
t_p = Pulse width (seconds)

This limits the specific absorption (SA) of each pulse to SA=28.8 joules/kg (whole-body or spatial average), or SA=144 joules/kg for 5 pulses.

For intermittent pulse sources with no more than five pulses during the averaging time, the single-pulse SA of < 28.8 joules/kg, though higher than the threshold for auditory effect (clicking), is three orders of magnitude lower than the SAs that produce RF-induced unconsciousness.

3. Maximum E field for any of the pulses should be no more than 100 kV/m. This peak E-field limit is prescribed to eliminate the possibility of air breakdown or spark discharges, which occur at 2,900 V/m. A large safety factor is applied to account for local field enhancements where nominally lower fields may result in arcing discharges.

Table 10-1. Controlled Environment Exposure Limits

Part A Electromagnetic Fields[a]

1 Frequency range (MHz)	2 Electric Field strength (E) (v/m)	3 Magnetic Field strength (H) (A/m)	4 Power density (S) E-field, H-field (mW/cm^2)	5 Averaging time $\|E\|^2$, $\|H\|^2$, or S (minutes)
0.003-0.1	61.4	163	(100, 1,000,000)[b]	6
0.1-3.0	61.4	$16.3/f$[c]	$(100, 10{,}000/f^2)$[b]	6
3-30	$1842/f$	$16.3/f$	$(180/f^2, 10{,}000/f^2)$[b]	6
30-100	61.4	$16.3/f$	$(180/f^2, 10{,}000/f^2)$[b]	6
100-300	61.4	0.163	1.0	6
300-3,000	—	—	$f/300$	6
3,000-15,000	—	—	10	6
15,000-300,000	—	—	10	$616{,}000\ f^{1.2}$

Part B Introduced and contact RF Currents[d]

Frequency range	Maximum current (mA)		Contact
	Through both feet	Through each foot	
0.003-0.1 MHz	$2{,}000\ f$	$1{,}000\ f$	$1{,}000\ f$
0.1-100 MHz	200	100	100

a. The exposure values in terms of electric and magnetic field strength are the values obtained by spatially averaging values over an area equivalent to the vertical cross section of the human body (projected area).

b. These plane-wave equivalent power density values, although not appropriate for near-field conditions, are commonly used as a convenient comparison with MPEs at higher frequencies and are displayed on some instruments in use.

c. The f = frequency in MHz.

d. It should be noted that the current limits given in this table may not adequately protect against startle reactions and burns caused by transient discharges when contacting an energized object.

NEC Article 527, *Temporary Installations*, requires removal of temporary wiring upon completion of the experiment for which it was installed.

An overly strict interpretation can obstruct the scientific objectives of the R&D configuration, but if a liberal interpretation is allowed, there is a possibility that unsafe wiring methods will be used. The AHJ must consider programmatic needs without sacrificing personnel safety.

Table 10-2. Uncontrolled Environment Exposure Limits

Part A Electromagnetic Fields[a]

1 Frequency range (MHz)	2 Electric Field strength (E) (v/m)	3 Magnetic Field strength (H) (A/m)	4 Power density (S) E-field, H-field (mW/cm^2)		5 Averaging Time (minutes)	
				$\|E\|^2$,	S	$\|H\|^2$
0.003-0.1	61.4	163	(100, 1,000,000)[b]	6 6		
0.1-1.34	61.4	$16.3/f$[c]	$(100, 10{,}000/f^2)$[b]	6 6		
1.34-3.0	$823.8/f$	$16.3/f$	$(180/f^2, 10{,}000/f^2)$[b]	$f^2/0.3$		6
3.0-30	$823.8/f$	$16.3/f$	$(180/f^2, 10{,}000/f^2)$[b]	30		6
30-100	27.5	$158.3/f^{1.668}$	$(0.2{,}940{,}000/f^{6.336})$[b]	30	$0.0636f$	1.337
100-300	27.5	0.0729	0.2	30		30
300-3,000	—	—	$f/1{,}500$	30		—
3,000-15,000	—	—	$f/1{,}500$	$90{,}000/f$		—
15,000-300,000	—	—	10	$616{,}000/f^{1.2}$		—

Part B Introduced and contact RF Currents[d]

Frequency range	Maximum current (mA)		Contact
	Through both feet	Through each foot	
0.003-0.1 MHz	$900\ f$	$450\ f$	$450\ f$
0.1-100 MHz	90	45	45

a. The exposure values in terms of electric and magnetic field strength are the values obtained by spatially averaging values over an area equivalent to the vertical cross section of the human body (projected area).

b. These plane-wave equivalent power density values, although not appropriate for near-field conditions, are commonly used as a convenient comparison with MPEs at higher frequencies and are displayed on some instruments in use.

c. The f = frequency in MHz.

d. It should be noted that the current limits given in this table may not adequately protect against startle reactions and burns caused by transient discharges when contacting an energized object.

10.9 METHODS

10.9.1 WIRING METHODS

10.9.1.1 HAZARDS

Unsafe wiring methods can cause electrical injury or fire hazards.

R&D work may require the use of wiring methods that are not anticipated in the NEC. These methods may not be consistent with normal commercial and industrial wiring methods, and should be reviewed by the AHJ for approval.

10.9.1.2 DESIGN AND CONSTRUCTION

10.9.1.2.1 DESIGN AND CONSTRUCTION AS AN INTEGRAL PART OF EQUIPMENT

If the AHJ determines that wiring is an integral part of an apparatus (e.g., instrumentation interconnections), then the wiring methods used should be evaluated by the AHJ as providing safe operating conditions. This evaluation may be based on a combination of standards and engineering documentation where appropriate. Such an evaluation should consist of an analysis of all stresses imposed on any electrical conductive elements, including, but not limited to electrical, magnetic, heating, and physical damage potential. The wiring methods selected must mitigate to the greatest practical extent any undesired effects of a failure sequence.

If cable trays are used as mechanical support for experimental circuits, they should be solely dedicated to this use and appropriately labeled. Any such use must be analyzed for detrimental heating effects of the proposed configuration.

10.9.1.2.2 POWER SUPPLY INTERFACE BETWEEN UTILITY SYSTEMS AND R&D EQUIPMENT

Utility supply voltages should be brought as near to the utilization equipment as possible using NEC-compliant wiring methods.

Any temporary wiring methods used (e.g., extension cords) should be approved by the AHJ for a specified limited time.

Flexible cords and cables should be routed in a manner to minimize tripping hazards.

The conventional use of cable trays is defined in NEC Article 392. If power cables are placed in a cable tray used for control and signal cables, separation is advised but not always required. According to NEC Article 392.6(E), multiconductor cables rated at 600 volts or less are permitted to be installed in the same cable tray. This presumes the cables are listed, having a minimum rating of 300 volts. However, cables rated over 600 volts require separation from those rated at 600 volts or less, per Article 392.6(F). Communications cables are required to be separated from light or power conductors by at least 2 inches, in accordance with NEC Article 800.52(A)(2).

Certain experimental configurations or physical constraints may require the unconventional application of cable trays. Only the AHJ may approve these unconventional applications. If deemed necessary, enhanced fire protection or other safety measures shall be used to ensure safety to personnel and equipment.

For coaxial, heliax, and specialty cables used for experimental R&D equipment, where NEC tray-rated cable types are not available which meet the technical requirements of the installation, the non-tray-rated cables shall be permitted with the approval of the AHJ. If deemed necessary, enhanced fire protection or other safety measures shall be used to ensure safety to personnel and equipment.

When metallic cable tray is being used, it shall be bonded to the equipment grounding system, but should not be relied upon to provide the equipment ground. The experimental equipment must be appropriately grounded by some other method.

10.9.1.3 OPERATION AND MAINTENANCE

The operation and maintenance of R&D systems which use wiring methods that are not anticipated by the NEC require special considerations from all personnel. The AHJ evaluation for safe operating conditions must include a review of unique features in the engineering documentation.

10.9.2 UNCONVENTIONAL PRACTICES

R&D performed by DOE contractors often incorporates the design of specialized equipment resulting in the need for specialized grounding and the use of materials and components in an unconventional manner. Even with these experimental needs and special design considerations, the maximum safety of personnel and equipment still needs to be ensured. The practice of using materials or components for purposes other than originally designed needs special consideration in their use, identification, personnel protection, and equipment protection.

10.9.2.1 GROUNDING

10.9.2.1.1 HAZARDS

The lack of proper grounding can cause electrical shock and/or burns to personnel. The NEC and NESC define legally-required grounding. To mitigate potential hazards, grounding shall be provided in accordance with the NEC and NESC.

10.9.2.1.2 DESIGN AND CONSTRUCTION

NEC, Article 250, "Grounding" notes that grounds also provide:

1. Voltage limitation in case of lightning, line surges, or unintentional contact with higher voltage lines

2. Stability of voltage to ground under normal operation

3. Facilitated overcurrent device operation in case of ground faults

4. A path to conductive objects that will limit the voltage to ground.

In R&D work there is one additional function for grounds: a common reference plane or system ground return for electronic devices, circuits, and systems. (See Section 9.3) It is recognized that such grounds are essential in some cases to control:

1. Noise associated with the primary power system:

    a. Incoming on the line

    b. Outgoing from local equipment

2. Ground wire noise

3. Circuit coupling

    a. Ground loop (shared circuit return)

    b. Magnetic, capacitive, or electro-magnetic.

If system return impedances are low enough, then simple radio-frequency chokes can be used to limit this noise with no effect on the safety function.

A 50-microhenry choke will add 1/50 of an ohm at 60 Hz, but will look like 2 ohms at 7.5 kHz and 30 ohms at 100 kHz. Such an RF choke will serve to discriminate against noise on the ground circuit.

An inexpensive RF choke may be installed in the safety ground by:

1. Pulling the green ground wire 20 feet longer than required.

2. Coiling the extra length on a 6-inch diameter (about 12 turns).

3. Securing it tightly wound with cable ties.

4. Connecting it into the circuit.

These actions satisfy the NEC requirement for a continuous ground and noise isolation is also enhanced.

Whatever scheme is used, the ground of experimental equipment shall be connected to the same ground as the facilities' electrical system to ensure equal potential.

For practices involving hazardous materials, such as explosives, the grounding shall also comply with the requirements of Section 5.0, *Special Occupancie*s.

10.9.2.1.3 NOISE COUPLING MECHANISMS.

Grounding can reduce the interference in the five types of coupling mechanisms listed here.

1. Conductive Coupling. (Source and load wired together) It is sometimes practical to provide a separate return path for both the source and the load. If the system layout allows this, then conductive coupling cannot occur between these two, as is shown in Figures 10-2 and 10-3.

2. Capacitive Coupling. (High-impedance proximity coupling) The technique for increasing resistance to capacitive coupling among cables is to ground one end of the shield to produce the shortest, most direct shunt path back to the source of the coupled current as is shown in Figures 10-4 and 10-5.

    Caution: It is possible to inadvertently *increase* coupling between source and load if the shield ground does not properly shunt the current coupled onto the shield.

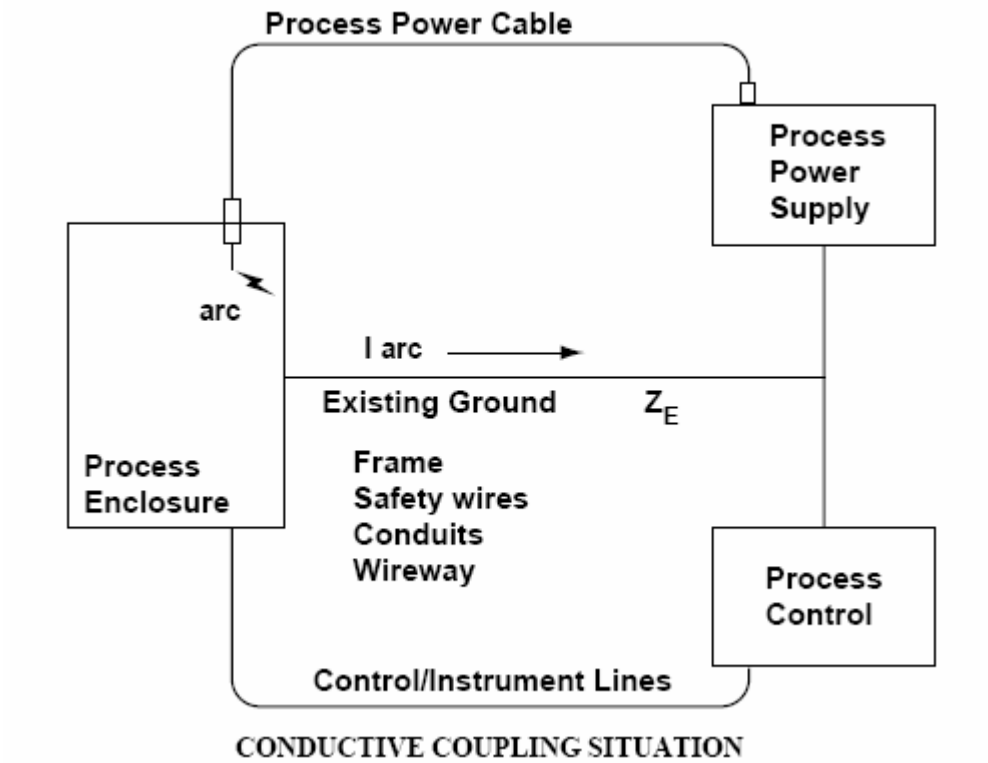

Figure 10-2. Arc currents through the process power supply return (existing ground) develop a voltage that appears in series with the process controls because they share that return.

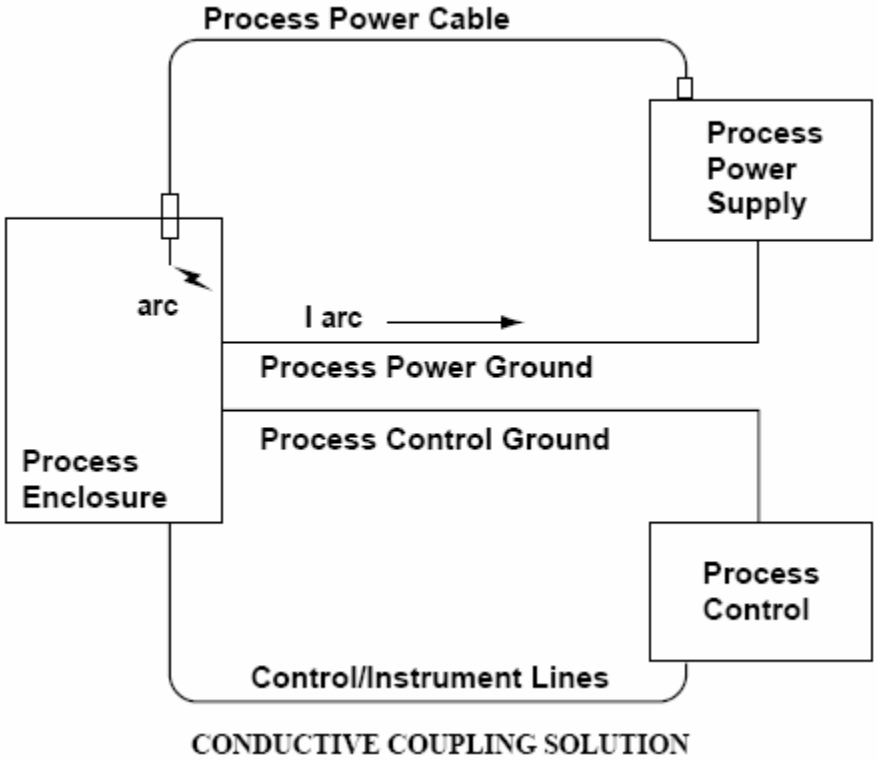

Figure 10-3. It has been possible to install a separate return conductor for the power supply. The arc currents no longer appear in series with the process controls. There is no conductive coupling.

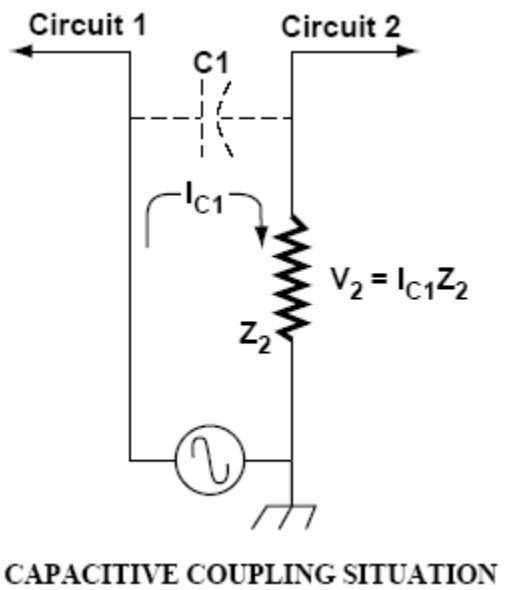

Figure 10-4. Capacitance between circuit 1 and circuit 2 is allowing current to be transferred into circuit 2 via an electric field. This current flows through Z_2, the impedance of circuit 2, and develops an interfering voltage.

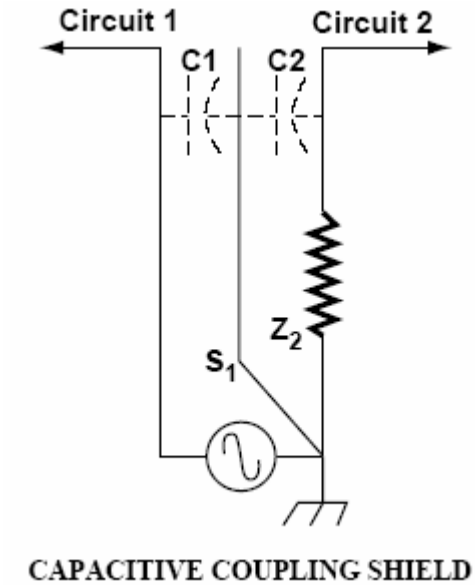

Figure 10-5. A shield has been interposed between circuit 1 and circuit 2. The coupling will be reduced as it shunts the coupled current around Z_2 instead of through it. The interfering voltage could be increased instead of decreased if not properly shunted.

3. Inductive Coupling. (Near-field, low-impedance loop-to-loop coupling) The technique for increasing resistance to magnetic coupling in shielded cables is to ground *both* ends of the shield to an effective signal return ground as is shown in Figures 10-6 and 10-7.

4. System Signal Returns. Each installation will require individual analysis and treatment. A single ground poses no problem, but multiple grounds can result in a ground loop. These can upset the proper functioning of instruments. A signal isolator offers a way of overcoming the problem.

5. Instrumentation Grounding[2]. Equipment that is used to implement a control instrumentation strategy (see Figure 10-8) makes use of a common signal ground as a reference for analog signals. Any additional grounds that are introduced into the control circuit will almost certainly cause ground loops to occur.

A typical process instrumentation loop is shown in Figure 10-8. It is a DC system that operates at a specific voltage (24 volts in this case) to a master ground reference called a signal ground. The instrumentation signal varies within the range of 4-20 mA, depending upon the value of the variable (pressure, temperature, etc.) seen by the sensor. A precisely calibrated circuit takes this mA signal and converts it into a form that can be used by a process-control computer, PLC,

---

[2] The information in this section and figures 10-8 and 10-9 is reprinted with permission from the September 1991 issue of EC&M magazine © 1991 Intertec Publishing Corporation. All rights reserved.

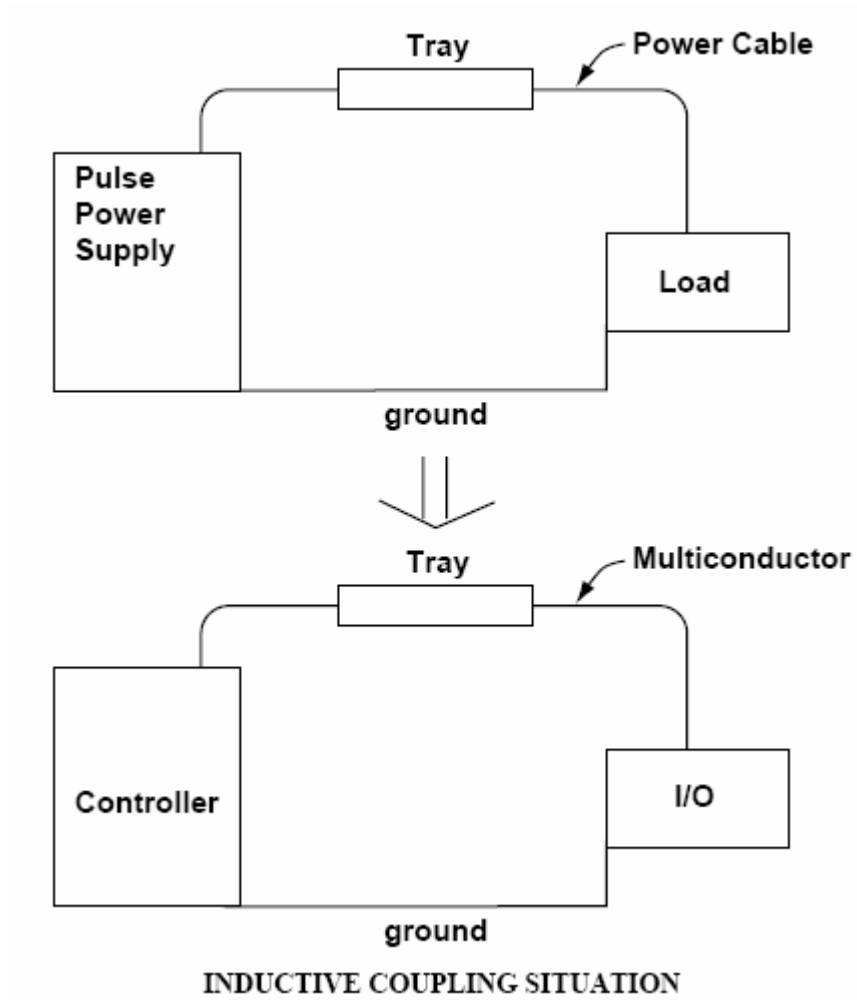

Figure 10-6. The pulse power supply, its cable, load, and return form a transmitting loop which couples into the loop formed by the controller, its multiconductor cabling, 1/0 and return. Note that in actual installations these loops can be very large and very close.

dedicated instrument, or whatever controller that supervises the system. In this example, the mA signal is converted to a 1-5 V signal for a chart recorder. At 4 mA, the voltage measured by the recorder is 250 x.004 = 1 V. At 20 mA, the measured voltage is 5 V. Normally, the recorder scale is calibrated so the voltage reads directly in °F, psi, etc.

In order to minimize the danger of introducing ground loops into this complicated network of sensitive equipment, a dedicated instrumentation system ground bus is usually employed. This bus ultimately receives grounds from the signal common, the do power supply common, the cabinet ground, and the instrumentation ac power ground. The bus is tied to earth via the building ground and the plant ground grid. Figure 10-9 shows the typical way in which interconnection of these various grounds is accomplished.

The cabinet ground is a safety ground that protects equipment and personnel from accidental shock hazards while providing a direct drain line for any static charges or electromagnetic interference (EMI) that may affect the cabinets. The cabinet ground remains separate from the do signal ground until it terminates at the master ground bus.

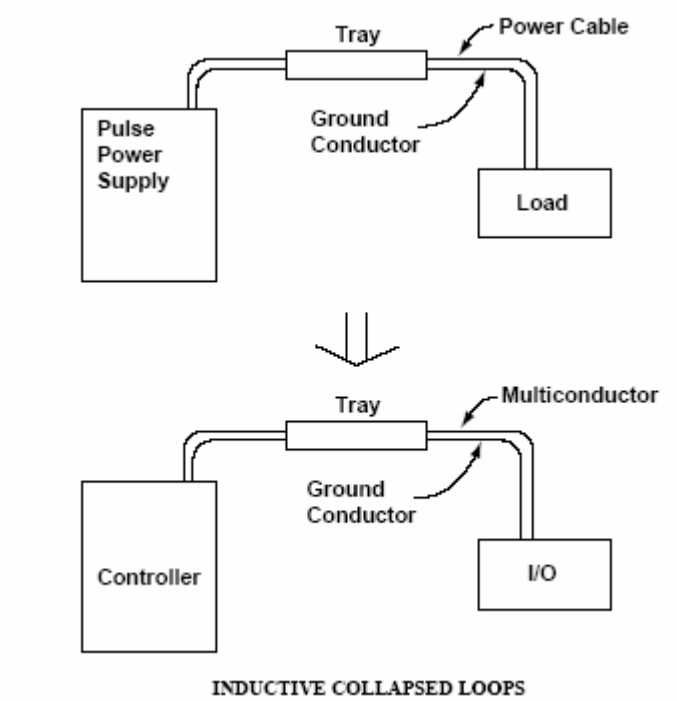

Figure 10-7. Intentional returns have been installed for both the pulse power supply and the controller right in the trays for the cables. Both loops have been reduced to small cross sections, reducing inductive coupling. Any electromagnetic (far field) radiation being generated by the pulse power supply and its cabling will also be reduced.

Eliminating grounds is not feasible for some instruments, such as thermocouples and some analyzers, because they require a ground to obtain accurate measurements. Also, some instruments must be grounded to ensure personnel safety.

When grounds cannot be eliminated, the solution to instrumentation ground loops lies in signal isolators. These devices break the galvanic path (dc continuity) between all grounds while allowing the analog signal to continue throughout the loop. An isolator also eliminates the noise of ac continuity (common-mode voltage)[3].

10.9.2.1.4 OPERATION AND MAINTENANCE

Before starting each operation (experiment, test, etc.) the exposed portions of the grounding system should be visually checked for any damage and to determine that all necessary connections have been made. If more than one operation is conducted every day, then visual checks should be performed only at the beginning of each shift, if the grounding system will be needed during that shift. The adequacy of the grounding system should be verified annually. It is recommended that the grounding impedance within the equipment be maintained at 0.25 ohms or less. (See IEEE 1100).

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[3] Much of the information above came from the article entitled *Causes and Cures of Instrumentation Ground Loops*, by Pat Power, Moore Industries, Houston, TX.

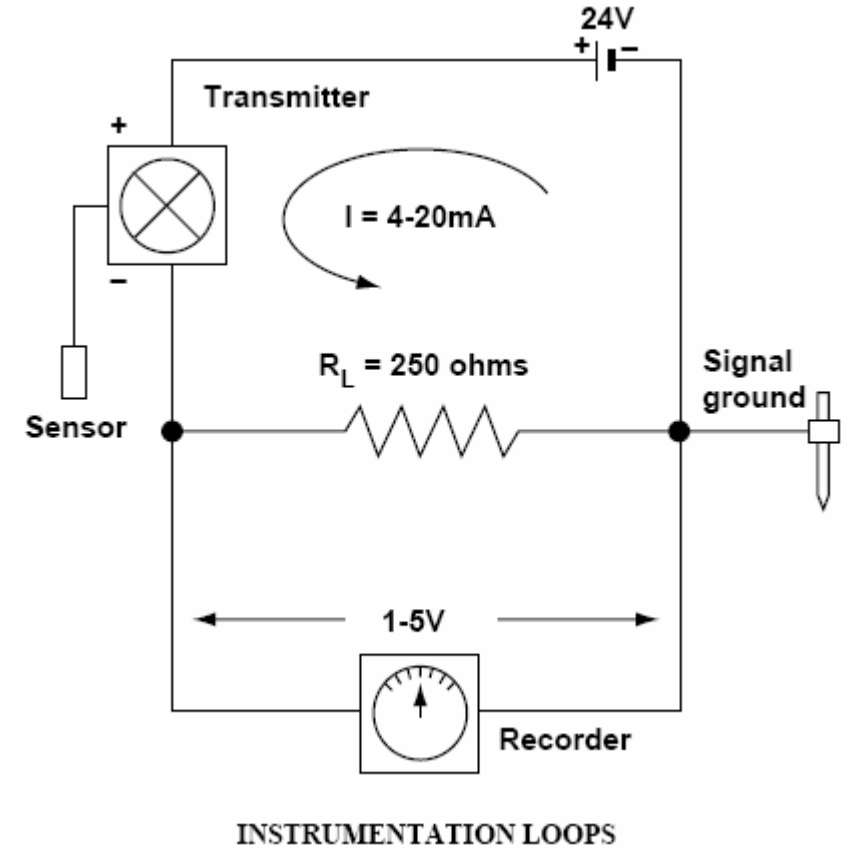

Figure 10-8. Typical Process Instrument Loop.

10.9.2.2 MATERIALS USED IN AN UNCONVENTIONAL MANNER

The practice of using materials or components for purposes other than originally designed needs special safety considerations in use, identification, personnel protection, and equipment protection.

10.9.2.2.1 HAZARDS

The use of materials for something other than their original design criteria has the potential for providing an additional hazard, especially to personnel unfamiliar with the research apparatus. Personnel may assume that the material is used as originally designed and can unknowingly expose themselves to hazards unless special precautions are followed.

Some examples of items used in an unconventional manner are:

1. Copper pipe used as an electrical conductor

2. Insulated flexible copper pipe used as an electrical conductor

3. Specially designed high-voltage or high-current connectors

4. Specially designed high-voltage or high-current switches

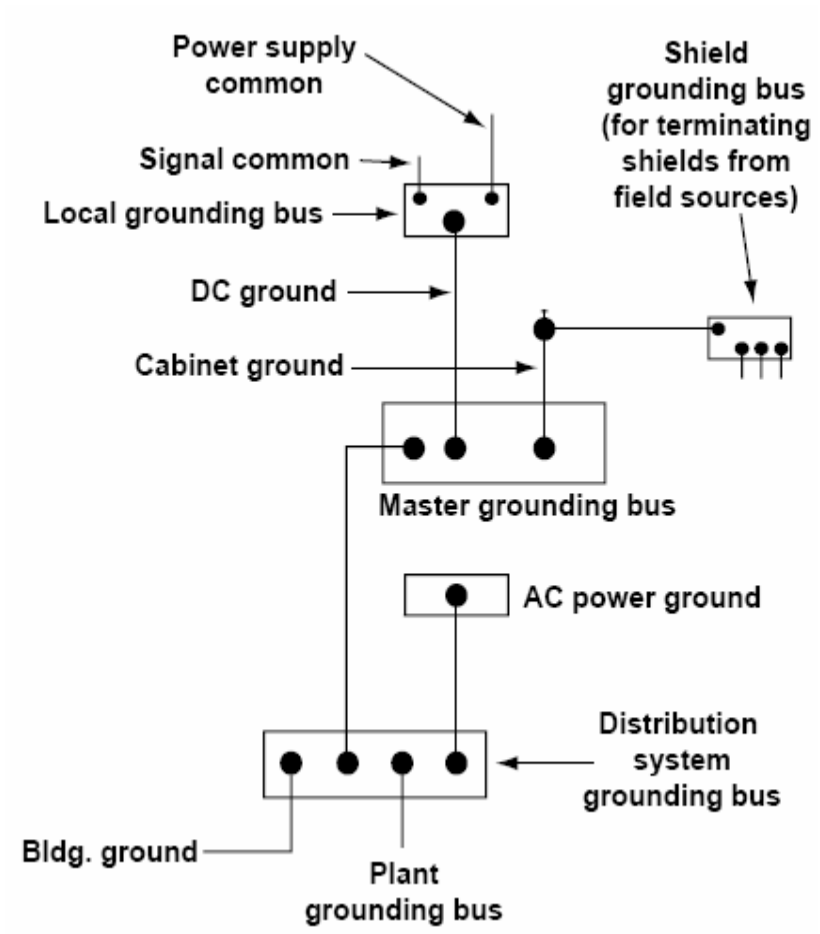

Figure 10-9. Typical control instrumentation ground system.

5. Water column used as a high-voltage resistor

6. Standard coax cable used in special high-voltage pulsed circuits

7. Water column used as a charged-particle beam attenuator

8. Commercial cable tray used as a mechanical support for experimental apparatus.

10.9.2.2.2 DESIGN AND CONSTRUCTION

During design, special consideration should be given to installing interlocks and protective barriers. Signs warning of the hazards should be posted to help prevent unsuspecting personnel from being injured.

10.9.2.2.3 OPERATION AND MAINTENANCE

Appropriate safety procedures and training should be part of the process to qualify personnel. The procedures should describe the methods used to promote safe work practices relating to work on energized circuits in accordance with Section 2.1.2, *Considerations for Working on Energized Systems and Equipment*, Section 2.13, *Work Practices*, and 29 CFR 1910.331-335.

10.9.3 WORK ON ENERGIZED OR DE-ENERGIZED ELECTRICAL EQUIPMENT

Unless explicitly stated otherwise in this section, all work on energized/de-energized equipment will conform to Section 2.0, "General Requirements."

10.10 REQUIREMENTS FOR SPECIFIC R&D EQUIPMENT

Electrical equipment and components used in research may pose hazards not commonly found in industrial or commercial facilities. Special precautions are required to design, operate, repair, and maintain such equipment. Electrical safety and personnel safety circuits (e.g., interlocks) are covered in this section as a guide to reduce or eliminate associated hazards. Training and experience in the specialized equipment are necessary to maintain a safe workplace.

All personnel involved with research electrical equipment should be trained and be familiar with the hazards they may encounter in the workplace. Only qualified electrical personnel should design, install, repair, or maintain electrical research equipment or components. Safety-related design, operation, and maintenance techniques should be incorporated into all new or modified equipment. Existing equipment should be modified when necessary to ensure safety. Equipment for which specific standards are not available should be constructed according to the principles of established standards, as determined by the AHJ.

Capacitors and inductors are used in research apparatus in special configurations as well as in their standard configurations. The design, operation, and maintenance of research apparatus using capacitors and inductors in these special configurations require that special consideration be given to the safety of both personnel and equipment.

10.10.1 CAPACITORS

This section covers capacitors that are used in the following typical R&D applications:

1. Energy storage
2. Voltage multipliers
3. Filters
4. Isolators

10.10.1.1 HAZARDS

Examples of capacitor hazards include:

1. Capacitors may store and accumulate a dangerous residual charge after the equipment has been de-energized. Grounding capacitors in series may transfer rather than discharge the stored energy.
2. A hazard exists when a capacitor is subjected to high currents that may cause heating and explosion.

3. When capacitors are used to store large amounts of energy, internal failure of one capacitor in a bank frequently results in explosion when all other capacitors in the bank discharge into the fault. Approximately 10^4 joules is the threshold energy for explosive failure of metal cans.

4. High-voltage cables should be treated as capacitors since they have the capability to store energy.

5. The liquid dielectric and combustion products of liquid dielectric in capacitors may be toxic.

6. Because of the phenomenon of "dielectric absorption," not all the charge in a capacitor is dissipated when it is short-circuited for a short time.

7. A dangerously high voltage can exist across the impedance of a few feet of grounding cable at the moment of contact with a charged capacitor.

8. Discharging a capacitor by means of a grounding hook can cause an electric arc at the point of contact. (See 10.10.1.2.3).

9. Internal faults may rupture capacitor containers. Rupture of a capacitor can create a fire hazard. PCB dielectric fluids may release toxic gases when decomposed by fire or the heat of an electric arc.

10. Fuses are generally used to preclude the discharge of energy from a capacitor bank into a faulted individual capacitor. Improperly sized fuses for this application may explode.

10.10.1.2 DESIGN AND CONSTRUCTION

The following cautions in design and construction should be considered:

1. Isolate capacitor banks by elevation, barriers, or enclosures to preclude accidental contact with charged terminals, conductors, cases, or support structures.

2. Interlock the circuit breakers or switches used to connect power to capacitors.

3. Provide capacitors with current-limiting devices.

4. Design safety devices to withstand the mechanical forces caused by the large currents.

5. Provide bleeder resistors on all capacitors not having discharge devices.

6. Design the discharge-time-constant of current-limited shorting and grounding devices to be as small as practicable.

7. Provide suitable grounding.

10.10.1.2.1 AUTOMATIC DISCHARGE DEVICES

1. Use permanently connected bleeder resistors when practical.

2. Have separate bleeders when capacitors are in series.

3. Use automatic shorting devices that operate when the equipment is de-energized or when the enclosure is opened, which discharges the capacitor to safe voltage (50 V or less) in less time than is needed for personnel to gain access to the voltage terminals. It must never be longer than 5 minutes.

4. For Class C equipment with stored energy greater than 10 J, provide an automatic, mechanical discharging device that functions when normal access ports are opened.

5. Ensure that discharge devices are contained locally within protective barriers to ensure wiring integrity. They should be in plain view of the person entering the protective barrier so that the individual can verify proper functioning of the devices.

6. Provide protection against the hazard of the discharge itself.

10.10.1.2.2 SAFETY GROUNDING

1. Fully visible, manual grounding devices should be provided to render capacitors safe while work is being performed.

2. Grounding points must be clearly marked.

3. Prevent transferring charges to other capacitors.

10.10.1.2.3 GROUND HOOKS

1. Conductor terminations should be soldered or terminated in an approved crimped lug. All conductor terminations must be strain-relieved within 15 cm.

2. Ground hooks must be grounded and impedance should be less than 0.1 ohms to ground.

3. The cable conductor must be clearly visible through its insulation.

4. A cable conductor size of at least #2 AWG should be used, and the conductor shall be capable of carrying the available fault current of the system.

5. Ground hooks shall be used in sufficient number to adequately ground all designated points.

6. Permanently installed ground hooks must be permanently grounded and stored in a manner to ensure that they are used.

10.10.1.2.4 DISCHARGE EQUIPMENT WITH STORED ENERGY IN EXCESS OF 10 JOULES

1. A discharge point with an impedance capable of limiting the current to 500A or less should be provided.

2. The discharge point must be identified with a unique marker (example: yellow circular marker with a red slash), and should be labeled "HI Z PT" in large legible letters.

3. A properly installed grounding hook should first be connected to the current-limiting discharge point and then to a low-impedance discharge point (< 0.1 ohm) that is identified by a unique marker (example: yellow circular marker).

4. The grounding hooks should be left on all of these low-impedance points during the time of safe access.

5. The low-impedance points shall be provided whether or not the HI-Z current-limiting points are needed.

6. Voltage indicators that are visible from all normal entry points should be provided.

10.10.1.2.5 FUSING

1. Capacitors connected in parallel should be individually fused, when possible.

2. Caution must be used in the placement of automatic discharge safety devices with respect to fuses. If the discharge will flow through the fuses, a prominent warning sign should be placed at each entry indicating that each capacitor must be manually grounded before work can begin.

3. Special knowledge is required for high-voltage and high-energy fusing.

10.10.1.3 OPERATION AND MAINTENANCE

1. The protective devices (interlocks) shall not be bypassed unless by qualified electrical personnel when inspecting, adjusting, or working on the equipment. Proper procedures need to be followed when bypassing interlocks.

2. Procedures should be established for tagging the interlock and logging its location and the time when bypassed and restored. Written approval shall be obtained from an appropriate authority before bypassing an interlock .

3. Only qualified electrical personnel (those trained in the proper handling and storage of power capacitors and hazard recognition) shall be assigned the task of servicing/installing such units.

4. Proper PPE shall be used when working with capacitors.

5. Access to capacitor areas shall be restricted until all capacitors have been discharged, shorted, and grounded.

6. Any residual charge from capacitors shall be removed by grounding the terminals before servicing or removal.

7. Automatic discharge and grounding devices should not be relied upon.

8. Grounding hooks shall be inspected before each use.

9. Capacitor cases should be considered "charged."

10. Protective devices should be tested periodically.

11. All uninstalled capacitors capable of storing 5 joules or greater shall be short-circuited with a conductor no smaller than #14 AWG.

12. A capacitor that develops an internal open circuit may retain substantial charge internally even though the terminals are short-circuited. Such a capacitor can be hazardous to transport, because the damaged internal wiring may reconnect and discharge the capacitor through the short-circuiting wires. Any capacitor that shows a significant change in capacitance after a fault may have this problem. Action should be taken to minimize this hazard when it is discovered.

10.10.2 INDUCTORS

This section covers inductors as well as electromagnets and coils that are used in the following typical applications:

1. Energy storage

2. Inductors used as impedance devices in a pulsed system with capacitors

3. Electromagnets and coils that produce magnetic fields to guide or confine charged particles

4. Inductors used in do power supplies

5. Nuclear Magnetic Resonance (NMR), Electron Paramagnetic Resonance (EPR), and Magnetic Susceptibility Systems.

10.10.2.1 HAZARDS

Examples of Inductor hazards include:

1. Overheating due to overloads, insufficient cooling, or failure of the cooling system could cause damage to the inductor and possible rupture of the cooling system.

2. Electromagnets and superconductive magnets may produce large external force fields that may affect the proper operation of the protective instrumentation and controls.

3. Magnetic fields could attract nearby magnetic material, including tools and surgical implants, causing injury or damage by impact.

4. Whenever a magnet is suddenly de-energized, production of large eddy currents in adjacent conductive material can cause excessive heating and hazardous voltages. This state may cause the release or ejection of magnetic objects.

5. The worker should be cognizant of potential health hazards.

6. Interruption of current in a magnet can cause uncontrolled release of stored energy. Engineered safety systems may be required to safely dissipate stored energy. Large amounts of stored energy can be released in the event of a "quench" in a superconducting magnet.

10.10.2.2 DESIGN AND CONSTRUCTION

The following should be considered:

1. Provide sensing devices (temperature, coolant-flow) that are interlocked with the power source.

2. Fabricate protective enclosures from materials not adversely affected by external electromagnetic fields. Researchers should consider building a nonferrous barrier designed to prevent accidental attraction of iron objects and prevent damage to the cryostat. This is especially important for superconducting magnet systems.

3. Provide equipment supports and bracing adequate to withstand the forces generated during fault conditions.

4. Appropriately ground electrical supply circuits and magnetic cores and provide adequate fault protection.

5. Provide means for safely dissipating stored energy when excitation is interrupted or a fault occurs.

6. Provide appropriate warning signs to prevent persons with pacemakers or similar devices from entering areas with fields of greater than 0.001 Tesla.

7. Personnel exposure to magnetic fields of greater than 0.1 Tesla should be restricted.

8. When a magnet circuit includes switching devices that may not be able to interrupt the magnet current and safely dissipate the stored energy, provide a dump resistor connected directly across the magnet terminals that is sized to limit the voltage to a safe level during the discharge and safely dissipate the stored energy.

10.10.2.3 OPERATION AND MAINTENANCE

Verify that any inductor is de-energized before disconnecting the leads or checking continuity or resistance.

10.10.3 ELECTRICAL CONDUCTORS AND CONNECTORS

The conductors and connectors covered here are only those used in unconventional applications.

10.10.3.1 HAZARDS

Examples of hazards are as follows:

1. Metallic cooling-water pipes that are also used as electrical conductors present shock hazards (i.e., they may not be readily recognizable as electrical conductors).

2. Improper application or installation of connectors can result in overheating, arcing, and shock hazards.

3. Hazardous induced voltages and arcing can result from inadequate separation between high- and low-voltage cables.

4. Use of an improper cable for a given type of installation (routing) can result in a fire hazard.

10.10.3.2 DESIGN AND CONSTRUCTION

When working with special conductors and connectors for R&D applications, the following guidelines shall be implemented for design and construction:

1. Select cables that are listed by an NRTL for a given type of installation (such as in conduits, trays, underground, or in an enclosure) whenever possible. Since cables used for R&D are sometimes unique (such as some coaxial cables), they may not be available as NRTL listed. In that case, obtain AHJ approval.

2. Where liquid- or gas-cooled conductors are used, sensing devices (temperature or coolant-flow) shall be provided for alarm purposes or equipment shutdown if the cooling system malfunctions. Provide adequate labeling, insulation, or other protection for metallic cooling-water piping used as electrical conductors.

3. Provide engineering calculations to support overrating of conductors for any application. Avoid conductor loops (wide spacing) between high-current supply and return conductors to prevent voltage and current induction in adjacent circuits or structural members.

4. Ground coaxial cable shielding when possible. If test conditions require an ungrounded shield, provide barriers and warning signs to notify personnel that the shield is ungrounded and should be assumed to be energized. Provide suitable routing and additional protection for coaxial cables used in pulsed-power applications where the braid of the coaxial cable rises to high voltage levels.

10.10.3.3 OPERATION AND MAINTENANCE

Cable connectors and connections should be checked after installation, periodically, and should be tightened as necessary. Special attention should be given to aluminum cable connections.

Ensure that charges are not built up on equipment that has been disconnected, such as vacuum feed through systems.

10.10.4 INDUCTION AND DIELECTRIC HEATING EQUIPMENT

This section describes electrical hazards associated with induction heating, RF equipment, and microwave equipment used in research. The hazards are mainly associated with high-power/high-frequency RF generators, waveguides and conductors, and the working coils producing high temperatures.

10.10.4.1 HAZARDS

1. RF power as high as 50 kW and frequency in the tens of kHz range to hundreds of MHz is supplied from the RF and microwave generators. Being close to or making contact with an unprotected coil, conductors or waveguide opening may result in severe body burns.

2. Dangerous voltages are present inside the power generators.

3. Dangerous levels of RF energy may be present in the laboratory.

10.10.4.2 DESIGN AND CONSTRUCTION

1. The heating coils, sources of high-frequency energy, and other live parts outside the generator cabinet must be shielded or guarded to prevent access or contact.

2. The heating coil should have its cold (outside) lead properly grounded.

3. A coaxial cable of correct impedance and adequate construction may be desirable to deliver the RF power to the coil in order to prevent the leakage of the RF energy in the laboratory.

10.10.4.3 OPERATION AND MAINTENANCE

1. Shielding must be maintained to minimize RFMW radiation.

2. Wearing metallic objects when operating or maintaining the induction heating system is prohibited.

3. Posting suitable warnings to indicate equipment hazards.

10.10.5 LASERS AND X-RAY EQUIPMENT

This section is applicable to laser systems and x-ray equipment used in research. Both fixed and portable equipment are covered regardless of input voltage. Only electrical hazards are addressed in this subsection. Refer to ANSI Z136.1 for laser hazards and 29 CFR 1910.306 (f) for x-ray hazards.

10.10.5.1 HAZARDS

1. Dangerous voltages are present inside the equipment.

2. Implosion hazards may exist with the covers removed.

3. Energy storage devices may present a hazard due to a residual charge even when the system is de-energized

4. Dangerous voltages can exist across the impedance of the grounding conductor during operation.

5. Failure of interlocks and safety devices may allow access to energized parts.

Design of Safe Electrical Equipment for Research

SLAC-I-730-0A11F-001-R000

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DESIGN OF SAFE ELECTRICAL EQUIPMENT FOR RESEARCH

by

J. L. Rand, R. W. Leep, and W. A. Bradley

PART 1. GENERAL HIGH-VOLTAGE TECHNOLOGY

ABSTRACT

Design information needed by research personnel engaged in the construction and operation of experimental apparatus is presented with emphasis on electrical safety. Figures, charts, and tables are used to present reference data.

I. INTRODUCTION

Research and development work requires the construction and operation of a wide variety of experimental apparatus. In most cases, the research scientist charged with building an experimental device is a specialist in a particular discipline. He cannot necessarily be expected to have the electrical and mechanical expertise required to build a complex piece of equipment that will operate reliably and safely under all conditions and that will also conform to numerous building and construction codes. Consequently, engineers, technicians, and safety specialists are employed to assist the scientist who has final responsibility for his equipment. A well-built device is inherently safer than one that requires continual troubleshooting and repair.

This manual is intended to help the research scientist who has limited knowledge in the electrical area, particularly in high-voltage design. It presents the fundamental concepts and basic data needed to assemble safe, reliable equipment in a practical manner. The figures, charts, and tables have been taken from standard texts and handbooks. Comments and suggestions

have been gathered from people with many years of practical experience in building and operating experimental equipment. Books have been written on every subject covered in this manual, and the user should consult the references listed to obtain a more complete discussion.

II. HIGH-VOLTAGE EQUIPMENT

Good practice in the design of high-voltage equipment requires an assessment of the electrical and mechanical stresses imposed on components and materials used in the equipment. The following discussion provides information to assist in evaluating these stresses without requiring a literature search for the various formulas and ratings. We assume that most high-voltage equipment will be built and operated by qualified people in a research laboratory environment. The safety of these people depends on trouble-free performance of the equipment, proper training, and an understanding of the possible hazards.

A. Electrical Stress in Dielectrics

The electric field stress within dielectric materials must be limited to prevent breakdown. Maximum limits are fixed by the dielectric strength of the materials involved. Electric field strengths can be calculated from the geometry of the conductors and insulators. Figure 1 gives formulas for calculating the maximum electrical stress in common geometries. See Appendix A, Figs. A1-A3, for additional configurations and charts.

B. Conductor Spacing with Air Dielectric

Sufficient spacing must be maintained between conductors, or conductors and grounded structures, to prevent breakdown of the insulating medium and consequent arcing. With air as the insulating material, the minimum safe spacing required is several times the distance implied by the dielectric strength of air, which is 29 kV/cm (75 kV/in.) at standard temperature (25°C) and sea level pressure. High temperature or decreased pressure will reduce the insulating property of air. For example, a 2.54-cm (1-in.) point gap in a warm piece of equipment (60°C is not uncommon) at Los Alamos, New Mexico*, will break down at less than 20 kV. A rule of thumb often used at Los Alamos is avoid using more than 10 kV/in. when air is the insulating medium. Figure 2

*Elevation - 2.2 km (7200 ft)

Electric Stress E at any point in a dielectric between two electrodes, across which a voltage V is applied, is the force on unit charge placed at the point. It is equal to the voltage gradient, i.e. $E = -dv/dx$ E is measured in kV/cm.

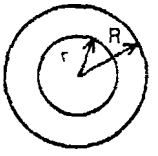
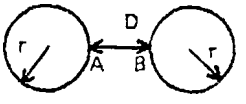
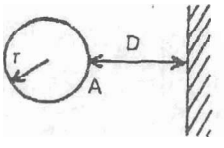
	Electrode Configuration	E_m = Maximum Electric Stress f = Field Divergence Factor = $\frac{\text{Max. Stress}}{\text{Mean Stress}}$
CYLINDERS	Concentric Cylinders  	E_m occurs at surface of inner cylinder $E_m = \frac{V}{r \ln \frac{R}{r}}$ $\quad f = \frac{\left(\frac{R}{r} - 1\right)}{\ln \frac{R}{r}}$ The optimum ratio of $\frac{R}{r} = e$, is the smallest R for specified V and E_m $E_m = \frac{V}{r} = \frac{Ve}{R}$
	Equal Parallel Cylinders, or Wires  	E_m occurs at points A & B $E_m = \frac{Vf}{D}$ $f = \frac{\sqrt{\left(\frac{D}{r}\right)^2 + 4\frac{D}{r}}}{2 \ln\left[\frac{D}{2r} + 1 + \frac{1}{2}\sqrt{\left(\frac{D}{r}\right)^2 + \frac{4D}{r}}\right]}$
	Cylinder/Plane  	E_m occurs at point A $E_m = \frac{Vf}{D}$ $f = \frac{\sqrt{\left(\frac{D}{r}\right)^2 + \frac{2D}{r}}}{\ln\left[\frac{D}{r} + 1 + \sqrt{\left(\frac{D}{r}\right)^2 + \frac{2D}{r}}\right]}$

Fig. 1.
Electric stress produced in the surrounding dielectric material by voltage applied to various conductor configurations.

shows the breakdown voltage of air plotted against gap spacing. The lower curve shows a recommended minimum spacing for safe operation at altitudes up to ~3000 m (10 000 ft).

Dust and water vapor in the air generally reduce the breakdown voltage. These factors will affect the electrical breakdown between sharp points more than between smooth spheres. The surfaces of high-voltage conductors attract dust. When the dust is conductive, dielectric spacing is reduced and the surface is electrically rougher than before. Thus, the air surrounding high-voltage apparatus should be kept clean and dry whenever possible. When air filters are impractical for dust removal, solid insulating material or additional spacing should be considered. The following are formulas for calculating the

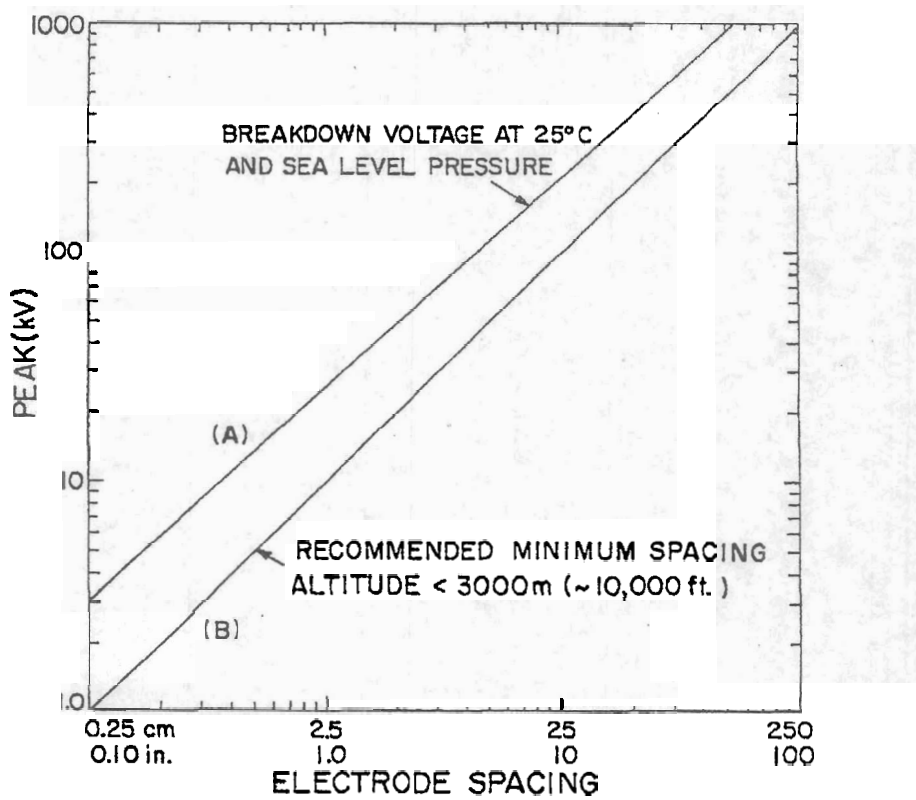


Fig. 2.
(A) Breakdown voltage for point gaps in air at standard temperature (25°C) and pressure (760 mm Hg). (B) Recommended minimum conductor spacing for altitudes up to 3000 m (10 000 ft); includes safety factor.

electrical breakdown field for common conductor geometries in air. The correction factor S used in the following formulas may be obtained from Fig. 3.

Parallel Plates (Uniform Field)

$$E = \frac{V_b}{d} = 24.2S + \frac{6.08S}{\sqrt{d}} ,$$

where E_b = Breakdown field (kV/cm);

S = Temperature-pressure correction factor (Fig. 3); S = 1 at 760 mm Hg and 25°C; and

d = Conductor spacing (cm); it must be larger than 0.01 cm.

Concentric Cylinders

$$E_c = 31S\left[1 + \frac{0.308}{(Sr)^{1/2}}\right],$$

where

E_c = Corona onset field (kV/cm),

and

r = Radius of inner conductor (cm).

Equal Parallel Cylinders

$$E_c = 30S\left[1 + \frac{0.301}{(Sr)^{1/2}}\right],$$

where r = Radius of conductor (cm).

C. Corona Discharge

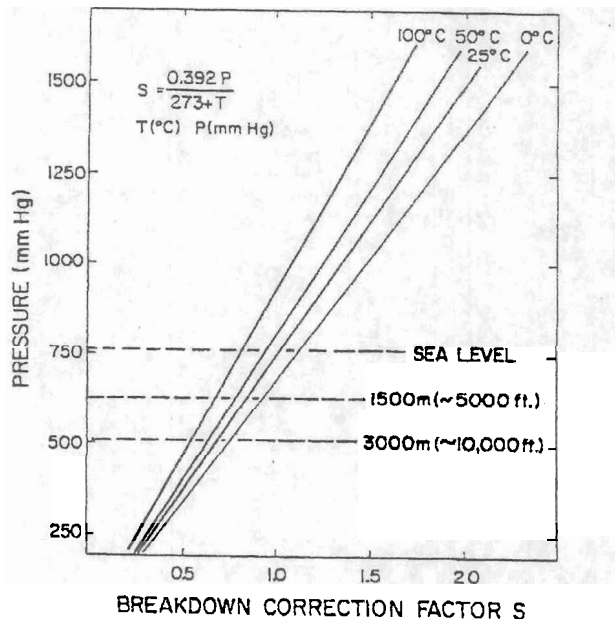


Fig. 3.
Correction factor variation for pressure and temperature.

Corona discharge is a familiar phenomenon wherever conductors surrounded by air, gas, or liquid insulating media are raised to potential levels of about 12 kV or higher. At this potential, the electrostatic field becomes concentrated near the conductor to a value large enough to ionize the surrounding material. The required potential level depends on the conductor shape, surface irregularities, and spacing between the conductor and a ground plane or a conductor of opposite polarity. When the insulating medium is air, corona can be seen as a bluish glow surrounding the conductor, and a hissing sound is produced by the discharge current flowing through the ionized air. This discharge current produces ozone and oxides of nitrogen, and in the presence of moisture, nitrous acid may form on surfaces near the discharge path. Many insulation materials are attacked by this acid, and eventually a surface track failure may be produced. A white deposit is often found on insulators and metal surfaces at the point of corona leakage.

Because corona discharge begins at points of maximum electric field concentration, conductors in high-voltage apparatus should be smooth and shaped to avoid sharp corners wherever possible. The corona shields seen on high-voltage equipment are conducting metal shapes geometrically designed to avoid

excessive voltage gradients at circuit connecting points. Figure 4 shows the principle involved in preventing corona discharge at a high-voltage bushing.

D. Point and Sphere Gap Breakdown Potentials

Figure 5 shows how conductor shape influences breakdown voltage for the simple case of points versus spherical surfaces. The voltage required to break down a 1-cm air gap between sharp points is about 12 kV. Where spheres of 1-cm diam are used as electrodes, the 1-cm gap breaks down at 27 kV, and with 2-cm or larger spheres at 32 kV. This improvement is mostly due to reduction of the electrostatic field in the air adjacent to the conductors, thus inhibiting corona discharge. Small spheres are no better than points at voltage levels above 50 kV. To use a 5-cm spacing at 50 kV, spheres of 15-cm diam or larger are required. The data presented in Fig. 5 are based on air at sea level pressure and 25°C temperature. Practical designs should include a safety factor of 3 or more.

E. Characteristics of Insulating Materials

1. Thickness Required. Various insulating materials used in high-voltage equipment are listed in Appendix Tables B-I and B-II. These tables can be used to estimate the conductor spacing required for insulators other than air. The dielectric strength listed is the maximum potential gradient that the material can withstand without breakdown. The dielectric strength of a material is usually measured in a uniform electric field, such as the field between two parallel

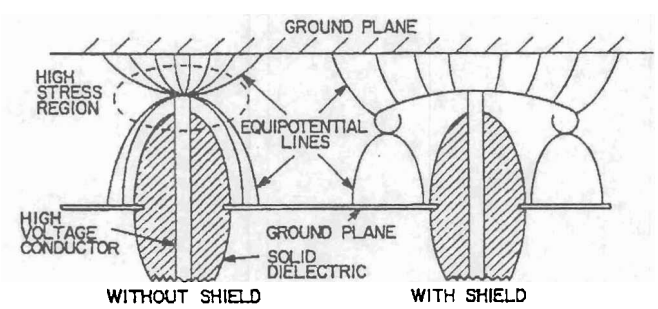


Fig. 4.
Corona shield attached to high-voltage conductor reduces the stress concentration on air surrounding a circuit connection point.

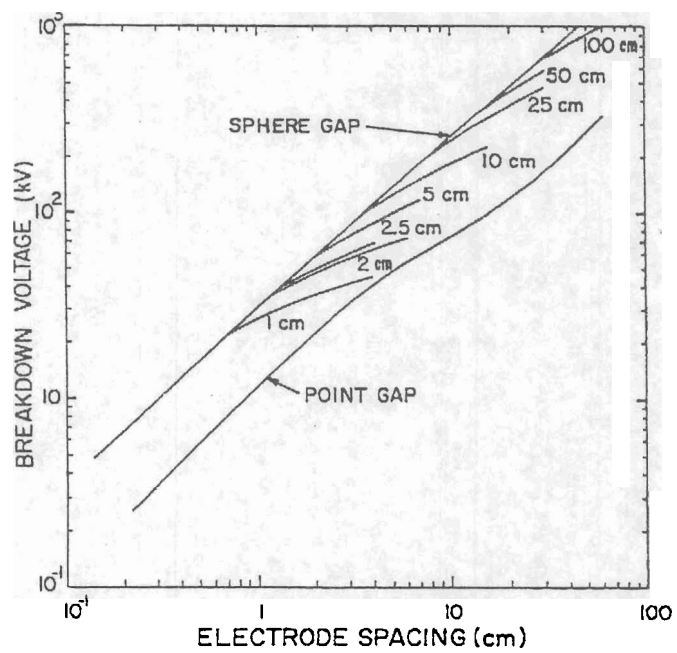


Fig. 5.
Breakdown voltage for sharp points and several sphere sizes used as electrodes in air at 25°C and sea level pressure (760 mm Hg).[1]

flat plates separated 2.5 mm (0.1 in.). Uniform fields are the exception rather than the rule in assembled devices, and the dielectric strength values quoted should be reduced by an appropriate safety factor. In air and high-quality dielectric oils a design safety factor of 6 to 8 is appropriate.

2. Gases. The insulating gases SF_6 (sulfur hexafluoride) and CCl_2F_2 (Freon 12) have a dielectric strength about 2.4 times the strength of air. They are commonly used at pressures of several atmospheres to reduce the required electrode spacing in switches and other devices. Paschen's Law states that the product of electrode spacing and pressure is approximately constant for a given gas at constant temperature. Thus, close electrode spacing at high voltages may be achieved by increasing the surrounding dielectric gas pressure.

Although high-dielectric strength gases may be mixed with air, maximum voltage hold-off can be achieved by using pure dielectric gas. When pure SF_6 is used, the containing vessel must be purged to eliminate air. This may be done by flushing the chamber several times with SF_6 or by vacuum pumping and back-filling.

Another precaution is to avoid electrically overstressing SF_6. Incipient corona discharge can decompose the SF_6 gas into a number of corrosive or toxic compounds. These compounds may attack dielectric materials and cause equipment failure. This problem is especially subtle in pulsed equipment, where peak voltages may approach the breakdown strength of the gas.

3. Liquids. Liquid insulators are also used to decrease the spacing required between conductors and thus reduce the physical size of high-voltage equipment. Liquids also provide a convenient. heat transfer mechanism for high-power equipment, arc quenching in switches, and a method for excluding air in spaces that are difficult to insulate with solid materials. Figure 6 shows the use of

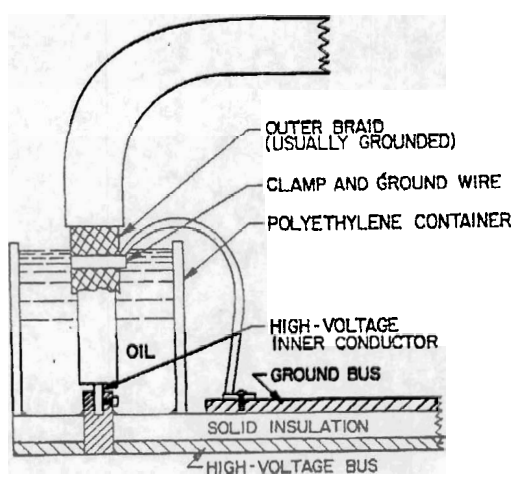


Fig. 6.
Termination of high-voltage pulse cable in an oil bath.

an oil bath to prevent arcing at a cable termination point.

Liquid insulators must be kept pure. Any contamination by dissolved minerals or gases, particulate matter, or gas bubbles will reduce the breakdown voltage. Water in dielectric oil at a concentration of 50 parts per million can reduce the breakdown voltage to 25% of normal. All insulating oils can dissolve about 10% by volume of air at atmospheric pressure. Both water vapor and oxygen in the air are undesirable contaminants, and oil-filled apparatus should be sealed. Some insulating oils will dissolve rubber, plastic, or varnish, and compatibility of materials must be considered. References 1 and 2 contain data on density, viscosity, chemical properties, and other characteristics that are important in choosing the best oil for a particular service.

4. Solids. Solid insulating materials are used in high voltage equipment to support bus bars or other conductors, to prevent accidental contact, and to reduce the required spacing of conductors. The materials most often used are listed in Appendix B. Because the predominant failure mechanism for many materials is the formation of a conductive pathway along the surface between points of high potential difference, Appendix B also presents a table of comparative tracking indices. The materials with high index numbers are more resistant to tracking than those with low index numbers.

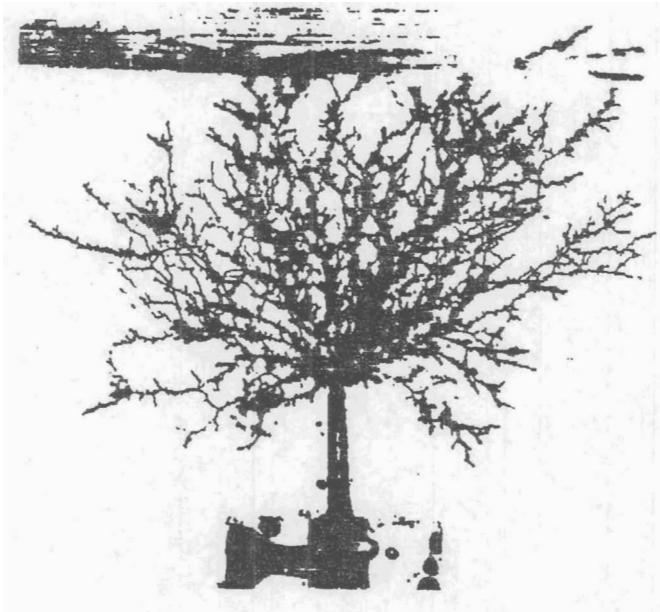
Breakdown voltages through solid insulators or across their surfaces are, at best, poorly defined parameters. Breakdown voltage for solid materials is influenced by practically every physical factor that can be imagined to be relevant, including

- temperature,
- humidity,
- test duration,
- whether dc or ac,
- frequency if ac,
- area of test electrodes,
- discharges in the ambient medium (usually air or oil),
- discharges in cavities within the insulation,
- polarity if there is assymetry of the electrodes,
- pressure on the electrodes, and
- recent applications of mechanical stress.

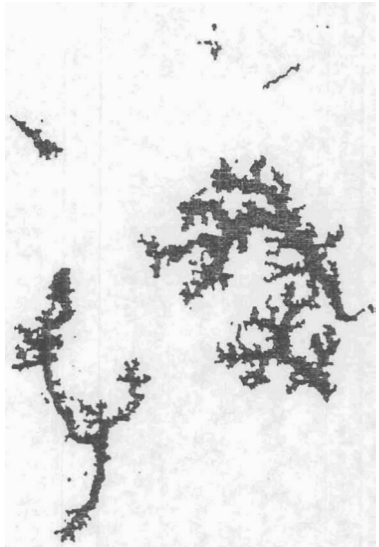
The values given in Appendix B should be used as comparative rough estimates of each material's ability to withstand electrical stress. High temperatures reduce insulating quality and life expectancy of all solid insulators. The temperature limits shown are approximate values used in achieving a practical operating life. Chapter 10 of Ref. 3 presents a discussion of temperature effects.

Generally, the mechanical properties and cost of materials will be more important in the design of equipment than the dielectric strength attainable with a given material. Solid materials are most often used in sheet form for conductor separation or in simple geometric shapes as conductor supports. The thickness required is usually several times the value implied from laboratory tests of dielectric strength. The maximum voltage a given insulator can withstand cannot be proportionately increased indefinitely simply by increasing its thickness. Generally, the withstand voltage increases as the square root of thickness. For example, two layers of tape rated at 9000 V will hold off about 12 000 V, not 18 000 V. Ordinary building wire has 10 to 20 times the insulation thickness required for its rated voltage, mainly to provide mechanical protection.

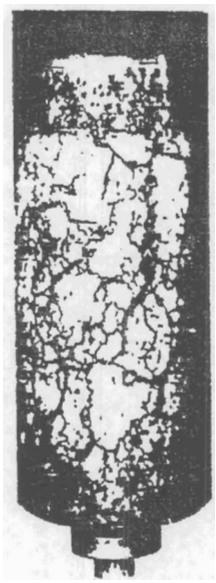
A solid insulator will often fail after a long period of satisfactory service. Figure 7 shows photographs of the progressive mechanisms called tracking and treeing, which cause such failures. Treeing is often started by tiny voids or imperfections in the solid material. Several layers of dielectric material will improve the insulator's resistance to treeing by interrupting the progressive treeing path and isolating imperfections within layers. Tracking is caused by a discharge current flowing across the insulator's surface in the boundary layer between solid material and the surrounding air or liquid medium. In either case, a conductive track of burned or carbonized material is produced, which is electrically equivalent to a resistive connection between the conductors. For practical designs the safe procedure is to use several times the minimum insulator thickness listed in withstand voltage tables and to always use the more stringent ac values of dielectric strength when selecting insulators. Good practice on porcelain line insulators used to support power lines requires a dry flashover rating (breakdown voltage across the insulator) 3 to 5 times the normal operating voltage and a surface tracking path twice the shortest air gap distance.[2]



(a)
Tree-like discharge channels in polymethyl methacrylate.



(b)
Tracking produced by a high-voltage discharge over the surface of a phenol formaldehyde-bonded paper board.



(c)
Tracking on a high-voltage bushing caused by water droplets in the oil in which it was used.

Fig. 7.
Tracking and treeing produced by high-voltage discharge within solid material (a) and across the surface (b and c).

Note: Photographs reproduced from Ref. 2, p. 146.

The porcelain used for insulators does not track, but dirt accumulated on the surface can cause a low resistance path to form.

Electrical systems always contain some inductive elements, and voltage transients will be generated whenever current in the system changes rapidly. These voltage pulses, or transients, can be several times the system operating voltage. Flashovers often occur when the apparatus is turned off following a successful operating period at rated voltage.

5. Vacuum. Evacuated chambers are used in a wide variety of experimental apparatus including high-voltage switches, spectrometers, spark gaps, and particle accelerators. In a high-vacuum environment there are few gas molecules or other materials to be ionized. A conductive path may be created by a high-electric field pulling electrons out of the electrodes or by other mechanisms providing current carriers in the electrode space. Electrically, a highly evacuated space behaves as a very good insulator. The nominal dielectric strength of vacuum varies with the metal used for electrodes, the shape of the electrodes, and the voltage wave form.

Much research has been done on the conductive mechanism and on materials for electrical construction in vacuum. Chapter 4 of Ref. 3 is an up-to-date summary of this subject. No electrical safety hazards are unique to high-voltage equipment in the vacuum environment. The major problem is cleanliness and the selection of materials that will not out-gas molecules into the vacuum. Dielectric strength will be reduced by any leak that provides current-carrier ions. Figure 8 gives a vacuum breakdown criterion derived from charge carrier energy considerations. This curve can be used for practical designs.

Flashover across solid insulators in vacuum is an important consideration in the design of any high-vacuum, high-voltage device. The vacuum chamber must be constructed of an insulating material, or the conductors must be insulated with bushings where they pass through the wall of a metallic vessel. Breakdown voltage across the surface of the insulator depends primarily on the insulating material, not on the electrode material. Table I shows the breakdown voltage measured in vacuum with various insulator and electrode materials. Polystyrene is clearly the best material with a measured breakdown strength of 75 kV across a 2.2-cm long-cylinder. This strength is much lower than the theoretical value expected for a vacuum gap with no solid material in between (400-1200 kV/cm).

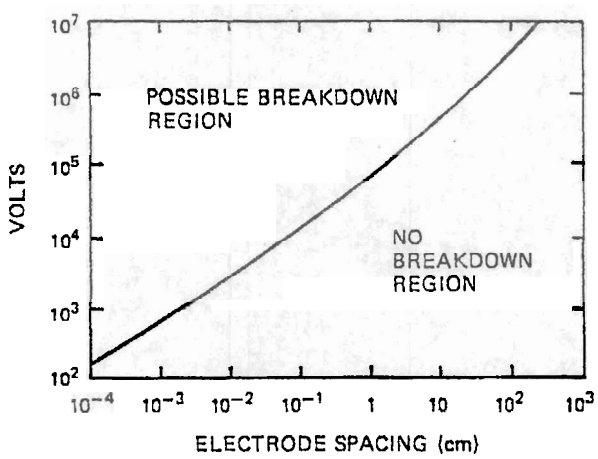


Fig. 8.
Kilpatric's vacuum breakdown criteria. Graph shows voltage applied across a gap vs electrode spacing.

TABLE I
BREAKDOWN VOLTAGES FOR DIFFERENT ELECTRODE AND INSULATOR MATERIALS IN VACUUM[4]

Insulators used were 2.2-cm-long cylinders with butt joint at the electrodes.

Electrode Material	Insulator Material	Breakdown Voltage (kV)
Copper	Polystyrene	75
Copper	Teflon	50
Copper	Steatite	50
Copper	Pyrex glass	44.5
Stainless steel	Pyrex glass	44.0
Copper	Soda lime glass	40
Copper	Zirconium dioxide	40
Aluminum	Pyrex glass	39.0

F. Coaxial Cable for High Voltage

1. General Characteristics. Sheathed cable is used extensively for power line service, for interconnecting experimental apparatus, and for carrying high-voltage pulse currents in laboratory work. Special types of high-voltage coaxial cable designed for low inductance and minimum overall size are available for pulse work. Cables with voltage ratings from 10 kV to 400 kV may be obtained. Maximum electrostatic stress occurs at the outer surface of the inner conductor. Insulating material between the cylinders is usually solid flexible plastic, foamed plastic, or oil-impregnated paper.

In properly terminated coaxial cables, the magnetic field is constrained to the volume between the inner and the outer conductors, and there is almost no external force on the cable. Consequently, coax provides a good nonwhipping transmission line for pulsed high currents. A list of coaxial cables and their characteristics is given in Table II.

2. Air Gap Problem. Air must be excluded if the full-voltage capability of the cable insulating material is to be realized. Air gaps may be created through manufacturing flaws within the cable or produced when a coaxial cable is terminated. Figure 9 shows the problem that develops in coaxial cable when a layer of air is present.[4] The air layer forms the dielectric for one capacitor, and the solid insulation forms the dielectric for another. Because the two capacitors are in series across the high voltage, the voltage will divide with the largest voltage across the smaller of the two capacitors.

The smaller capacitor is usually the air dielectric capacitor, and the electric stress developed may exceed the air breakdown voltage. When this occurs, ionization of the air layer leads to a corona discharge current, erosion of the solid insulating material, and eventual failure of the cable.

In some cables a carbon-loaded semiconducting paper or polymer layer is applied at the conductor-insulation interface to avoid air gaps and to cover any sharp imperfections on the metal conductor. It also increases the apparent surface area of the inner conductor, thereby reducing the electric stress. Modern cable manufacturers use vacuum impregnation, heat treatment, and special extrusion techniques to produce reliable cables. Thick oil or grease may be used to displace air in fabricating some types of cable.

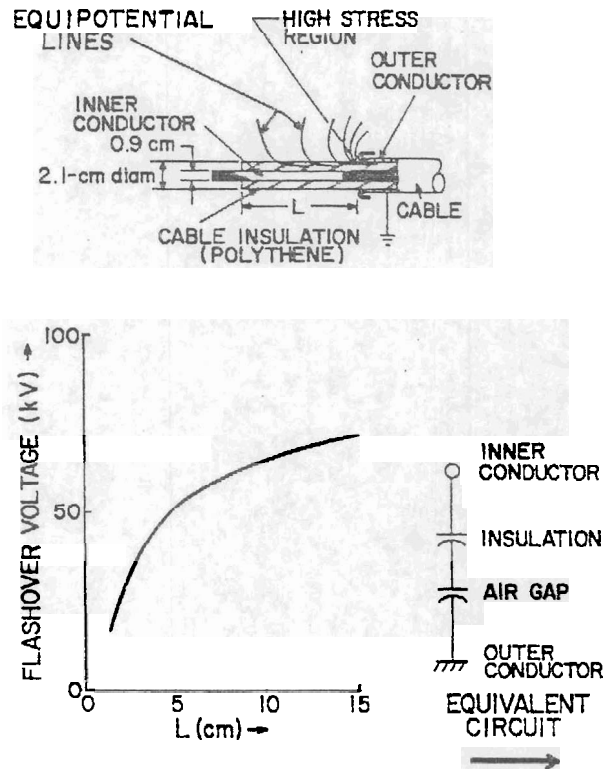


Fig. 9.
Air gap created by simple method of terminating a high-voltage cable can cause flashover. See App. C for more detail and information on designing graded terminations.[5]

3. Terminating. The air gap problem returns when the cable must be terminated. When the outer conductor is peeled back to make a connection, an air gap is created, as shown in Fig. 9. No matter how far back the outer conductor is removed, there is always a high-stress region where the braid leaves the insulation. The cable is likely to fail at this point well below its rated voltage. Specially designed materials and procedures are employed to exclude air from the gap and distribute electrical stress on the surrounding air. The theory behind these procedures is too complex for description here but can be found in Appendix C. Kits of premolded rubber shapes, conductive tape, paper, and grease or oil are sold with instructions for proper application to all sizes of high-voltage cable.

TABLE II
SOME MEASURED CHARACTERISTICS OF COAXIAL CABLES[c]

Type	Inductance[a] (nH/ft)	Resistance[a] (ohms/ft)	Capacitance (pf/ft)	Average Insulation Thickness (in.)	V^b (kV)
Solid Center Conductor Cables					
RG213/u (RG8/u	104	3.7	29.8	0.104	25
RG19/u	86	0.97	29.5	0.330	95
20-P2 BICC	35	1.9	129	0.050	25
RG217/u (RG14/u)	95	2.0	30	0.121	30
RG218/u (RG17/u)	86	1.1	29.5	0.242	70
Braided Center Conductor Cables					
8/59 (14/13)	50	4.8	65	0.067	25
8/142	55	3.9	40	0.070	30
Type 4 (P14-4)	26	3.1	120	0.036	20
17/14	36	1.1	78.2	0.110	50
17/14 HV Graded	47	1.1	75.5	0.140	60
19/14	49	-	51.7	0.225	95
19/14 HV Graded	54	0.97	53.5	0.225	95
19/17	17	0.71	136	0.100	55
YK198 (Belden)	28	2.3	110.5	0.048	25

[a]Data taken in the frequency range 12-64 kHz.

[b]This value is calculated and represents the voltage on the cable that gives a maximum field (E_m) equal to 250 kV/cm (25 MV/m).

[c]Reference G. P. Boicourt, "Electrical Characteristics of Coaxial Cable," Los Alamos Scientific Laboratory report LA-3318 (1965).

For practical work in the laboratory the graph of flashover voltage vs peel-back length for the 100-kV cable shown in Fig. 9 can be used to estimate the voltage a given cable will withstand when terminated in air. Cables used at peak voltages over 50 kV should be terminated with a stress cone kit or by some other method that relieves the field concentration in the surrounding air. One method commonly used on large laboratory equipment is immersion of the entire cable termination in an oil bath as shown in Fig. 6.

G. High-Voltage Capacitors

1. Shock Hazard. Any capacitor charged to 300 V with a stored energy of 30 J or more is considered lethal. At an operating level of 10 kV, a 0.2-μF capacitor contains 10 J and must be respected. Energy storage capacitors range from 1 to 100 F and operate between 3 and 100 kV. Stored energy is usually between 100 and 3000 J per capacitor. Table III shows the energy stored in capacitors for several sizes and charging voltages.

TABLE III
ENERGY STORED IN CAPACITOR

Capacitors (μF)	Joules @ V = 10kV	20kV	50kV	100kV
0.1	5	20	125	500
0.2	10	40	250	1 000
0.5	25	100	625	2 500
1	50	200	1 250	5 000
2	100	400	2 500	10 000
5	200	1 000	6 500	25 000
10	500	2 000	12 500	50 000
20	1 000	4 000	25 000	100 000
50	2 500	10 000	62 500	250 000
100	5 000	20 000	125 000	500 000

2. Mechanical Damage Hazard. A capacitor charged to the 100-J level has available energy equivalent to a 22-caliber rifle bullet and can do significant damage. The energy storage capacitors are designed for low internal inductance and can produce peak discharge currents of 100 kA or more. The energy released in a short-circuit discharge can cause explosion, fire, and serious injury to unprotected personnel.

3. Handling Energy Storage Capacitors. Strict technical and administrative procedures should be established for people working with high-voltage energy storage capacitors. These innocent-looking devices can store a lethal charge indefinitely, even when completely disconnected. Some types can generate an appreciable charge from relaxation of internal dielectric stress after they are discharged and removed from service. Capacitors with plastic dielectric are especially prone to this. Appendix D gives measured charge recovery data on several energy storage capacitor types. All out-of-service energy storage capacitors must be kept short-circuited with a metal strap or heavy wire at all times.

Special care must be taken when defunct energy storage capacitors are opened for examination. Large capacitors have been known to fail in a manner that leaves one or more foil packs isolated and charged within the unit. This condition is an unexpected shock hazard to anyone cutting into the capacitor, even though a shorting strap is connected to the unit's terminals.

H. High-Voltage Resistors

1. Solid Type. Specially designed resistors are required in circuits operating at voltage levels higher than a few kv. Ordinary carbon resistors

used in electronic work will not do the job. Wire-wound resistors have been used in some applications, but difficulties with corona discharge and heat dissipation favor the use of a deposited resistive film on a ceramic substrate. Resistance values from 1800Ω to 20000 MΩ are available. See Tables E-I to E-IV in Appendix E.[6]

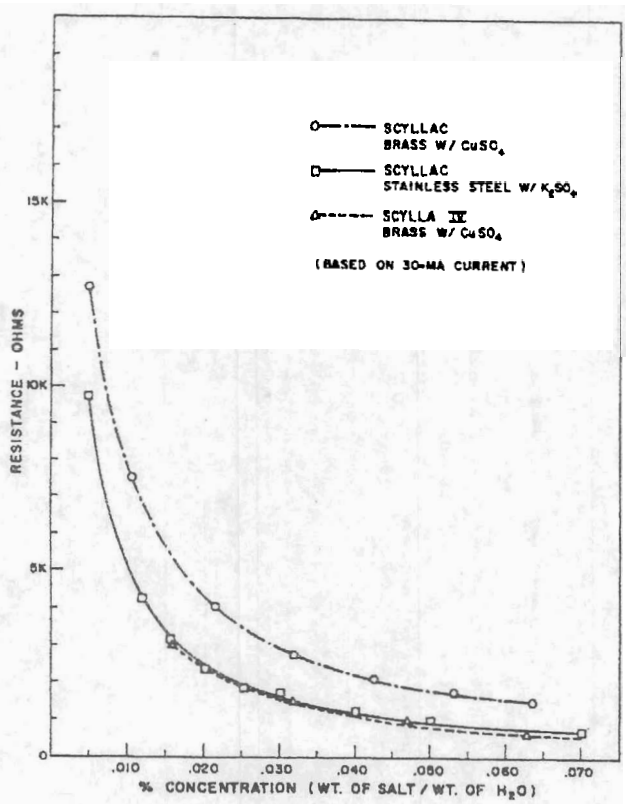
The composition-carbon or pyrolytic precision film is usually deposited as a helix on a ceramic tube. Careful handling is necessary to avoid scratching the surface or breaking the ceramic tube. Good cooling air flow is required to avoid hot spots during transient overload conditions. A power safety factor of two or more should be used in design; that is, a 2-W resistor where 1 W of heat dissipation is expected. Also, the manufacturer's recommended temperature derating factor should not be overlooked. The composition-carbon film resistor will safely dissipate rated power at 25°C but will dissipate only 1/2-rated power at 62.5°C and zero power at 100°C. These ratings are for sea level air pressure and must be further derated for higher altitudes. The pyrolytic-alloy resistors are rated for full-load operation at 85°C and derate to zero load at 150°C.

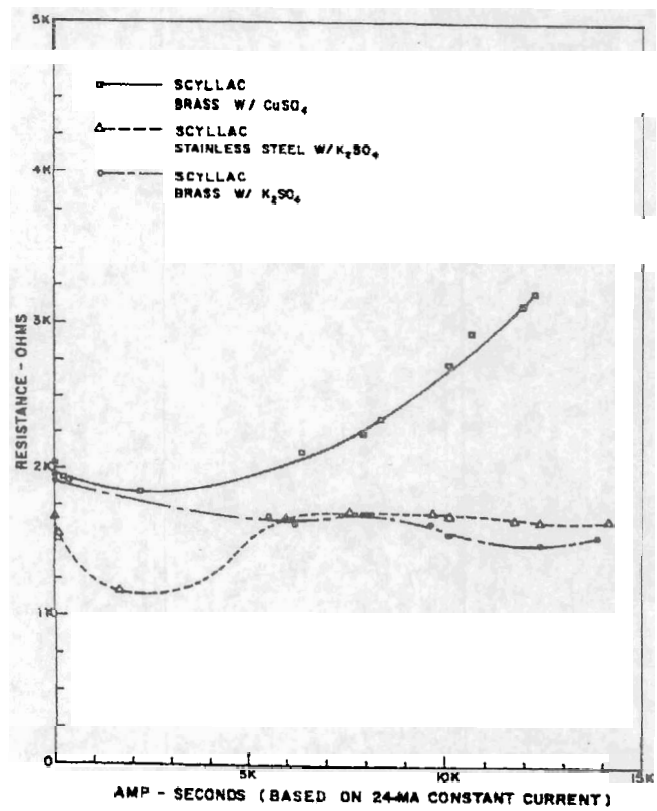
2. Liquid Resistors. When the high-voltage application requires periodic dissipation of a large amount of energy, such as dumping the charge from a capacitor bank, the liquid or electrolytic resistor should be considered. The liquid resistor has the advantage that a large heat capacity can be obtained by using a water-salt solution as the resistive material. One liter of water at room temperature (25°C) can absorb more than 300 kJ without boiling. Figure 10 shows some data obtained on a liquid resistor developed for the Scyllac thermonuclear experimental machine at the Los Alamos Scientific Laboratory (LASL).[7]

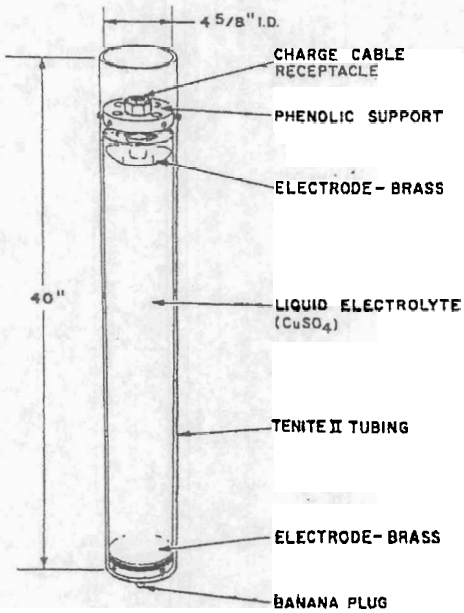
Problems with liquid resistors are resistance change from heating and applied voltage, a possible open circuit because of liquid evaporation or leakage, and lack of a ready commercial source. These resistors, as they are built at LASL, are large devices mounted vertically to facilitate adding electrolyte as needed. They should be mounted in clear view of the equipment operator.

I. Mechanical Considerations

1. Conductor Support. High-voltage apparatus usually requires rigid support for the current-carrying conductors to provide insulation and mechanical strength. Although operating currents may be small, the peak current pulse







SCYLLAC LIQUID RESISTOR

Fig. 10.
Scyllac liquid resistor. (Adapted from Ref. 7).

available under short-circuit conditions may be in the kilampere range, and large electromagnetic forces can develop between the conductors. Any high-voltage device storing or transmitting energy of 100 J or more should be built with conductors and supporting hardware designed to withstand the stress of a large current pulse.

2. Electromagnetic Force Between Conductors. The mechanical force between two current-carrying conductors is

$$F = \frac{2 \times 10^{-7} I_1 I_2 \ell}{d} \text{ N},$$

where d is in meters and

ℓ is in meters, or

$$F = \frac{4.5 I_1 I_2 \ell}{d} \times 10^{-8} \text{ pounds},$$

where

d = conductor spacing in inches (1 in. = 2.54 cm),

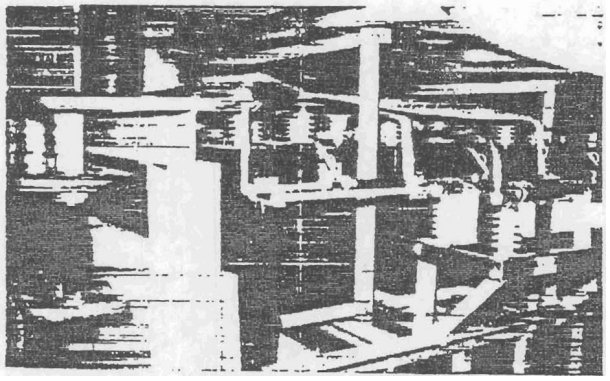
ℓ = conductor length in inches,

I_1 = current in the conductors in amperes, and

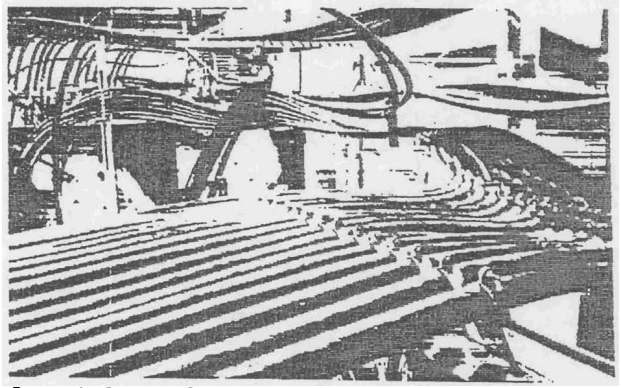
I_2 = current in the conductors in amperes.

As an example, the force is about 0.3 N/m (0.02 pounds per foot) for conductors spaced 6.35 mm (1/4 in.) carrying 100 A. If the short-circuit or pulse current is 10 kA, conductors spaced 6.35 mm (1/4 in.) apart will experience a force of 3154 N/m (216 pounds per foot) of length. This is force enough to break insulators, bend metals, and break connections not securely bolted.

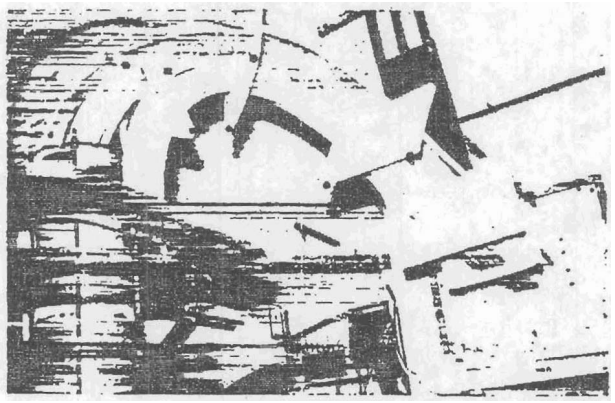
Short-circuit current depends on several factors, including stored energy available, source impedance, and how the short circuit is applied. In most situations the stored energy will be dissipated as heat in an arc at the point of contact, but the force tending to move the conductors can be destructive. The current and forces in any situation can be calculated if the circuit resistance and inductance are known. However, time is saved if you know that any high-voltage device with appreciable energy storage can produce destructive electromagnetic forces and that current busses must be built as strong as possible within the limits of economics and available space. Long loose wires draped from one component to another should be avoided, and flexible cable should be tied to the supporting rack or clamped down. Figure 11 shows several



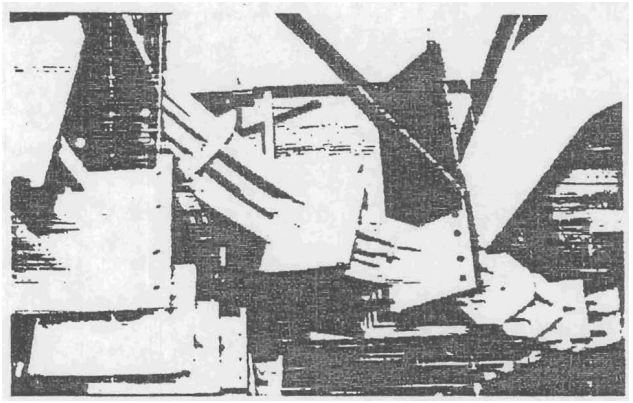
Open bus used on capacitor bank. Support structure is fiber glass.



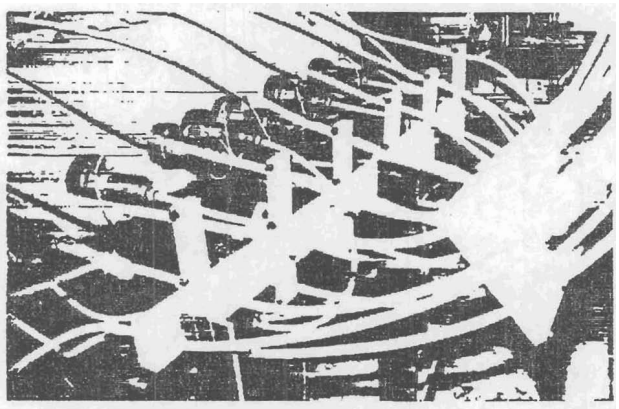
Coaxial cables parallel connected for 300-kV, 60-kA pulse on 8-beam CO_2 laser.



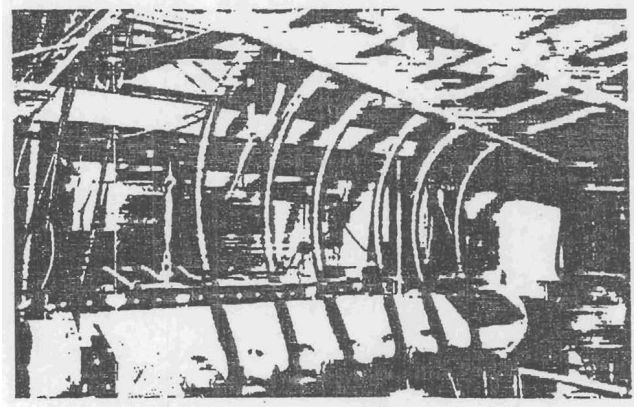
Cables leaving Marx bank 300-kV pulse generator. Note polyethylene support spacers and door interlock.



Insulated wire supported by polyethylene/phenolic supports. 300-kV, 16-kA pulse.



Insulated wire connections to in-line laser amplifier. Note castor oil-filled boots to prevent corona discharge at high-voltage terminal.



Coaxial cable termination on laser amplifier. 18-kV, 5-kA pulse.

Fig. 11.
Examples of high-voltage bus and cable installation.

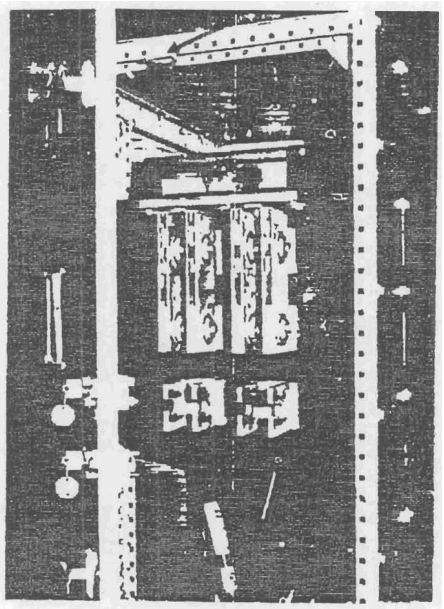
examples of well-built bus and cable installations. Appendix C contains design information on force between conductors in various configurations.

3. Equipment Enclosures. High-voltage equipment must be properly enclosed to protect operating personnel from electrical shock under normal operating conditions and from flying debris, burns, or smoke inhalation when things go wrong. High-voltage switchgear for power lines is usually mounted in sheet metal cabinets and placed inside locked fences well out of reach. The same precautionary measures should apply to laboratory equipment. If the experimental device is small, a sheet metal box with properly interlocked access doors is acceptable. When the equipment is large, walk-in enclosures are required with locked doors and interlock systems to shut off power and to discharge capacitors or other energy storage devices when a door is opened. The Kirk key interlock system is widely used and recommended for this service. Figure 12 shows typical equipment enclosures.[7]

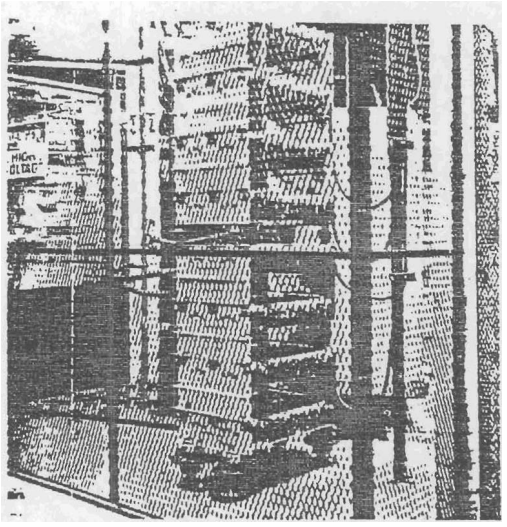
Polymethyl-methacrylate acrylic plastic, better known as Plexiglas or Lucite, is often used in sheet form for construction of experimental apparatus. These sheets are easily worked, have good insulating properties, and are transparent. They are useful as windows and protective covers on high-voltage equipment but should not be used as the major part of a large high-voltage equipment enclosure. This material will soften at 70 to 100°C and will burn slowly. Its insulating properties are degraded by mechanical stress or surface imperfections that may be produced by cleaning solvents. High-strength glass in a metal framework is recommended for large equipment enclosures where appearance and transparency are important.

4. Equipment Support Racks. High-voltage experimental work usually involves the stacking of capacitors, mounting of switches, and physical arranging of electronic equipment, such as power supplies and monitoring devices. Various types of standard equipment mounting racks may be purchased from manufacturers or fabricated locally to suit the need. Figure 13 shows some of the hardware used.[7] Usually the equipment support structure will be connected to the ground side of a current conducting system.

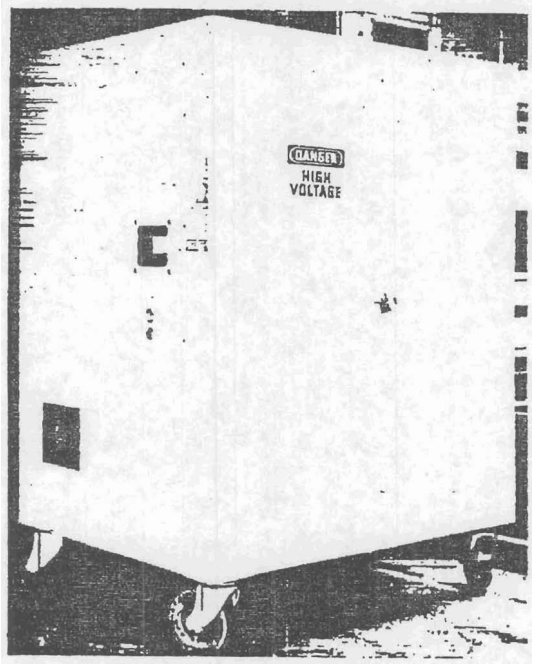
5. Nongrounded Racks. Special hazards exist when the rack is insulated from ground and operated at a high voltage. Such racks should be painted a distinctive color, identified by prominent caution signs, and treated as part of the high-potential network. Operating personnel should be instructed to use extra precautionary measures when working around these racks. No one



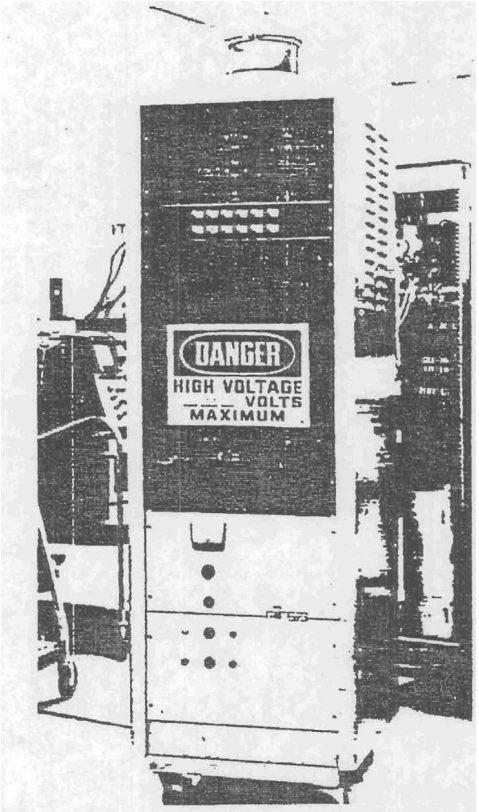
Magnet field reversing switch, Brookhaven National Laboratory, Upton, New York. Note key-operated and electrical interlocks on the access door.



Resistor bank used in the ripple filter circuit of the ring magnet supply, zero-gradient synchrotron, Argonne National Laboratory, Argonne, Illinois.

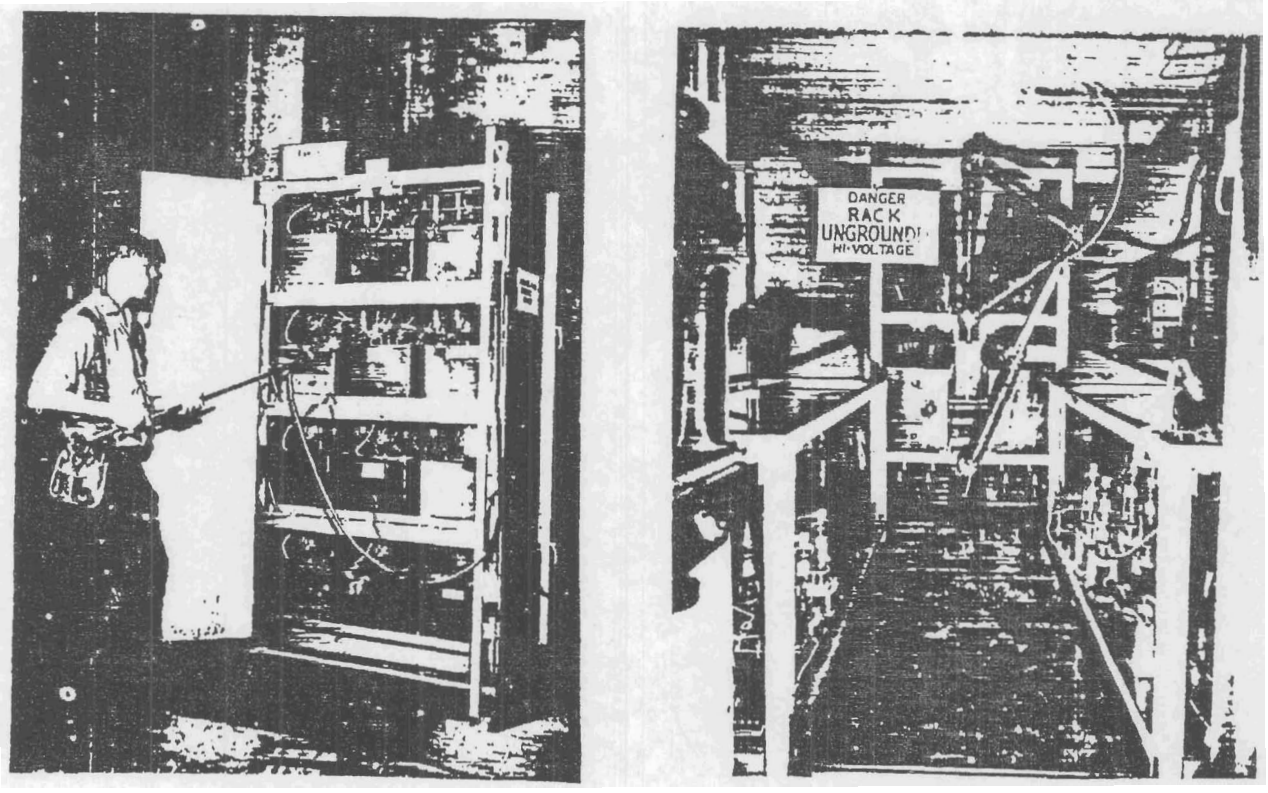


Enclosure for portable 35-kV, 25-kVA, rectifier power supply, Plasma Physics Laboratory, James Forrestal Research Center, Princeton, New Jersey. Note locked access doors, recessed voltmeter with plastic window and readily accessible main power circuit breaker.



Portable 20-kV power supply for experimental use. Zero-gradient synchrotron. Argonne Laboratory, Argonne, Illinois. Note warning lamp on top of cabinet.

Fig. 12.
High-voltage equipment enclosures with interlock systems, warning signs, etc.[8]



Capacitor bank, bevatron, Lawrence Radiation Laboratory, Berkeley, California. Twelve sets of five 1-μF, 25 000-V capacitors in parallel connected to output cables through high-voltage fuses. Bleeder resistors are provided and an automatic discharge relay operates when the bank is de-energized. Manual grounding is achieved by a grounding hook with current-limiting resistors in transparent high-strength tubes. Electrical interlocks are provided on the access doors.

Current-limiting and grounding resistors used with pulsed supply capacitor bank to provide RF heating plate supply, Plasma Physics Laboratory, James Forrestal Research Center, Princeton, New Jersey.

Fig. 13.
Typical equipment support racks.[8]

should touch or climb upon these racks until he has touched the rack with an appropriate grounding hook and attached a clamp-on grounding device permanently connected to the building ground system. Before removing the ground straps and returning the equipment to service, operating personnel should make

sure that crowbars, ladders, crane hooks, or other tools have not been left in contact with the rack.

III. HIGH-VOLTAGE SAFETY AND HAZARD CHECK LISTS

Before placing any new high-voltage apparatus into service, a thorough review should be made with the safety check list and list of hazards below.

Safety Check List

- Are written Operating Procedures posted at the control point?
- Are all involved personnel instructed and trained?
- Are written emergency procedures posted?
- Are lifesaving procedures posted?
- Are warning signs posted?
- Are all out-of-service capacitors strapped?
- Is there an overvoltage protective circuit for monocyclic operation?
- Are critical components easily monitored, both visually and by instruments?
- Are shorting hooks accessible for short-circuiting all capacitors?
- Are interlocks used at all equipment enclosure entrances?
- Are there adequate barricades against flak and flaming liquids?
- Has radiation shielding been considered?
- Have ground loops been eliminated?
- Are liquid levels in liquid resistors and oil baths easily checked?
- Has fire detection and extinguishing been provided for?
- Are enclosures grounded?

List of Hazards

Fire:

- An arc through plastic containers.
- Arcing across flammable dielectrics.
- Exploding capacitor (shorted capacitor absorbing charge from others in bank).
- Loose joints in ground plane conductors (can cause an arc in unexpected locations).
- Arcs between groups of capacitors (from timing errors).
- Fireballs from breakdown in oil.

Electric Shock:

- Metering circuits rising to a high voltage from malfunction.
- Instruments at high potential from an ungrounded rack or enclosure.
- Sneak paths in ground loops.
- Charge buildup on capacitors after discharge.
- Charged capacitors.
- Unstrapped, out-of-service capacitors.
- Instruments pulsed to high-voltage by inductance in ground circuits.
- Ungrounded enclosures.

Radiation:

- X ray and uv from high-energy discharges.
- X ray from high-voltage vacuum devices.

Other:

- Flying fragments from exploding capacitors or apparatus.
- Molten metal from arcs or short circuits.
- Toxic gas release from breakdown of dielectrics.

DESIGN OF SAFE ELECTRICAL EQUIPMENT FOR RESEARCH

PART 2. MARX GENERATORS AND CAPACITOR BANKS

ABSTRACT

General information on the construction and use of Marx generators and high-voltage capacitor energy storage banks is presented with emphasis on electrical safety.

I. MARX GENERATORS

The Marx bank, or modified Marx generator, is a commonly used source of high-voltage pulses. Commercially built machines are available in ratings from 15 kV at 50 J to 2 MV at 10 MJ. User-built machines are common in research laboratories. The basic circuit is shown in Fig. 14. Many modifications and variations of this circuit have been developed for special purposes such as pulse-charging capacitor banks, shock-heating plasma, pulsing lasers, and testing materials. The switches shown may be spark gaps, ignitrons, vacuum tubes, or solid-state devices depending on the service and voltage output required. When simple spark gaps are used, the charging supply is turned on and the voltage allowed to build up until one gap breaks down. All gaps will then be over-volted and will fire very quickly. The resulting discharge of all capacitors in series across the output terminals produces the desired pulse. Triggered (3-element) spark gaps and various mechanical arrangements of the capacitors are used to improve output pulse rise time. Reference 8 describes many variations of the basic circuit. The physical size of these devices ranges from portable units to large permanent machines (15 m tall) in high-voltage laboratories. Charging power sources usually run between 15-kV and 200-kV open circuit potential.

Operation of the Marx generator requires connection to the charging power supply for a time sufficient to charge all the storage capacitors (C_1, C_2, . . . C_n) to their rated voltage followed by triggering to produce the output pulse. When the gaps are fired all capacitors will discharge through the switches and the load. The output voltage is essentially n times the source voltage (V), and the design requires components and containment rated for the high voltage (nV).

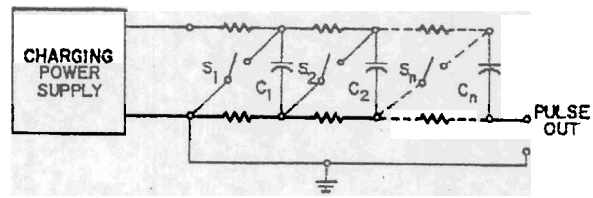


Fig. 14.
Basic circuit for Marx-type pulse generator . Switches may be spark gaps, vacuum tubes, or solid-state electronic devices.

The Marx generator is inherently a trouble-free, high-voltage pulse supply as long as it is functioning properly. Because the energy storage capacitors are connected in parallel by the charging resistors or inductors and the charging source should contain a bleeder resistor, there will normally be zero charge on the capacitors when the supply is off. However, if the bank fails to fire, one or more of the capacitors can be left charged and ready to yield a lethal shock to the person troubleshooting the apparatus. Precautions must be taken during design and construction to minimize component failures and to provide a safe means of discharging the individual capacitors before troubleshooting. If one of the resistors should open, the bank will not fire, and one or more capacitors will be left in the charged condition. The operator must then make sure each and every capacitor in the bank is discharged before proceeding to locate and repair the open circuit. To assure that every capacitor is discharged, he must short-circuit the terminals of each capacitor at the capacitor.

Figure 15 shows a shorting hook designed for a typical capacitor commonly used in Marx generators and energy storage banks. The builder should design appropriate shorting hooks for the capacitors used in his particular bank. When very large capacitors are discharged, a reliable current-limiting resistor should be built into the shorting hook to avoid melting or exploding the shorting hook.

Some of the smaller Marx banks are constructed so that the capacitor terminals are impossible to reach. In these cases the method shown in Fig. 16 can be used to bring the individual capacitor terminals out to a safe and

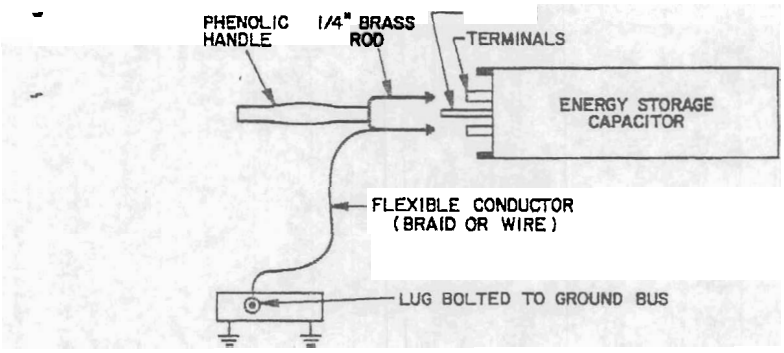


Fig. 15.
Shorting hook for one type of energy storage capacitor. Brass rod provides a low-resistance "hard" discharge path. With very large capacitors, a resistor may be incorporated in the discharge path to provide a current-limiting discharge or "soft dump" characteristic.

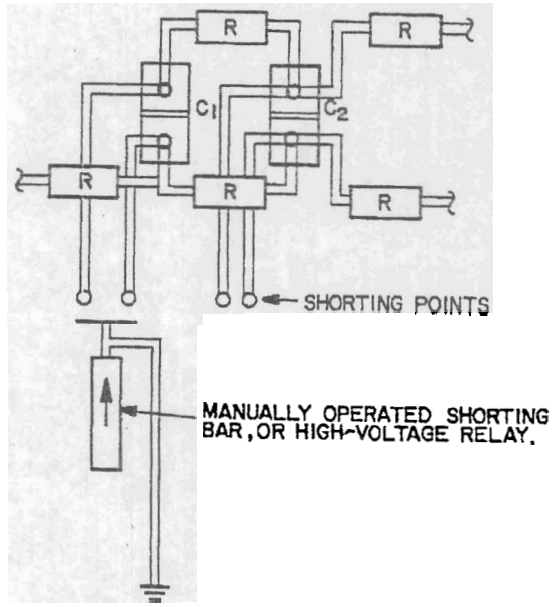


Fig. 16.
Inaccessible capacitors in the Marx generator can be connected to shorting points for grounding and discharge by manually or automatically operated devices.

convenient location for shorting and grounding. High-voltage relays energized by the charging power supply can also be incorporated into the system design to automatically short-circuit each capacitor when the power supply is shut off. However, these relays should not be relied on as the final hard short before equipment servicing. Conductors used between the capacitor terminals and shorting point <u>must</u> <u>not</u> carry the normal output pulse current. These conductors must also be heavy enough to carry the short-circuit current of the capacitor.

Special problems exist when the modified Marx bank is used to pulse-charge large capacitor banks. Here the Marx generator provides a convenient link between a power source of 10 to 20 kV and the storage capacitor bank operating at perhaps 100 kV or more. The Marx bank stores charge at a relatively low voltage until it is transferred to the high-voltage capacitor bank. Inductors are used in place of the resistors shown in Fig. 14. The charging power source is connected to the Marx generator by a switch that is opened when the Marx bank capacitors have reached their rated voltage. With the

switch open, there is no discharge path for the Marx bank capacitors except the normal path to the load. In this case, the Marx bank may be left with a partial charge on each capacitor at the end of the pulse charge. To alleviate this condition, a bleeder resistor can usually be designed with a discharge time constant that will not adversely affect the operation. Alternatively, a time delay relay can be used to connect a bleeder resistor at a set time after the switch opens.

II. PARALLEL CAPACITOR ENERGY STORAGE BANKS

These banks are composed of many large capacitors charged and discharged in parallel. Energy stored is usually between 0.1 MJ and 10 MJ. High currents and fast pulse rise times require low-inductance transmission systems (usually parallel plate lines or coax cables in parallel) and low-inductance switches. Crowbar switches may be used to prolong the current pulse to the load beyond the natural period of the source-load circuit.

Design considerations must include the possibility of

(1) high-voltage reversal on the capacitors in case of crowbar switch failure,

(2) dumping a large amount of energy into a shorted capacitor,

(3) similar dumping through firing malfunctions, and

(4) high mechanical stresses on the load current conductors.

The charging power supply is often a monocyclic network and rectifier capable of charging the capacitor bank to several times its rated voltage (Fig. 17). The monocyclic network is essentially a series resonant circuit tied to the ac power line that produces a constant current output. The design of these systems must assure that the load is never removed from an energized monocyclic network. If a switch or some other connector opens before the monocyclic network is turned off, dangerously high voltages will be produced. Fast acting over-voltage detectors must be used at the rectifier output to sense such a condition and to trip the ac circuit breaker feeding the monocyclic network.

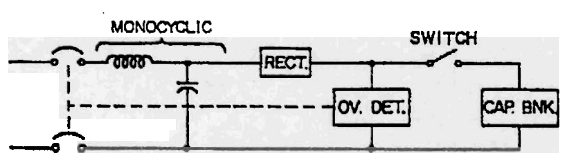


Fig. 17.
Monocyclic network used to charge capacitors (single phase). See Appendix D for further discussion.

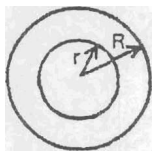
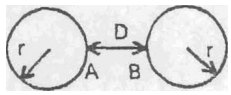
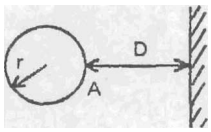
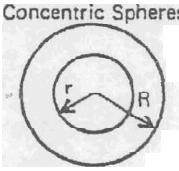
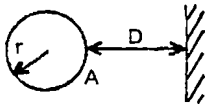
The use of a series switch between a monocyclic network-type power supply and the capacitor bank increases the hazards in two ways. First, the power supply becomes a potential source of extremely high voltage if the switch opens before the monocyclic network is de-energized. Second, the capacitor bank is isolated from the power supply, has no discharge path back through the power supply, and can thus be left in a charged condition.

Bleeder resistors (as described for Marx bank capacitors) can be applied to storage banks also. Some type of automatic discharge system must be included in large energy storage banks because the capacitors can generate a charge when left with terminals open-circuited (see Appendix D). All of the precautions discussed in Part I, Sec. G, should be observed in the design and construction of energy storage banks. "Elements of Energy Storage Capacitor Banks," reproduced in Appendix D, contains information and practical suggestions that should be considered in designing energy storage banks.

APPENDIX A

ELECTRIC STRESS IN TYPICAL HIGH-VOLTAGE CONFIGURATIONS

This material is adapted from Culham Laboratories Design Information Manual, Vol. 1, Index No. 110, by P. J. Rogers.

	Electrode Configuration	E_m = Maximum Electric Stress f = Field Divergence Factor = Max. Stress/Mean Stress	
CYLINDERS	Concentric Cylinders  	E_m occurs at surface of inner cylinder $E_m = \frac{V}{r \ln \frac{R}{r}}$ $f = \left(\frac{R}{r} - 1\right) \Big/ \ln \frac{R}{r}$	Optimum ratio* $\frac{R}{r}$ and corresponding max. stress $\frac{R}{r} = e$ $E_m = \frac{V}{r} = \frac{Ve}{R}$
	Equal Parallel Cylinders  	E_m occurs at points A & B $E_m = Vf/D$ $f = \frac{\sqrt{\left(\frac{D}{r}\right)^2 + 4\frac{D}{r}}}{2 \ln \left[\frac{D}{2r} + 1 + \frac{1}{2}\sqrt{\left(\frac{D}{r}\right)^2 + \frac{4D}{r}}\right]}$	
	Cylinder/Plane  	E_m occurs at point A $E_m = Vf/D$ $f = \frac{\sqrt{\left(\frac{D}{r}\right)^2 + \frac{2D}{r}}}{\ln \left[\frac{D}{r} + 1 + \sqrt{\left(\frac{D}{r}\right)^2 + \frac{2D}{r}}\right]}$	
SPHERES	Concentric Spheres  	E_m occurs at surface of inner sphere $E_m = \frac{VR}{r(R-r)}$ $f = \frac{R}{r}$	Optimum ratio* $\frac{R}{r}$ and corresponding max. stress $\frac{R}{r} = 2$ $E_m = \frac{2V}{r} = \frac{4V}{R}$
	Equal Spheres	E_m occurs at points A & B $E_m = Vf/D$ $f = \frac{\frac{D}{r} + 1 + \sqrt{\left(\frac{D}{r} + 1\right)^2 + 8}}{4}$	
	Sphere/Plane  	E_m occurs at point A $E_m = Vf/D$ $f = \frac{\frac{2D}{r} + 1 + \sqrt{\left(\frac{2D}{r} + 1\right)^2 + 8}}{4}$	

*Gives the smallest value of R for specified values of V and E_m

Fig. A-1.

Electric stress formulas. Electric stress E at any point in a dielectric between two electrodes, across which a voltage V is applied, is the force on unit charge placed at the point. It is equal to the voltage gradient, i.e., E = -dv/dx. E is measured in kV/cm.

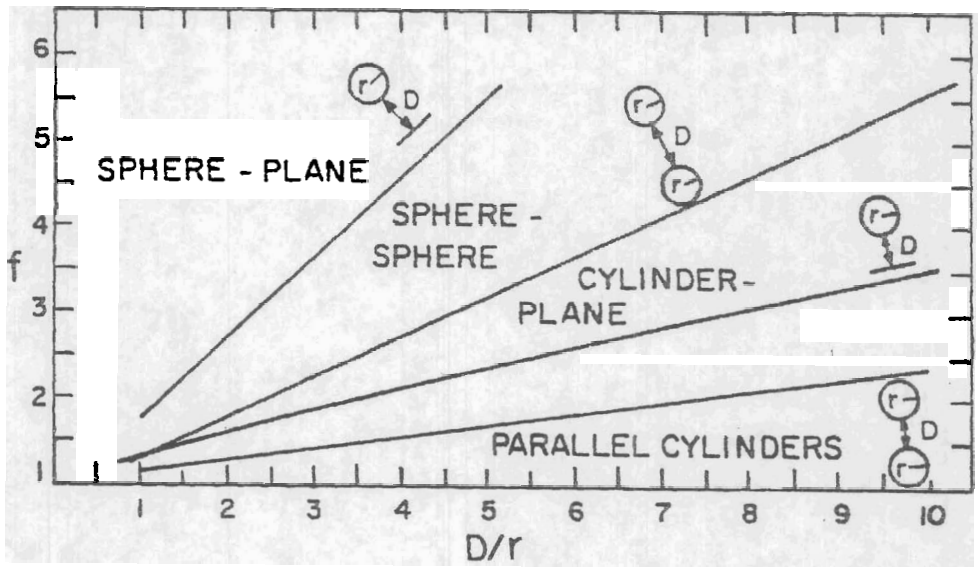


Fig. A-2.
Dependence of the ratio $f = \frac{\text{maximum stress}}{\text{mean stress}}$ on electrode configurations.

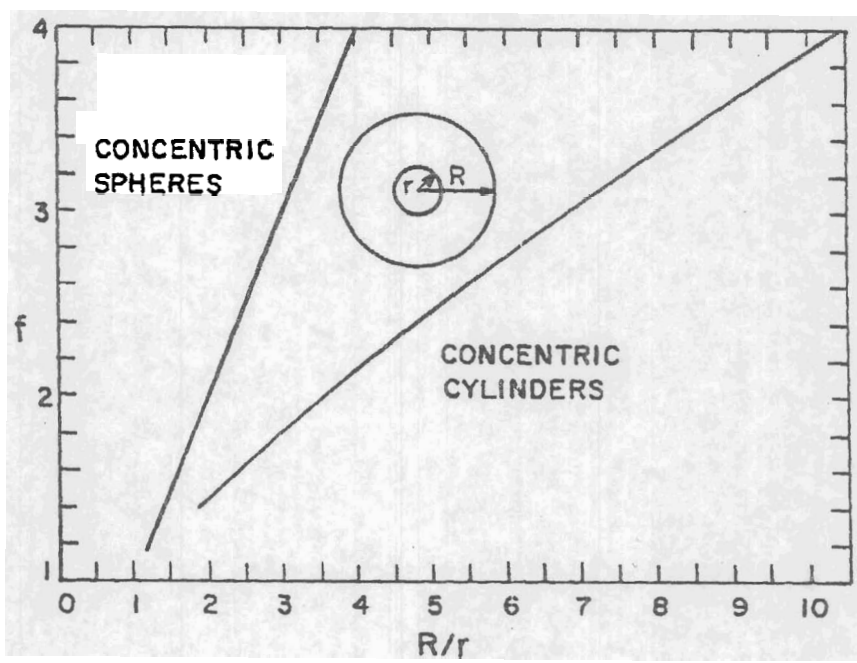


Fig. A-3.
Dependence of the ratio $f = \frac{\text{maximum stress}}{\text{mean stress}}$ on $\frac{R}{r}$ for concentric cylinders and spheres.

APPENDIX B

INSULATING MATERIALS

TABLE B-1

APPROXIMATE RATINGS FOR INSULATING MATERIALS

Material	Dielectric Strength V/mil	Dielectric Strength kV/cm	Relative Dielectric Constant @60 Hz	Temperature Limit (°C)
Gases				
Air (760 mm Hg, 25°C)	75	29.5	1.0	
Sulfur hexafluoride (SF_6)	197	69	1.0	150
Freon 12 (CCl_2F_2)	180	71	1.0	
Hydrogen	45	15	1.0	
Carbon dioxide	71	28	1.0	
Nitrogen	79	31	1.0	
Helium	11	4.3	1.0	
Liquids				
Water (resistance = 40 kΩ between points 1 cm apart)	144	57	78	100
Mineral oil	1000	394	2.3	
Transformer oil	1000	394	2.2	120
Castor oil (dielectric strength measured by L Div., LASL)	84	213	4.8	85
Silicone oil	1000	394	2.8	250
Transil oil	300	118	2.2	
Parafin wax	1000	394	2.2	60
Askarels (nonflammable, toxic)	900	350	4.5-4.7	
Solids				
ABS	350-500	138-197	2.4-3.8	100
Acrylics (plexiglas, Lucite)				
(Thin, up to 25 mils)	500-700	197-276	2.2-3.2	60-90
(Bulk, over 25 mils)	200-300	79-118		
Cellulose acetate	250-600	98-236	3.2-7.0	60-90
Cellulose nitrate	300-600	118-236	6.4	60
Epoxy (glass filler)	300-400	118-157	3.5-5.0	150-260
Epoxy encapsulant	250-400	98-157	3.5-5.0	150-260
Fluorocarbon (FEP)	500-600	197-236	2.1	200
Melamine	250-430	98-169	6.5-8.4	100-120
Nylon	400-580	157-228	3.2-4.7	80-150
Paper (Kraft)	500-1000	197-394		85-100

APPROXIMATE RATINGS FOR INSULATING MATERIALS

TABLE B-1 (cont)

Material	Dielectric Strength V/mil	Dielectric Strength kV/cm	Relative Dielectric Constant @60 Hz	Temperature Limit (°C)
Phenolic				
Mica filler	350-400	138-157	4.2-5.2	120-150
Glass filler	140-400	55-157	4.5-7.0	175-290
Polycarbonate	450	177	3.0-3.5	140
Polyethylene	1000	394	2.3	70
Polystyrene				
General purpose	500-700	197-276	2.4-2.6	65-80
Thin film	1000	394	2.3	65
High impact	300-600	118-236	2.4-3.8	60-80
Polyvinylchloride (PVC)	250-800	98-315	3.5-4.5	55-65
Silicones	200-400	79-157	3.2-6.3	260-400
Silicone varnish	1000-2000	394-787	3.0	250
Mica (Ruby)	500-1000	197-394	5.4	200
Ceramics				
Magnesium silicate	200-300	79-118	5.4-7.0	150-200
Alumina	40-160	16-63	4.5-8.4	
Titania rutile	100-150	39-59	70-90	120
Porcelain	40-400	16-157	6.0-8.0	
Titanate	100	39	120	
Steatite	200-400	79-157	5.5-7.5	
Glass				
Soft, lead-soda	500	197	6.5-6.8	200
Hard, borosilicate	500	197	4.0	200
Teflon (PTFE)				
Thickness 12 mils	1000-2000	394-787	2.0	285
Thickness 12-18 mils	400-500	157-197	2.0	260
Plastic tubing				
Polyethylene	850	335	2.5	110
Synthetic resin, Vartex No. 54	600	236		80
Vinyl, type VS	700-800	275-315		105
Fiber	150-300	20-118		105
Polyester film (2-mil Mylar)	3000-4000	1180-1575	2.9-3.7	100
Quartz, fused	410	161	3.8	1660
Resinous sheet and tape, heat sealing	1000-1800	394-709		150
Rubber, hard	470	185	2.8	
modified	620	244	2.4-2.7	

APPROXIMATE RATINGS FOR INSULATING MATERIALS

TABLE B-1 (cont)

Material	Dielectric Strength V/mil	Dielectric Strength kV/cm	Relative Dielectric Constant @60 Hz	Temperature Limit (°C)
Shellac	200-600	79-236		
Vinyl chloride	600-1000	236-394	3.5-4.5	
Combined materials				
Adhesive tapes				
7 mil glass cloth	3000[a]			130
11 mil cotton cloth	2500-3000[a]			120
9.5 mil Acetate	7000[a]			120
2.5 mil Mylar	5500[a]			120
3.5 mil Mylar	8000[a]			120
6 mil Silicone varnish treated glass cloth	5500[a]			320
7 mil vinyl, pressure sensitive	9000[a]			
10 mil vinyl, pressure sensitive	10 000[a]			
20 mil vinyl, pressure sensitive	15 000[a]			
Laminated plastic				
Sheets 1/32" to 1"	100-700	39-276	4.0-6.8	90-205
Silicone-glass laminated				
Plastic sheets	160-580	63-228	3.7-4.2	205
Polyester laminates				
10 mil	850-1300	335-512	4.2-5.1	105-150
40 mil	550-875	217-345	4.2-5.1	105-150
Varnished tubing and sleeving	1500-7000	590-2756		220
Silicone rubber-glass				
Cloth tubing, grade A	1500-8000	3150		200
Silicone resin-coated glass cloth				
4 mil	900	354	2.9-3.5	250
10 mil	750	295	2.9-3.5	250
Varnished cambric				
5 to 15 mils	1000-1300	394-512		
Varnished canvas duck				
16 mil	800	315		
40 mil	400	157		
Varnished glass cloth				
3 mil	1800	709		130
30 mil	500	197		130

[a] Dielectric strength shown is total withstand for thickness given. These tapes are heat curing.

APPROXIMATE RATINGS FOR INSULATING MATERIALS

TABLE B-1 (cont)

Material	Dielectric Strength V/mil	Dielectric Strength kV/cm	Relative Dielectric Constant @60 Hz	Temperature Limit (°C)
Varnished Silk				
2 mil	1800	709		
8 mil	1500	590		
Varnished Paper				
1 mil	2000	787		
10 mil	1000	394		
15 mil	500	197		
Teflon Coated Glass Cloth				
3 mil	290	114	2.0	180
10 mil	150	59	2.5	180

NOTE: Values given in this table are taken from Refs. 10-13 listed at the end of the Appendixes and from other standard reference handbooks.

TABLE B-II

COMPARATIVE TRACKING INDICES OF SOME INSULATING MATERIALS

Resin	Filler or reinforcement	CTI
Phenolic	Paper cotton fabric, nylon fabric, wood, rubber	80-120
Polycarbonate		
Phenolic	Asbestos paper or fabric, glass fabric	
Polyphenylene oxide		120-220
Phenolic-epoxide	Mica	
Epoxide*	Silica and alumina or glass fabric or fiber	
Butyl rubber-PVC copolymer		
Alkyd	Mineral or glass fabric	
Polystyrene		
Various polyesters	Glass fabric	220-300
Silicon resin	Glass Fabric	
Polyamide film		
Melamine	Glass or asbestos fiber	
Urea formaldehyde	Wood flour	
Diallyl phthalate	Glass fiber	
Nylon	Glass fiber	
Melamine	Glass fiber	300-500
Alkyd	Mineral	
Butyl rubber		
Rigid PVC		
Urea formaldehyde		
Epoxide	Asbestos	500-700
Silicone rubber		
Acetal resin		
Polypropylene		
Polyester	Glass fiber	
Polymethyl methacrylate		greater than 700
Polyethylene	Unfilled or carbon filled	
Polytetrafluorethylene		

*This table does not include alicyclic epoxide resins with hydrated alumina filler, which have a very high CTI.

Measured according to BS 3781. Based on data provided by the Electrical Research Association and by GEC Ltd. From Ref. 2, p. 78.

APPENDIX C

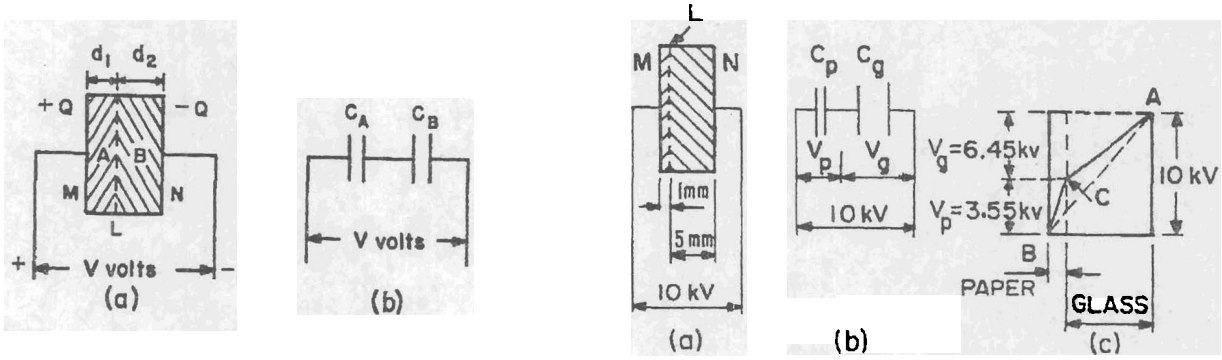
CALCULATION OF ELECTRICAL AND MECHANICAL STRESS

I. ELECTRIC STRESS IN COMPOSITE DIELECTRICS

If two different-sized capacitors are connected in series across a voltage source, each will receive the same quantity of charge (Q). The voltage (V) across each capacitor will be $\frac{Q}{C}$. Thus, the smaller capacitor will be charged to a higher voltage than the larger capacitor. When two metal plates are separated by two layers of insulating material, the same kind of voltage division is observed. Figure C-1 shows a capacitor formed by two metal plates, M and N, with two layers of dielectric material, A and B, in between. Because the potential drop in a dielectric equals potential gradient times thickness, all points on surface L are at the same potential. If a thin metal foil were inserted between the dielectric layers, it would not alter the electric field in the dielectrics. Thus, the assembly can be treated as two capacitors connected in series. The size of each capacitor will be determined by the dielectric constant and thickness of the material used.

The following example calculation (Fig. C-2) shows the electric stress or potential gradients produced when a layer of glass plus a layer of paper are used as insulation between two metal plates. Assume that each metal plate is 40 cm by 40 cm and the space between is filled with a glass plate 5-mm thick and a paper layer 1-mm thick. The dielectric constant (K_g) for glass is 5.5, and K_p for paper is 2.0.

Neglecting any fringing flux, calculate the capacitance and the potential gradient in each dielectric in kilovolts per millimeter resulting from a



potential difference of 10 kV between the plates. From the formula for parallel plate capacitors,

$$C = \frac{8.854\ aK \times 10^{-12}}{d} \text{ farads (F)}$$

where a = plate area in square meters, d = spacing in meters, and
K = dielectric constant of material between the plates.

$$\text{Then } C_p = \frac{8.854 \times 0.4 \times 0.4 \times 2 \times 10^{-12}}{0.001} = 2.833 \times 10^{-9} F$$

$$\text{and } C_g = \frac{8.854 \times 0.4 \times 0.4 \times 5.5 \times 10^{-12}}{0.005} = 1.559 \times 10^{-9} F.$$

Because C_p and C_g are in series across 10 kV, the voltage across the paper is

$$V_p = \frac{10 \times 1.559}{2.833 + 1.559} = 3.548 \text{ kV, and the voltage across the glass is}$$

$$V_g = \frac{10 \times 2.833}{4.392} = 6.452 \text{ kV.}$$

These voltages are represented graphically in Fig. C-2 (c).

$$\text{Potential gradient in the paper dielectric} = \frac{3.548}{1} = 3.548 \text{ kV/mm.}$$

$$\text{Potential gradient in the glass dielectric} = \frac{6.452}{5} = 1.290 \text{ kV/mm.}$$

The electric stress on the thin layer of paper is much more severe than the electric stress on the glass.

If the paper is removed, a .001-m air gap is introduced, then

$$C_{air} = \frac{8.854 \times 0.4 \times 0.4 \times 1 \times 10^{-12}}{0.001} = 1.416 \times 10^{-9} F,$$

$$C^g = 1.559 \times 10^{-9} \text{ as before,}$$

$$V_{air} = \frac{10 \times 1.559}{1.416 + 1.559} = 5.24 \text{ kV, and}$$

$$V_g = \frac{10 \times 1.416}{1.416 + 1.559} = 4.76 \text{ kV.}$$

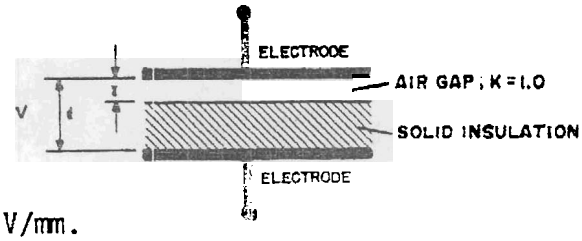


Fig. C-3.
Stress intensification in an air gap.

Electric stress in the air gap = 5.24 kV/mm.
Electric stress in the glass = 0.95 kV/mm.

This simple example shows how electric stress has been increased in the 1-mm air space by changing the dielectric material from paper to air. When equal thickness dielectrics are in series, electric stress or potential gradient will be larger in the medium of lower dielectric constant. Because air has a dielectric constant of 1.0 and most solid insulators have a dielectric constant between 2 and 8, an air gap will generally be severely stressed and a breakdown or arc may be produced. In Fig. C-3, the stress in the air gap is given by

$$S_{air} = \frac{V\,K_{solid}}{d + X(K_{solid} - K_{air})},$$

$$\text{or } 10 \text{ kV} \quad \frac{5.5}{6 + 1(5.5-1.0)} = 10(.5238) = 5.24 \text{ kV/mm}$$

for the example problem.

When the gap distance X is much smaller than the plate separation d, the stress in the air gap approaches

$$S_{air} = \frac{V\,K_{solid}}{d} \quad \text{or } \frac{10 \times 5.5}{6} = 9.16 \text{ kV/mm.}$$

When two conductors are separated by solid insulating material, air must be excluded because nearly all of the voltage applied could appear across the air gap.

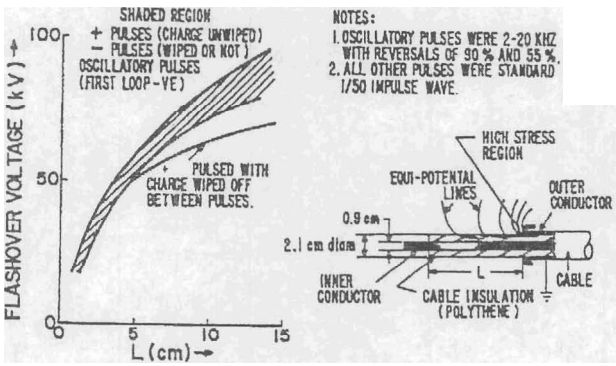


Fig. C-4.
Flashover characteristics of a 100-kV coaxial cable terminated by peeling back the outer conductor.

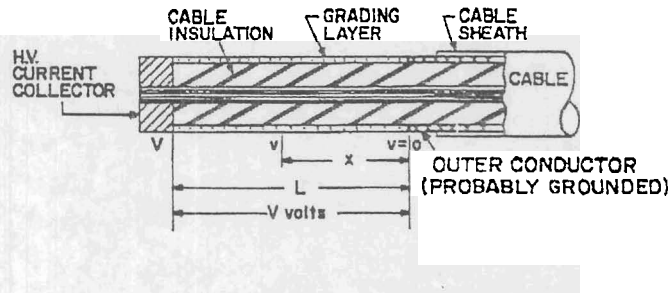


Fig. C-5.
Basic grading arrangement.

II. HIGH-VOLTAGE COAXIAL CABLE TERMINATIONS

A. Introduction

The need for effective cable termination design is illustrated by Fig. C-4. This figure shows the simplest of terminations: the outer conductor peeled back to a suitable length. The cable is a 100-kV pulse type, but the lowest curve on the graph shows that a positive pulse will make the termination flashover well below 100 kV regardless of the peel-back length. The cause is excessive electric stress in the air at the outer (grounded) conductor, where the equipotential lines are concentrated.

B. Voltage Grading

Figure C-5 shows a coaxial cable peeled back to a suitable length L with a semiconductive layer of material added between the cable sheath and a metal current collector at the cable's end. This grading layer can be either a liquid (water, mineral oil, or castor oil) or a solid.

The termination can be represented as a chain of capacitors as shown in Fig. C-6. Here the high voltage will be divided across the string of capacitors, and the net effect is to spread out the equipotential lines shown concentrated in Fig. C-4. The graphs in Fig. C-6 show calculated values of potential and stress distribution (from transmission line theory) for sine wave voltages. The ungraded termination has 80% of the total applied voltage acting on the air adjacent to the first 10% of the peel-back length. The 0.64-cm layer of water assumed for the graded case improves the distribution to 80% of the total voltage over 60% of the total length.

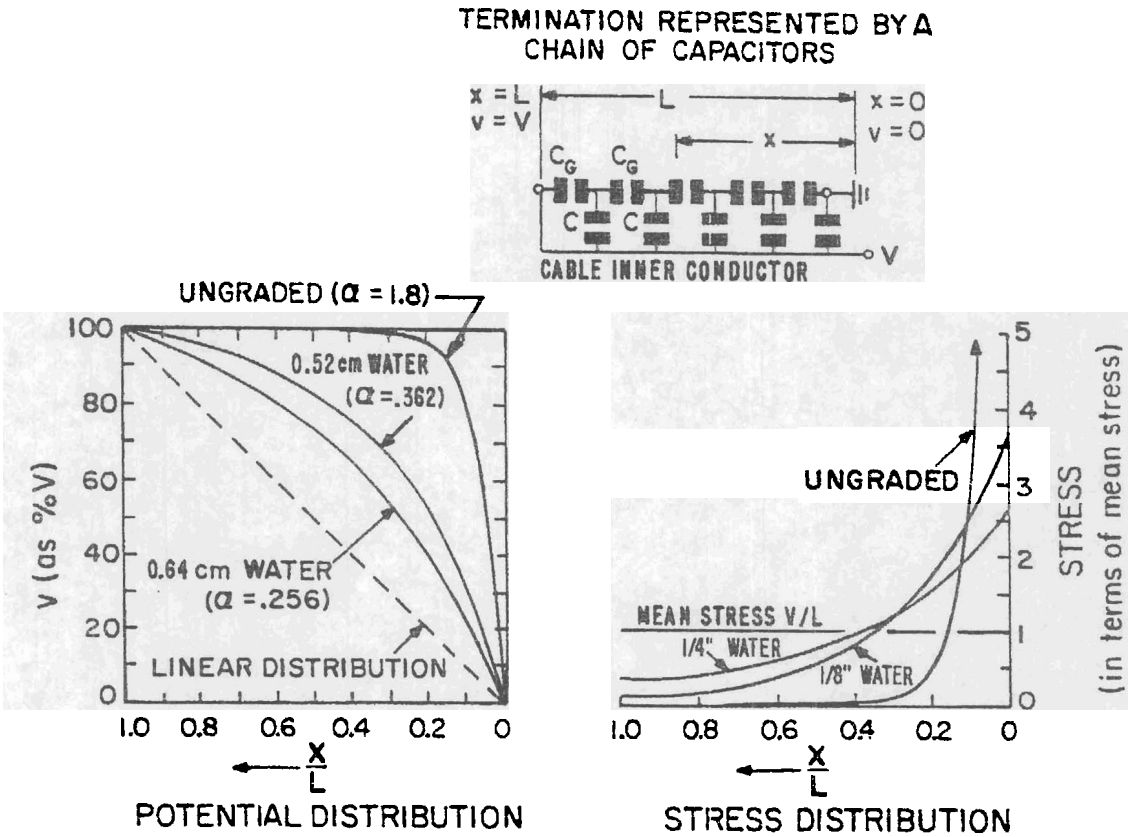


Fig. C-6.
Effect of capacitive layer grading.

Water has been chosen as the grading layer for this illustration because it has a very high dielectric constant of 80, and a thin layer is effective.

$a = \sqrt{\frac{C}{C_G}}$ for the capacitive representation.

When liquids other than water are used, a thicker layer is required for the same effect. Water has several advantages.

- High permittivity (K = 80)
- High dielectric strength (50 kV/cm)
- Makes intimate contact with cable insulation and conductors, excludes air, and makes tolerances less critical
- Cheap and easy to replace

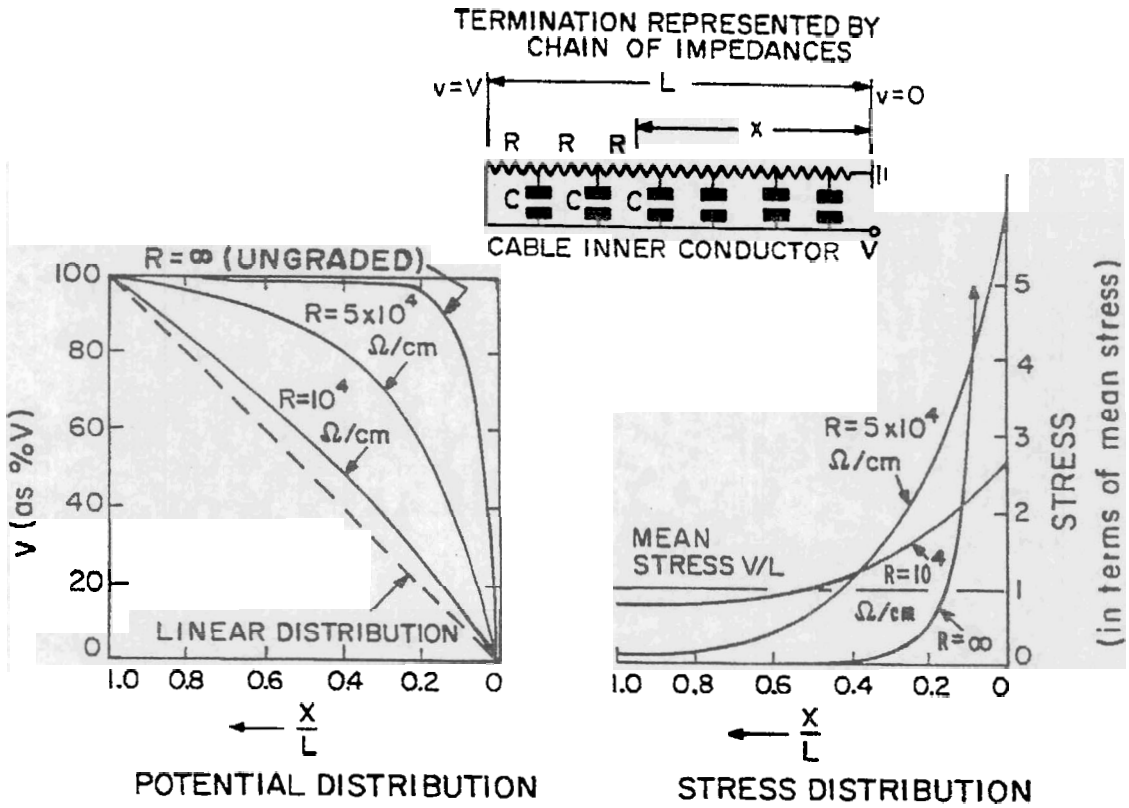


Fig. C-7.
Effect of resistance layer grading.

- Can be made suitably conductive by additives
- High resistivity
- High thermal capacity

Dielectric oils are used extensively at LASL (see Figs. 6 and 11 in the text). Usually the thickness of the liquid grading layer is determined by the size of container or boot available and the space available.

A high permittivity tape is available for the grading layer. This is a self-amalgamating elastomer tape in which the high permittivity is produced by a filling of very small metallic disks insulated from each other and oriented so that they are all parallel to one plane. Permittivities up to 70 can be produced in this way.

The cable termination can also be represented as a chain of impedances as in Fig. C-7. Here the high stress is relieved by distributing the voltage across a resistive voltage divider. The theoretical improvement obtained by

applying a layer of material with resistivity of 10 k /cm is within 10% of the ideal linear distribution.

Materials available for the resistive grading layer are semiconducting PVC or polyethylene, water with additives, and the various cloth tapes and rubber compounds sold in cable terminating and splicing kits. Many types of cable have a layer of semiconducting plastic between the insulation and outer conductor. Water solutions that can be used are

1. potassium dichromate, 1 g/liter of water $\approx 2 \times 10^3\ \Omega\cdot$cm, and
2. copper sulfate, 0.3 g/liter $\approx 10^4\ \Omega\cdot$cm.

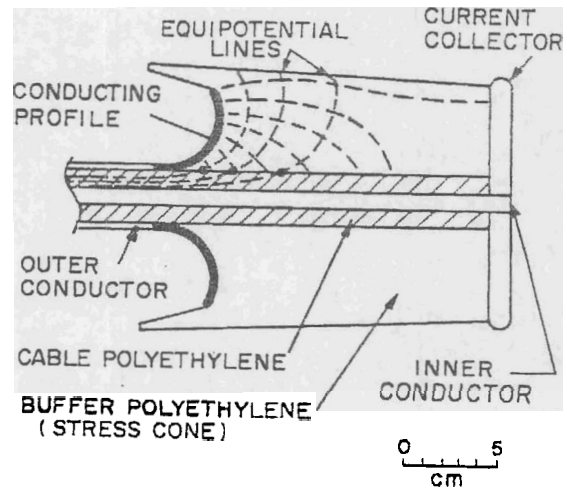


Fig. C-8.
Stress-cone termination for 100=kV cable.

When resistive terminations are used, power dissipation must be considered. The heat produced will be

$$\frac{1}{R_T}\int V^2 dt\ ,$$

where V = voltage applied and R_T = total grading resistance.
When a water solution is used, the gas released by electrolysis will equal

$$\frac{0.15}{R_T}\int V\ dt\ \text{cm}^3\ .$$

If service is continuous, the gas evolved and water make-up requirements are a problem, and other liquids or solid materials should be considered.

C. Buffer Terminations (Stress Cones)

The stress cone is another form of capacitive grading used to reduce the high stress in the air at the end of the cable's outer conductor. A fundamental form of stress cone terminator is shown in Fig. C-8. Here a polyethylene cone is slipped over the cable's polyethylene up to the end of the outer conductor. The polyethylene cone provides a properly shaped surface to support

a layer of conductive paste labeled "conducting profile" in Fig.C-8. This conductive surface spreads the equipotential lines in the same way that a corona shield spreads them at a bushing or connecting point (see Fig. 4 in the text).

Specially designed kits of insulating and semiconducting rubber pieces with tape, connectors, and complete instructions are sold by high-voltage cable and hardware suppliers. A typical kit designed for 35-kV power line service carries a tested impulse-withstand voltage rating of 265 kV. This kit produces a termination 10 cm in diameter and 66 cm long for outdoor service. Smaller terminations are available for indoor service. Grease and/or oil supplied with these kits is used to prevent air from being trapped between the mating surfaces.

III. ELECTROMAGNETIC FORCE BETWEEN CONDUCTORS*

When the currents flowing in two adjacent conductors are in the same direction, the force is one of attraction, and when in the opposite direction, one of repulsion.

The force between two conductors carrying current

$$F = \frac{2 \times 10^{-7} I_1 I_2}{d} \text{ N/m},$$

where I = ampere and d = meters.

By definition the ampere is the current that, flowing in two straight, parallel conductors of infinite length, of neglible circular cross section, and placed at a distance of one meter from each other in a vacuum, produces between the conductors a force of 2×10^{-7} newton per meter length.

In English units, the electromagnetic force developed between two straight parallel conductors of circular cross section and length ℓ carrying currents of I_1 and I_2 amperes, respectively, may be calculated from

$$F = 4.5 \times I_I I_2 \times \frac{\ell}{d} \times 10^{-8},$$

* This material is adapted from Culham Laboratories Design Information Manual, Vol. 1, Index No. 103 by L. W. Sharpe and D. E. Shelton.

where F = the force of attraction or repulsion in pounds,

ℓ = length of conductors in inches,

d = axial distance between conductors in inches, and

I = current in amperes.

Also $F = 2.04 \times I_1 I_2 \times \frac{\ell}{d} \times 10^{-8}$,

where F is in kg's, ℓ and d in cms.

For conductors of rectangular cross section, a correction factor K is introduced and the formula becomes

$$F = 4.5 \times I_1 I_2 \times \frac{\ell}{d} \times K \times 10^{-8} \text{ etc.}$$

Values of K are obtained from Fig. C-9 curves.

The ratio $\frac{d - a}{a + b}$ has to be calculated. Then the value of K may be read from the curve for the correct ratio $\frac{a}{b}$, where

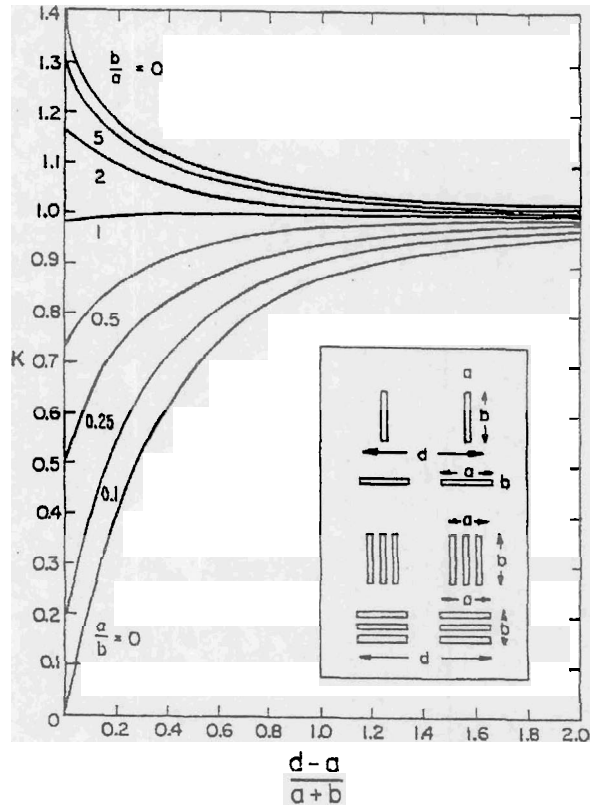


Fig. C-9.
Shape factor for rectangular copper conductors.

a = the width of bar or group of bars,

b = the depth, and

d = the spacing between center lines as indicated in Fig. C-9.

The effect of conductor shape decreases rapidly with increased spacing and is a maximum for thin strip conductors. It is practically neglible for bars of square cross section, and for circular conductors K is unity.

The mechanical force exerted between magnetic flux and a current-carrying conductor is also present inside the conductor itself and is called the pinch effect. The force between the infinitesimal filaments of the conductor is one of attraction so that a current in a conductor tends to contract the conductor.

APPENDIX D

ENERGY STORAGE CAPACITOR BANKS

I. ELEMENTS OF ENERGY STORAGE CAPACITOR BANKS

E. L. Kemp

Large magnetic fields are common laboratory tools today mainly because of the increased interest in thermonuclear research and plasma propulsion. Fields are usually generated by passing high currents through solenoid coils, which require large amounts of power during the time of interest. The capacitor bank, the most universal system for storing and delivering this power, can deliver very high currents for short periods and is cheap compared to a high-current generator

The primary components in a capacitor bank are the capacitor, switch, transmission system, and charging system. The pertinent characteristics of each of these will be discussed.

COMPONENTS

Capacitors • Energy storage capacitors are rated from 1 to 100 μf at voltages between 3 and 100 kv. They usually store between 1 and 3 kilojoules at rated voltage. Their internal inductance is less than 0.1 μh so that they may routinely produce peak discharge currents of more than 100 kiloamperes. A typical guaranteed life is 1,000 shots at the design rating.

Fig. 1 shows three typical capacitors. They are a 100-μf 3-kv capacitor, a 15-μf 20-kv capacitor, and an 0.8-μf 120-kv unit.

When these capacitors fail they usually develop an internal short circuit. If several units are connected in parallel, the unit which short-circuits will receive all the energy stored in that module. Most energy storage capacitor cans are able to absorb a maximum of 25 kilojoules without rupturing.

Switches • The capacitor bank switch must hold off voltage during the charge cycle, close with a small jitter, and pass large currents. Historically, spark gaps were used for capacitor bank switching. A single 2-ball spark gap was connected in series with the load, and the bank was charged until the gap was overvolted, discharging the capacitors into the load. Today, a triggering pin has been added to the 2-element gap, and under proper conditions, the 3-element "triggertron" is an inexpensive, reliable bank switch. Its disadvantage is its limited operating voltage range, 10 to 15 per cent of the maximum. Triggertrons are operated at atmospheric pressure at voltages up to 25 kv. Some pressurized models operate at 40 kv.

A vacuum spark gap[1] has been developed which will operate from 100 volts to 20 kv. The vacuum gap requires constant pumping and the usual vacuum technology, but the reliability and wide voltage range make it attractive for some low-inductance banks.

Spark gaps can also be designed to operate at higher voltages. Fig. 2 shows a 4-element spark gap which operates from 60 to 100 kv with a maximum jitter of 10^{-8} seconds.[2,3] It resembles the common 3-electrode gap with an additional triggering electrode. The center electrode is biased at a potential midway between the upper and lower electrodes. The fourth electrode is the irradiating spark plug. The gap is triggered by driving the center electrode to the breakdown potential of one of the gaps. This trigger pulse also causes the spark plug gap to break down and irradiate both halves of the gap, actually before the center electrode reaches the breakdown point. When

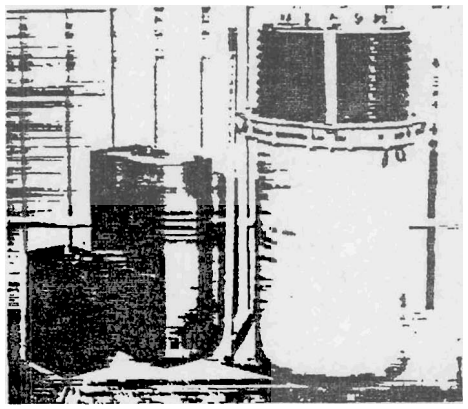


Fig. 1.
Three typical energy storage capacitors.

E. L. Kemp is with the Los Alamos Scientific Laboratory, University of California, Los Alamos, N.M.

The author gratefully acknowledges the assistance and criticisms of the following people: G. P. Boicourt, H. K. Jennings, J. P. Mize, T. M. Putnam, A. E. Schofield, Elizabeth J. Pohlmann, and Mary E. Smith.

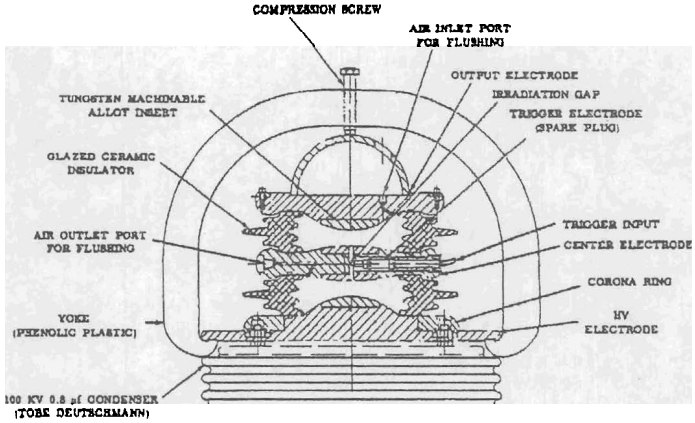


Fig. 2. Cross section of a 4-element spark gap

one-half of the gap breaks down, the other half is immediately overvolted and follows.

Spark gaps are reliable and have low jitter, so many of them can be used in parallel. Usually, each new bank design requires a unique spark gap design, and such designs are often unavailable from commercial sources.

Ignitrons are the only commercially available switches suitable for general capacitor bank switching. The size *A (left)* and size *D* ignitrons shown in Fig. 3 are the most popular. The size *A* is relatively inexpensive, has a low inductance, and has recently been improved for reliable operation above 20 kv.[4] The size *D* is more rugged and will handle large currents for milliseconds.

The size *A* ignitron is available with a carbon anode or a metal anode. The carbon anode model is reliable at voltages up to 15 kv, passing peak currents of 15 ka (kiloamperes). The metal anode ignitron will operate above 20 kv, passing peak currents greater than 100 ka.

The size *A* ignitron has less than 0.25-μsecond jitter when properly triggered. The trigger pulse should be over 3 kv and have a rise time comparable to the required jitter. The peak trigger current should be at least 250 amperes. After 1,000 shots or more, the resistance of the ignitor in a metal anode tube will drop from its nominal value of 25 to 50 ohms to perhaps 0.1 ohm and make the tube fail to fire when the ignitor is triggered. The ignitor resistance can be increased to nearly the original value by applying a 500- to 1,000-ampere short pulse to the ignitor for a few times when there is no voltage on the anode.

The operating characteristics of a bank will usually determine the choice of the switch. Spark gaps are indicated for operating voltages above 30 kv. They can be designed for low inductance and low jitter, but they must be designed for each application.

Ignitrons will operate reliably below 30 kv. They are commercially available and economical. They must be mounted vertically and usually require a water-cooling clamp. Their inductance is low if the mounting is coaxial. Ignitrons are more rugged than spark gaps and will sustain accidental short-circuit currents without requiring subsequent maintenance.

Transmission Systems • The transmission system for a capacitor bank may be bus work, a coaxial cable array, or a parallel plate transmission line, depending on the inductance and flexibility of the bank.

Open bus work is satisfactory where the inductance of the bank is not critical. The voltage hold-off distance should be conservative. One accidental discharge in air will make a true believer of any designer.

The bus should be designed for the maximum short-circuit current available from the bank. The electrical engineer is aware that parallel currents attract and opposing currents repel. This should be kept firmly in mind when designing bus work for capacitor banks. Kiloampere currents will generate magnetic fields that play havoc with a bus that is not sturdily made.

Fig. 4 shows a test bank using a bus transmission system. This bank stores 25,000 joules at 20 kv and delivers 60,000-ampere peak current into an inductive load.

Coaxial cables are well suited for capacitor banks where the load is flexible and when the transmission system must have low inductance. The standard types of RG-8/U, RG-14/U, RG-17/U, and RG-19/U can be used for voltages between 20 and 100 kv, respectively. They will pass peak currents of 30,000 amperes at a repetition rate of two shots per minute. These cables have a nominal high-frequency inductance of approximately 0.08 μh per foot.

Some special low-inductance cable has been developed for capacitor bank application. It is now commercially available and is usually designated by its component diameters, type 17/14 being a typical case. This cable has RG-17/U braid as the outer

conductor and RG-14/U braid as the inner conductor. The central core is foamed polyethylene. The dielectric between conductors is normal polyethylene. It is covered with the usual RG-17/U vinyl jacket.

This cable has a measured low-frequency inductance of 0.036 μh per foot with a resistance of approximately 1 milliohm per foot. Combinations of RG-14/8 and RG-19/14 and other nonstandard designations are also available.

Parallel plate transmission lines can be designed for any desired inductance if space is available.

The inductance for a parallel plate transmission line is

$$L = 4\pi \cdot 10^{-7} \frac{t}{w} \; h/m \qquad (1)$$

where t is the separation distance and w is the width, both dimensions in meters.

The current flowing in opposite directions in the two parallel plate transmission lines creates a magnetic pressure which tends to separate the plates. The pressure generated by the magnetic field is

$$P = 2\pi \left(\frac{I}{W}\right)^2 10^{-12} \text{ atm} \qquad (2)$$

I is current in amperes and W is the width of the plates in meters.

Although this pressure will last for only a short time, its amplitude may be quite large. The problem of holding parallel plate lines together often proves formidable.

Charging Systems - The simplest charging scheme for a capacitor bank is an R-C circuit. When this method is used, the charge resistor will dissipate an amount of power equal to the power stored in the bank. The wattage rating for the charge resistor can be computed at one watt per 8 joules of stored energy for a repetition rate of 2 shots per minute. The power dissipated in the charge resistor and the long charge time make the R-C method unsuitable for charging large capacitor banks.

A constant-current charging system is more desirable. It is efficient in power transfer, while the charge time is limited only by the current capacity of the power supply. A power supply whose output voltage is changing at a constant rate will deliver a constant current into a capacitor bank.

A motor driven autotransformer in the primary of a power supply will provide the dv/dt characteristic. The system has one disadvantage: if the bank switches fire during the charge cycle, the bank will discharge and present a low impedance to the power supply. The resulting high current will destroy the power supply rectifiers unless they are protected by a fast circuit breaker in the primary.

Fig. 5 shows another constant-current circuit often called a monocyclic network. The inductor and capacitor are in series resonance at the line frequency. The network is connected to the primary of the power supply and maintains a constant output current independently of the impedance connected to it. It can be shown[5] that at resonance

$$i_{ss} = j\frac{V}{X} \qquad (3)$$

where

$$X = \omega L = \frac{1}{\omega C} \qquad (4)$$

In this application X is chosen to equal the reflected impedance of the power supply. The value of X will be

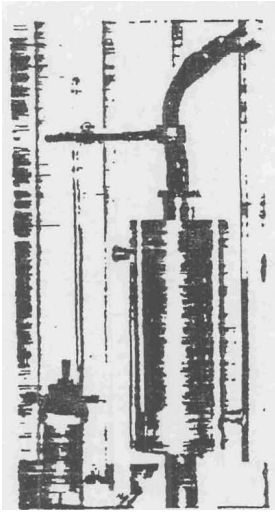


Fig. 3.
Size A and size D ignitrons.

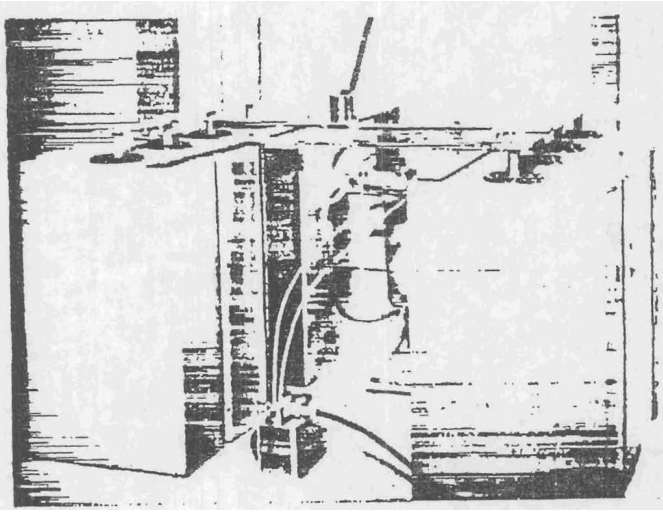
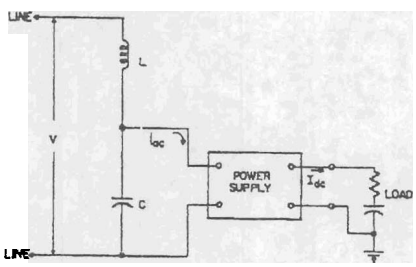


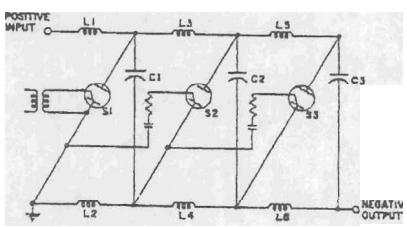
Fig. 4.
A capacitor bank connected with open bus.

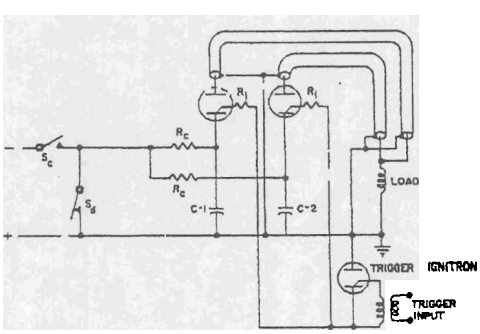
$$X = \frac{V_{ac}^2}{V_{dc} I_{dc} K} \qquad (5)$$

The constant K, sometimes called the "line power factor," is a characteristic of the power supply circuit and can be found in a power supply handbook.[6] The inductance and capacitor are chosen to present this impedance at the line frequency. This circuit is applicable in a single-phase or a 3-phase circuit.

The major disadvantage of the circuit is its tendency to deliver a constant current into any load, regardless of the load impedance. This characteristic will produce output voltages that are several times the rated value if the output impedance is high. For example, it will charge a capacitor bank to several times the rated voltage if the voltage detector system fails. This circuit will likewise produce a high voltage if the power supply output sees an open circuit.







When a monocyclic network is used, the bank should be protected with an overvoltage detector. It is also necessary to turn off the power supply before it is isolated from the bank at completion of charge.

Surge charging has several advantages for charging capacitor banks operating at high voltages. It provides high voltage from a modest supply, and it charges a bank quickly, keeping the voltage on the components for a minimum time.

Modified Marx generators are usually used to surge-charge capacitor banks. The modified circuit uses inductors rather than resistors to minimize power dissipation. The switches are reversed from the usual Marx circuit. This keeps the load capacitor bank grounded except when it is being charged, an important safety feature when the bank may store many joules at high voltage. The output polarity is opposite the input polarity.

Fig. 6 is a schematic of a 3-stage modified Marx generator which can be used to charge a capacitor bank. This circuit uses ignitrons as switches. With the polarities shown, the triggering of the switches is automatic after $S1$ triggers. The voltage on $C1$ is impressed across L_2 and on the ignitor of $S2$. The resistor and capacitor in the ignitor circuit limit the ignitor current. When $S2$ fires, it fires $S3$ in the same way. More stages can be used as necessary. If a positive output is required, each switch can be inverted and the bank charged negative. The ignitor capacitor must then hold off the charge voltage during charge. A pulse transformer to each ignitor will also operate in this circuit. Spark gaps are also well suited for Marx generator switches.

CIRCUITS

The capacitor bank circuit is usually determined by the size of the bank, its operating characteristics, and the switching system. In large banks, it is necessary to isolate each capacitor in some way to prevent it from exploding when it short-circuits at the end of its life. Exploding wire fuses[7] have been used successfully in some applications to protect each capacitor, but the inductance of the fuse will sometimes prevent the use of fuses in low-inductance banks.

The circuit in Fig. 7 can be used for protecting the capacitors in a low-inductance bank. An ignitron is mounted directly on each capacitor in a coaxial housing. The size A ignitron in such a housing has an inductance of approximately 0.02 μh. One or more coaxial cables are used to carry current to the load. Each capacitor has its own charging resistor. If one capacitor fails during the charge cycle, current from the other capacitors is limited by the charging resistors. If a capacitor fails during discharge, it is in parallel with the load, but it is isolated by its cable. The impedance of the cable is high compared to the load, so most of the bank energy goes into the load.

This circuit has performed satisfactorily in systems having over 100 units in parallel.

Fig. 7 also shows a simple triggering method that has proved reliable. The capacitors are charged negative. When the trigger ignitron is fired, it grounds the ignitors, making them positive with respect to their cathodes. The firing energy is taken from the storage capacitors. Ignitor current is limited by the resistor R_i in each ignitor lead. A large number of ignitrons can be fired in this manner from one trigger ignitron.

BANK PARAMETERS

Since most capacitor bank circuits are simple *RLC* circuits, their performance can be calculated accurately. The energy stored in the bank will be

$$U = 1/2\ CV^2 \text{ joules} \tag{6}$$

In most cases, the bank will be designed to produce a maximum current from the energy stored.

The peak current will be

$$I_p = V\sqrt{\frac{C}{L}}\ e^{-(Rt/2L)} \tag{7}$$

where t is the time to the first quarter cycle.

Expressions for the ringing frequency, the charge time, and other incidental characteristics of a bank are well known.

CAPACITOR BANK SAFETY

All energy storage banks are lethal! Adequate personnel safety must be the first specification for any bank design. There are several areas where thoughtful design will eliminate potential hazards.

The bank should be placed in unconfined quarters. Visual and manual access to all parts is an operating necessity. The bank should be barricaded behind strong walls. Many times when a capacitor fails or a bus arcs over, there will be shrapnel flying with considerable velocity.

All entrances to the bank should be interlocked. All banks should have reliable fail-safe short-circuits on them except when in use. Short-circuiting hooks should be available to reach each capacitor. An unshort-circuited energy storage capacitor will recover a lethal charge. They should always be short-circuited during handling or while in storage.

The fire danger in a bank is acute. Energy storage capacitors may be impregnated with mineral oil, castor oil, or chlorinated diphenyl, the first two of which are inflammable. If a capacitor short-circuits during discharge, it sometimes ruptures and spews impregnant over a considerable area. If the impregnant is flammable, a highly noxious fire may start. The fire-fighting personnel should be informed of the hazards in spraying water on a bank which may be charged.

Ground currents are always a problem in bank design. Banks should be grounded at only one point to a counterpoise ground with wide, low-inductance straps.

REFERENCES

1. Some Properties of a Graded Vacuum Spark Gap, J. W. Mather, A. H. Williams, *Review of Scientific Instruments*, New York, N. Y., vol 31, Mar. 1960, pp 297-303
2. J. L. Tuck, *Proceedings*, Second International Conference on the Peaceful Uses of Atomic Energy, United Nations, Geneva, Switzerland, vol 32, 1958, p 19.
3. "High Powered Spark Gap Switches," E. L. Kemp, Report *TID-6670*, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1960, p. 10.
4. Report *LAMS-2416*, C. P. Boicourt, E. L. Kemp, F. K. Tallmadge, Los Alamos Scientific Laboratory, Los Alamos, Calif., Dec. 1959.
5. Charging Large Capacitor Banks in Thermonuclear Research, H. K. Jennings, *Electrical Engineering*, June 1961, pp. 419-21.
6. Reference Data for Radio Engineers, International Telephone and Telegraph Corp., New York, N. Y., fourth edition, 1956, p. 306.
7. Report *UCRL-4733*, H. B. McFarlane, Lawrence Radiation Laboratory, Livermore, Calif., Aug 9, 1956.

II. CHARGE BUILDUP IN UNSHORTED PAPER-CASTOR OIL ENERGY STORAGE CAPACITORS

G. P. Boicourt

One of the safety problems associated with the use of energy storage capacitors is the charge buildup in unshorted units after they have been removed from a system. This charge buildup is due to the release of charge trapped by absorption in the dielectric. Measurements have been made on four paper-castor oil capacitors of different types and used in different applications. One type of application commonly occurring in controlled thermonuclear research involves the capacitor being charged in time t_c and discharged either in a crowbarred or ringing mode followed by period of time t_s during which the capacitor is shorted. Three of the measurements involve capacitors operated in this way. In another common operating procedure, the capacitor is charged continuously at a constant rate and discharged when the desired voltage is reached, without disconnecting the power source. In this case, as in the former, the discharge may be either reversing or nonreversing. The fourth measurement was made on a unit used in this type of operation with a reversing voltage.

Figure D-1(a) shows the charge buildup in a 75-kV, 1.5-μF capacitor. This unit was charged in 10 s to 75 kV, discharged immediately and then left shorted for 10 s before the cycle was repeated. It had been operating in this mode for 24 h before the measurement. The charge buildup reached 4.5 kV or 6% of operating voltage.

Figure D-1(b) was taken under the same conditions as for Fig. D-1(a) except that it was a 0.7-μF, 75-kV capacitor. This particular unit is designed to operate with a considerably lower dielectric stress than the one used to obtain Fig. D-1(a).

The graph in Fig. D-1(c) was obtained from a 10-kV, 180-μF capacitor designed for high dielectric stress and crowbarred operation. In this case it was charged to 10 kV in 10 s, fired in a crowbarred circuit that kept the voltage reversal below 20%, and then left shorted for 50 s. The charge buildup is considerably slower than for the first two units but reaches 8% of rated voltage.

The charge buildup in a 1.85-μF, 60-kV capacitor that had been operated with continuous charge and ringing discharge is shown in Fig. D-1(d). In this case the charge rapidly builds up to over 6 kV, greater than 10% of operating voltage.

No measurements have been made on units operated strictly at direct current; presumably this would give rise to greater charge buildup than in the case of Fig. D-1(d).

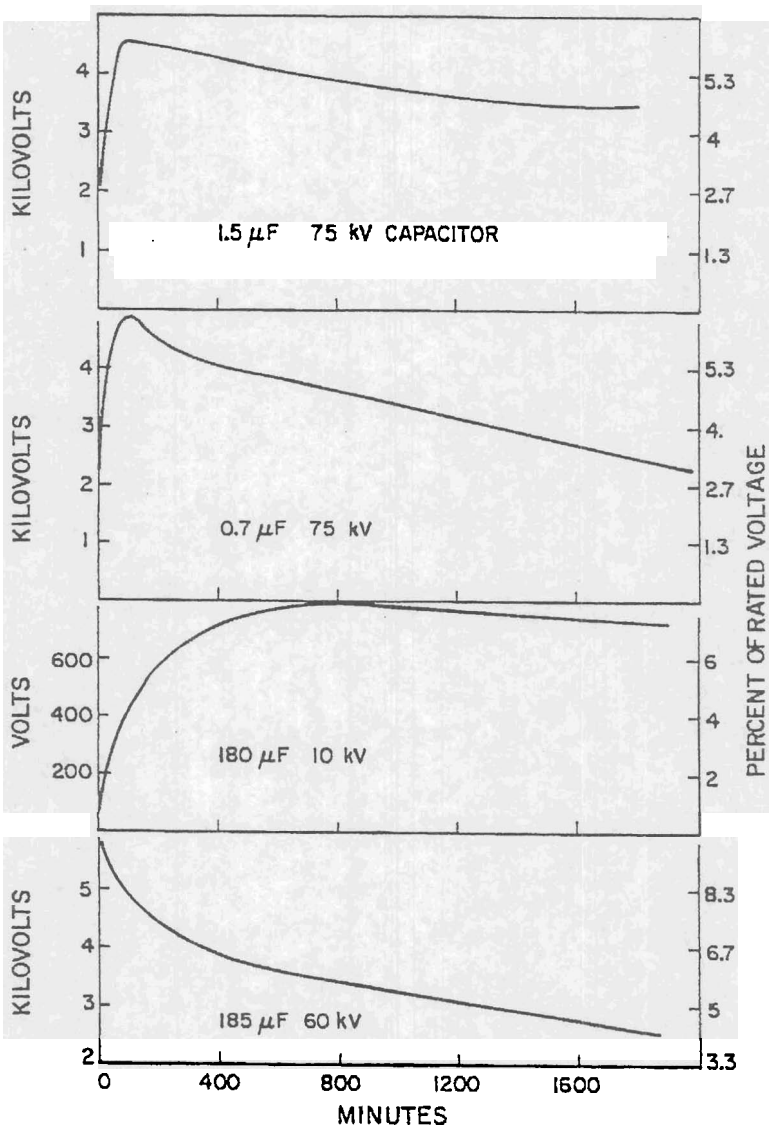


Fig. D-1.
Charge buildup in various sizes of high-voltage capacitors vs time.

APPENDIX E

HIGH-VOLTAGE RESISTORS

TABLE E-I
AXIAL-LEAD TYPES

Power rating (W)	Peak voltage rating (V)	Minimum resistance (Ω)	Maximum resistance (MΩ)	Nominal body length (in.)	Nominal body diameter (in.)	Nominal lead length (in.)
1	3 500	1 800	5 000	1	1/4	1 1/2
2	10 000	5 000	20 000	2	1/4	1 1/2
3	15 000	10 000	20 000	3	1/4	1 1/2

TABLE E-II
HIGH-VOLTAGE PROBE RESISTORS

Peak voltage rating (V)	Minimum resistance (MΩ)	Maximum resistance (MΩ)	Standard tolerance (%)	Nominal body length (in.)	Nominal body diameter (in.)
30 000	100	1 500	2.0	5 1/2	5/16
30 000	100	1 500	2.0	6	5/16

Note: Ends tapped for No. 6-32 screw, supplied with 7/8-in.-long solder lug if specified.

TABLE E-III

GENERAL TAPPED-CERAMIC-TYPE HIGH-VOLTAGE RESISTORS

Power rating (W)	Peak voltage rating (V)	Minimum resistance (Ω)	Maximum resistance (MΩ)	Nominal body length (in.)	Nominal body diameter (in.)
1	3 500	2 500	5 000	1	5/16
2	7 500	5 000	20 000	1 3/4	5/16
3	15 000	10 000	20 000	3	5/16
4	15 000	20 000	20 000	2 1/2	9/16
5	30 000	20 000	20 000	5 1/2	5/16
6	25 000	50 000	20 000	4	9/16

TABLE E-IV

HIGH-VOLTAGE RESISTORS WITH TERMINALS OF COLLOIDAL SILVER, LUGS, AND FERRULES

Power rating (W)	Peak voltage rating (V)	Minimum resistance (Ω)	Maximum resistance (MΩ)	Nominal body length (in.)	Nominal body diameter (in.)
2	5 000	2 500	15 000	1 3/4	5/16
4	5 000	10 000	20 000	2	9/16
5	10 000	20 000	20 000	3	9/16
7.5	12 000	50 000	20 000	4 5/8	1
10	15 000	50 000	20 000	4 1/2	3/4
20	25 000	200 000	20 000	6 1/2	1 1/8
25	40 000	300 000	20 000	9 13/16	1 1/8
30	50 000	400 000	20 000	10 1/2	1 1/8
90	100 000	1000 000	20 000	18 1/2	2

Note: Ferrule units are usually slightly longer for the same power rating. Two types of ferrules are generally available: one builds up the diameter of the resistor proper; the other reduces the diameter of the resistor body.

Standard tolerance is ± 5. ± 10, and ± 20 per cent, although some of the very low resistance values may not be available in the ± 5 per cent tolerance.

REFERENCES

1. International Telephone and Telegraph Corp., Reference Data For Radio Engineers, 4th Ed. (Stratford Press Inc., New York, 1956).

2. R. W. Sillars, Electrical Insulating Materials and Their Application, IEE Monograph series 14 (Peter Peregrinus Ltd., Stevenage, England, 1973).

3. D. G. Fink and J. M. Carroll, Standard Handbook for Electrical Engineers, 10th Ed. (McGraw Hill Book Co., New York, 1968).

4. L. L. Alston, High Voltage Technology (Oxford University Press, London, 1968).

5. P. J. Rogers, Culham Laboratory engineering data, unpublished data.

6. C. L. Wellard, Resistance and Resistors (McGraw Hill Book Co., New York, 1960).

7. R. A. Haarman, "Liquid Resistor Development," in "Proceedings of Symposium on Engineering Problems of Fusion Research, April 8-11, 1969," Los Alamos Scientific Laboratory report LA-4250 (January 1970).

8. Safety and Fire Protection Technology, Bull. No. 13, Electrical Safety Guides for Research (ERDA Division of Operational Safety, Dec. 1967).

9. J. D. Craggs and J. M. Meek, High-Voltage Laboratory Technique (Butterworth & Co. Ltd. Scientific Publications, London, 1954).

10. F. B. A. Frungel, High-Speed Pulse Technology 1 (Academic Press, Inc., New York, 1965).

11. C. A. Harper, To Compare Electrical Insulators, Electron. Des. 24, 11 (May 24, 1976).

12. Electrical Insulation Manual, (Insulation Manufacturers Corp., 1956).

13. Handbook of Materials Science 3 (Chemical Rubber Co. Press, Cleveland, 1974).

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051-075	5.25	176-200	9.00	301-325	11.75	426-450	14.00	551-575	16.25
076-100	6.00	201-225	9.25	326-350	12.00	451-475	14.50	576-600	16.50
101-125	6.50	226-250	9.50	351-375	12.50	476-500	15.00	601-up	

Appendix A

Clear All Fields!

Electrical Equipment Field Report

>120 V Checklist

Field report number	
Date submitted	
Field Rep Name	

1	**Equipment Information**			
1.1	Conditions/Restrictions on use			
1.2	Operating environment/Intended use			

		Approve	Reject	NA
2	**Modifications**			
2.1	Performance consequences			
2.2	Safety consequences			
2.3	Change in rating (volts, power, current)			
2.4	Cooling alteration			
2.5	Additional wiring			
2.6	Prior NRTL			
2.7	Enclosure			
2.8	Other			
2.9	Modifications comments			

		Approve	Reject	NA
3	**General Construction**			
3.1	Enclosure			
3.2	Not damaged			
3.3	Complete			
3.4	Appropriate construction, design & clearance			
3.5	Appropriate material			
3.6	No open knockouts or holes			
3.7	Other			
3.8	General Construction comments			

		Approve	Reject	NA
4	**Mechanical Assembly**			
4.1	No loose parts			
4.2	Corrosion protection			
4.3	Switches, lamp holders, etc. securely mounted			
4.4	Other			
4.5	Mechanical Assembly comments			

		Approve	Reject	NA
5	**Wiring - Internal**			
5.1	Power supply connections			
5.2	Polarity			
5.3	Free of sharp edges			
5.4	Separate line voltage from other wiring			
5.5	Wiring terminals and leads			
5.6	Clearance/creepage distance			
5.7	High temperatures			
5.8	Neat assembly workmanship			
5.9	Components used correctly			
5.10	Mechanical bracing of conductors			
5.11	Overcurrent protection			
5.12	Other			
5.13	Wiring - Internal comments			

		Approve	Reject	NA
6	**Strain Relief**			
6.1	No tension on terminals/connectors			
6.2	Correct fittings			
6.3	Other			
6.4	Strain Relief comments			

		Approve	Reject	NA
7	**Switches and Controls**			
7.1	Readily accessible			
7.2	Anti-restart (motors)			
7.3	Appropriately identified/labeled			
7.4	Lockable disconnect (for LOTO)			
7.5	Other			
7.6	Switches and Controls comments			

		Approve	Reject	NA
8	**Extension Cords and Power Strips**			
8.1	Correctly rated			
8.2	Undamaged			
8.3	Grounding			
8.4	Minimize trip hazards			
8.5	No daisy chains			
8.6	Other			
8.7	Extension Cords and Power Strips comments			

		Approve	Reject	NA
9	**Bonding and Grounding**			
9.1	Bonding wires securely terminated			
9.2	All non-current-carrying metal properly bonded			
9.3	Equipment ground is run with circuit conductors			
9.4	Auxiliary grounds: terminators and general condition			
9.5	Other			
9.6	Bonding and Grounding comments			

		Approve	Reject	NA
10	**Foreign Power Supplies and Equipment**			
10.1	Connected to SLAC approved adaptors			
10.2	Correct voltage and frequency			
10.3	Correct AWG for US system			
10.4	Fusing in ungrounded conductors only			
10.5	Other			
10.6	Foreign Power Supplies and Equipment comments			

		Approve	Reject	NA
11	**Wiring - Electrical**			
11.1	Correct wire rating			
11.2	Correct insulation type			
11.3	Correct connectors			
11.4	Strain relief			
11.5	Not subject to damage			
11.6	Cable shield grounded			
11.7	Cable trays and wireways properly installed and grounded			
11.8	Other			
11.9	Wiring - Electrical comments			

		Approve	Reject	NA
12	**Tests (may be performed by others as necessary)**			
12.1	Input current test			
12.2	Starting current test			
12.3	Leakage current test			
12.4	Dielectric breakdown voltage test (HIPOT)			
12.5	Temperature test			
12.6	Strain relief test			
12.7	Capacitor test			
12.8	Bonding overload test			
12.9	Resistance of ground path test			
12.10	Other			
12.11	Test comments			

		Approve	Reject	NA
13	**Failure Modes**			
13.1	Effect of single component failure			
13.2	Effect of overload			
13.3	Effect of ground fault			
13.4	Effect of incorrect setting			
13.5	Other			
13.6	Failure Modes comments			

		Approve	Reject	NA
14	**Accessibility of Live Parts**			
14.1	No parts accessible >50 volts and 5 mA or 10 J			
14.2	During normal use			
14.3	During routine maintenance			
14.4	Covers in place; removable only by tool			
14.5	Electrically "dead" front panel			
14.6	Enclosures accessible without using tools are interlocked			
14.7	Interlock (hardware) removes power to accessible parts			
14.8	Other			
14.9	Accessibility of Live Parts comments			

		Approve	Reject	NA
15	**Cords and Plugs**			
15.1	Not frayed			
15.2	Not damaged			
15.3	Grounding conductor included			
15.4	Ampacity for rated current			
15.5	Other			
15.6	Cords and Plugs comments			

		Approve	Reject	NA
16	**Insulating Material**			
16.1	Appropriate mechanical strength and rigidity			
16.2	Appropriate flame and smoke properties			
16.3	Other			
16.4	Insulating Material comments			

		Approve	Reject	NA
17	**High Voltage (>600 volts)**			
17.1	Correct connectors			
17.2	Stafing means			
17.3	Discharge circuit			
17.4	Drop switch			
17.5	Insulation			
17.6	Associated dielectrics			
17.7	Other			
17.8	High Voltage (>600 volts) comments			

		Approve	Reject	NA
18	**High Current/Low Voltage (<50 volts and > 1000 VA)**			
18.1	Over-current devices			
18.2	Safe terminal spacing			
18.3	Mechanical bracing			
18.4	Other			
18.5	High Current/Low Voltage (<50 volts and > 1000 VA) comments			

		Approve	Reject	NA
19	**Other**			
19.1	Any other hazard areas including non-electrical that may warrant further investigation			
19.2	Other comments			

		Approve	Reject	NA
20	**Marking Requirements (Clearly Labeled)**			
20.1	Hazards			
20.2	Restrictions and limitations			
20.3	Other			
20.4	Marking Requirements (Clearly Labeled) comments			

		Approve	Reject	NA
21	**Other Information**			
21.1	Photographs, diagrams, sketches, catalog cut sheets			
21.2	Procedures			
21.3	Training and qualification of users			
21.4	Other			
21.5	Other Information comments			

Equipment Inspection Summary

Click red area at right to certify the form and save it with a digital signature.