Using Ground Sticks to Discharge Capacitance

Using Ground Sticks as a Personal Safety Device in non-Utility Applications

EFCOG ESCoP Best Practice

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1 Purpose

The purpose of this Best Practice is to provide minimum requirements for the design, construction, testing, inspection, and use of ground stick assemblies used in achieving an electrically safe work condition, including energy removal, verification, and maintaining an electrically safe work condition. They are primarily used on equipment containing hazardous discrete capacitors at any voltage or stray capacitance (for voltages > 1 kV). Ground sticks are also use as a part of the verification process for any high voltage circuit (> 1 kV), regardless of capacitance being present. All procedures using a ground stick will include risk assessment and evaluation consistent with NFPA-70E (10CFR851 requirement).

Although much of the content of this Best Practice (not all) is covered by Article 360 and Annex R of the 2021 and 2024 editions of NFPA 70E (Standard for Electrical Safety in the Workplace) many sites have not yet adopted these newer versions. This Best Practice serves as a resource to those sites. This Best Practice also supplements the material in the DOE Electrical Safety Handbook. Since this document is a Best Practice, it does not set requirements, with “shalls”. Once the 2021 or 2024 versions of NFPA 70E are adopted several of the “shoulds” in this document will then become “shalls”, as NFPA 70E now has requirements for managing the hazards of capacitors.

2 Scope

2.1 Safe Control of Stored Capacitive Electrical Energy

This best practice is focused on equipment in laboratories and industry containing hazardous discrete and stray capacitance. It also covers the capacitors found in utility, facility, and residential energy conversion technologies, including the power electronics used in rectification and inversion associated with ac-dc, dc-dc, and dc-ac energy conversion (see thresholds for capacitor hazards Figure 1). Examples include pulsed power, high-voltage, RF power supplies, electrostatic field sources, accelerators, HV coax-cables, x-ray generators, Marx circuits, power electronics, Variable Frequency Drives (VFDs), etc. Each facility should publish safe work practices for their use of ground sticks.

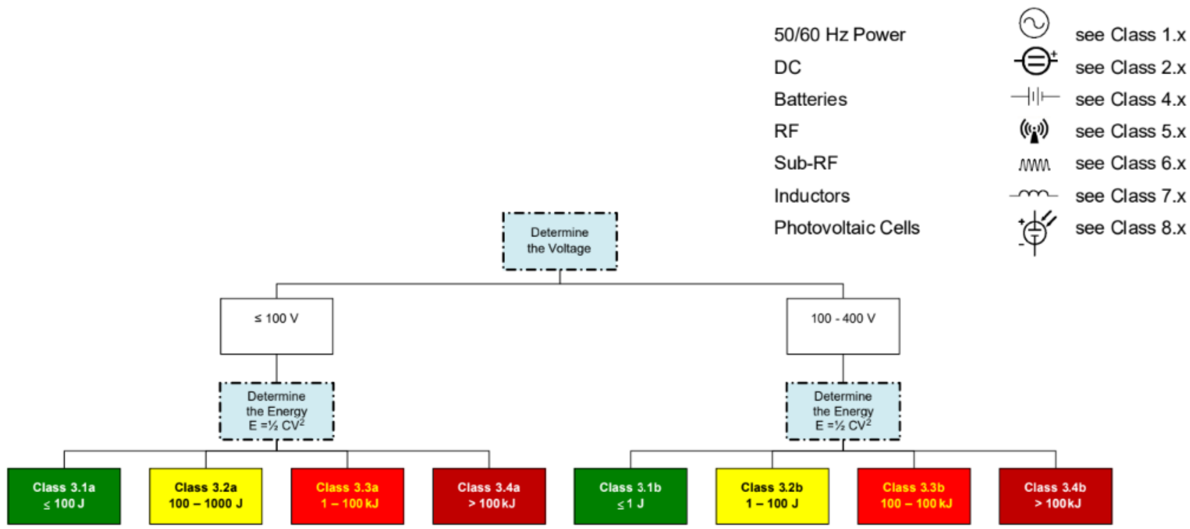


Figure 1a. Hazard Classes 3.x - Capacitors ≤ 400 V.

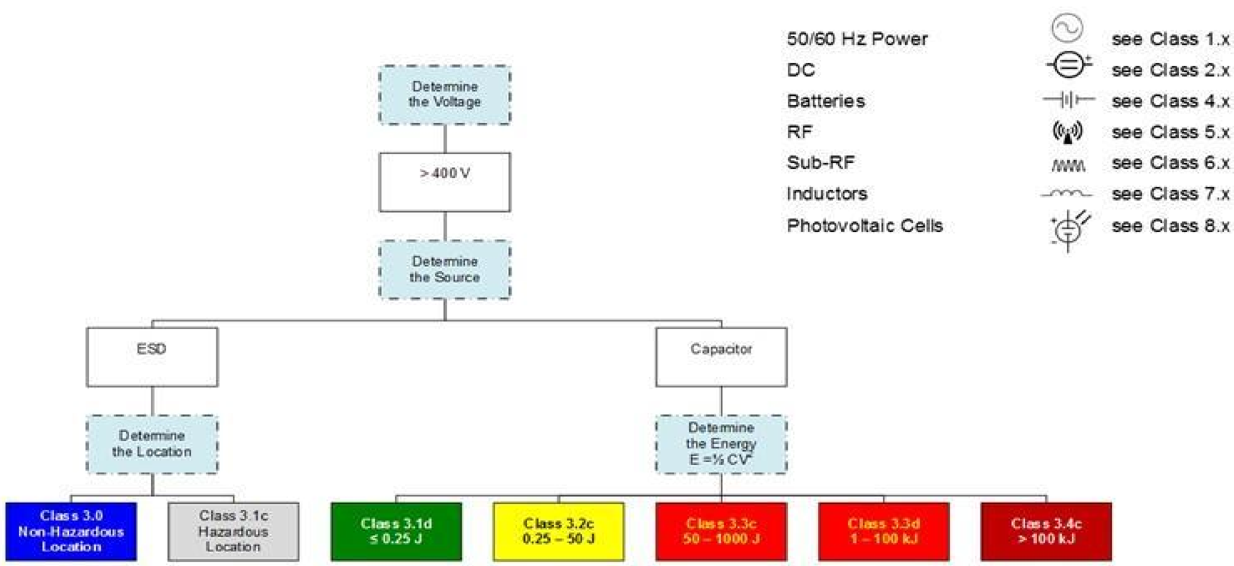


Fig. 3-14. Hazard Classes 3.x, Capacitors, >400 V.

Notes on use:

1. Voltage is peak of the Ac$_{rms}$ or dc maximum charge voltage on the capacitor.
2. Energy is maximum energy stored in the capacitor as determined by $E = \frac{1}{2} CV^2$.
3. The hazards for greater than 400 V, Classes 3.2c, 3.3c, 3.3d, 3.4c are energy deposited through a short circuit, a shock hazard with a strong reflex action for Class 3.2c, and serious tissue injury and/or death for 3.3c and above.
4. Class 3.3d and 3.4c have the added hazards of mechanical damage due to high currents and strong pulse magnetic forces during a short circuit.
5. For Class 3.1c, the hazard is not electrical; refer to an explosive or hazardous location SME to manage the hazard.

Figure 1b. Hazard Classes 3.x - Capacitors > 400 V.

2.2 Not for AC Utility Use

This standard is not intended to cover the safety grounding of ac power utility and facility distribution equipment, such as power factor correction capacitors The personal safety grounds used in utilities (known as ground clusters) also function to prevent inductively coupled energy and to withstand large fault currents from lightning or short circuits between systems. Other codes, standards and regulations govern such equipment.

2.3 Soft/Hard Resistor

The construction of the ground stick (hook) may be either or both current limited (soft ground stick) and non-current limited (hard ground stick). Discharge current may be limited by using a stick-mounted resistor (section 4.4). Some equipment assemblies will use two separate ground stick devices (one hard and one soft) to be applied to designated locations. Safe work practices determine which types of ground sticks are to be used in each application.

2.4 NFPA 70E 2021/2024

The NFPA 70E 2024 edition introduced ground sticks in Article 360, Safety-Related Requirement for Capacitors, and provides additional information in Annex R, Working with Capacitors. DOE facilities follow various editions of this consensus standard, and may not have adopted the 2021 edition, which was the first edition of NFPA 70E to cover capacitor safety.

3 Definitions

Arc Blast Hazard

A source of possible injury or damage to health from the energy deposited into acoustical shock wave and high-velocity shrapnel.

Authority Having Jurisdiction (AHJ)

An organization, office, or individual responsible for enforcing the requirement of a code or standard, or for approving equipment, material, an installation, or a procedure (from 2021 NFPA 70E).

Note: At some DOE sites, the term AHJ is primarily used for the implementation of NFPA 70, the National Electrical Code (NEC). In this case the AHJ includes inspection, approval, and granting exceptions, variances, or alternate methods covered by the NEC. These sites may use the term Electrical Safety Authority (ESA) to cover the implementation, enforcement and oversite of electrical worker safety (NFPA 70E).

Some sites use the term "AHJ" to include the implementation and oversite of both installation (NEC) and electrical worker safety (NFPA 70E).

Bleed Resistor

A resistor or resistor network connected in parallel with a capacitor's terminals that drains the charge after power has been disconnected.

Charge Transfer

Improper discharging of capacitor networks that results in transferring from one capacitor to another capacitor instead of fully discharging the stored energy.

Current-Limiting Resistor

A resistive element installed in series with a ground stick probe to limit the discharge current from a capacitor to a safe level (500A peak). This element needs to be rated for the instantaneous power, the maximum capacitor voltage, and the maximum energy to be dissipated.

Dielectric Absorption

The property of certain capacitors to recharge after being discharged.

Note: A voltage recharge from 0.02 percent (polystyrene and polypropylene) up to 10 percent (some electrolytics) can occur a few minutes after the grounding or shorting device has been removed.

Discharge Time

The time required to discharge a capacitor to below a stored energy hazard threshold.

Dual-bushing capacitor

A capacitor module which provides two connector terminals to the internal capacitor. The case floats electrically with respect to the internal capacitor component. The case presents a stray or parasitic capacitance to the internal capacitor and to ground. This must also be brought to ground potential to achieve an electrically safe work condition.

Duty Cycle

The fraction of time which is defined by the time for a discharge divided by the cooling period for the discharge resistor. This may also be referred to by the terms discharge frequency or rest time. Duty cycle is determined based upon a combination of resistor rating and the stored energy to be dissipated for the specific equipment for which it is used.

Electrical Safety Authority (ESA)

An electrical safety committee, engineer, or equivalent qualified individual who ensures the use of appropriate electrical safety-related work practices and controls. The ESA shall be permitted to delegate authority to an individual or organization within their control (from Article 350, 2021 NFPA 70E).

Note: Those sites that implement an ESA for the approval of unlisted electrical equipment and electrical worker safety (NFPA 70E) typically have a separate AHJ for the approval and enforcement of facility installations (NEC).

Ground Stick

A device that is used to ensure that the capacitor is discharged by applying it to all terminals of the capacitor element.

Note: This is also called a ground hook and could incorporate power/voltage-rated discharge resistors for higher energy applications.

Hearing Protection Boundary

Worker distance at which a 1 percent probability of ear damage exists from a 20 kPa (3.0 psi) shock wave.

High-Impedance Discharge

The process of discharging a capacitive storage element to ground through a resistor or resistor network to limit peak current and control the energy discharge. This process limits current and occurs more slowly than a low-impedance discharge.

Note: This may also be known as a “soft dump” or “soft ground”.

Low-Impedance Discharge

The process of discharging a capacitive storage element directly to ground, or across the two terminals of an isolated capacitor. This process does not limit current significantly and occurs much more rapidly than a high-impedance discharge. The discharge current should be limited to 500 A to manage impulse magnetic forces on the ground stick cable.

Note: This may also be known as a “hard dump” or “hard ground”.

Lung Protection Boundary

Worker distance at which a 1 percent probability of lung damage exists from a 70 kPa (10 psi) shock wave.

Marx Bank

A capacitor bank configuration whereby the capacitive elements are charged in parallel and discharged in series. Grounding or safing of such a configuration requires adequate risk assessment to ensure energy removal has been completed and maintained in a safe manner. Failure analysis must be included because certain failures result in an isolated capacitive element that may remain fully charged.

Probe

A term used in this document that refers to the tip of the ground stick that will make contact with the high voltage terminal. The probe may be a straight tip, or curved to facilitate handing on a terminal. The probe may have other geometric shapes to facilitate the contact of the high voltage terminal, or the bridging of two capacitor terminals.

Qualified Worker

One who has demonstrated skills and knowledge related to the construction and operation of electrical equipment and installations and has received safety training to identify the hazards and reduce the associated risk (NFPA 70E-2021).

Ringing

An underdamped oscillation upon capacitor discharge that has voltage reversal. Many capacitive systems cannot withstand this voltage reversal. This will usually occur during a low-impedance discharge with a hard ground stick (i.e., no damping resistor).

Safe, Safing

The action of discharging the stored energy of a capacitor is the “Safing Process”. It is common to use “Safe” as a verb and “Safing” as a process.

Shorting Sticks

A device for those applications which do not allow the capacitor to be brought to ground potential, but do require discharge of a capacitor. Cables connect the two or more sticks involved and are rated for the capacitor voltage and the system voltage to ground.

Note: This is also called differential stick and could incorporate power/voltage-rated discharge resistors for higher energy applications.

Shorting (Drain) Wire

Conductor applied to capacitor terminals after energy has been safely discharged to ensure residual charge or induced charge cannot build back up.

Single-bushing capacitor

A capacitor module which uses the conductive case as the return connector for charge/discharge current flow.

Time Constant

The time it takes for the voltage to drop by ~ 63 percent (1/e) during discharge.

4 General Ground Stick Construction Requirements

4.1 General Requirements

Engineering controls should be incorporated into the initial design of a capacitor bank. Bleeder resistances, voltage isolation and worker access to grounding and shorting terminals should be engineered into the system as part of the original design. This design should be approved by the site AHJ or ESA.

Systems which store energies above 100kJ should be engineered with remote discharging subsystems to mitigate worker exposures to potentially fatal arc blast hazards based on the lung collapse boundary (see 2021/2024 NFPA 70E, Article 360 and Annex R).

The specific needs of the capacitor or capacitor bank and the process for applying grounds sticks should be considered in the design of the ground stick, as each system may have unique requirements. This includes consideration in the design of the shaft, hand stop, probe, resistor, cable, and connections.

4.2 Ground Stick Shaft/Hand-stop Requirements

The diameter of the shaft should be selected to provide tensile strength without adding a weight so excessive that the average worker cannot readily manipulate the ground stick in a controlled fashion for the interval necessary to bring the capacitor to a safe condition. The length of the shaft should be selected so as to ensure that the worker's hands remain outside of the Restricted Approach Boundary (RAB), as defined by NFPA 70E, 2021/2024 edition, Table 130.4(E)(b) *Shock Protection Approach Boundaries to Exposed Energized Electrical Conductors or Circuit Parts for Direct - Current Voltage Systems*. The hand-stop element must be designed to prevent the worker's hand from encroaching on the Restricted Approach Boundary (RAB). It must be located such that the worker can easily maneuver the stick toward the capacitor.

Note: For higher voltages the distance to the hand-stop element may be less than the RAB as approved by the Authority Having Jurisdiction (AHJ) or Electrical Safety Authority (ESA). The RABs listed in NFPA 70E were taken from the utility industry for bare wires able to move on overhead transmission/distribution lines and were not meant for fixed equipment.

4.3 Ground Stick Probe Requirements

The ground-stick probe metal should be selected to minimize corrosion and oxidation which would diminish the conductivity of the probe. It should be robust enough to handle the expected discharge current without suffering undue mechanical strain. The shape of the probe should be engineered to facilitate ease in contacting the capacitor terminals or other bus work associated with the system and, if appropriate, land or rest upon the conductor throughout the de-energization interval (this leads to a common use of a "hook"). The geometry of the probe should be appropriate for the purpose.

4.4 Soft Ground Stick Resistor Requirements

The resistor element should be selected to meet the electrical parameters (voltage and energy) of the capacitor(s) to be discharged. The resistor must be rated for the maximum capacitor voltage for its intended use, to prevent internal or surface flashover failure of the resistor. Location altitude may need to be considered for the voltage rating.

For larger capacitors the design should avoid voltage reversal of an under-damped discharge waveform (ringing). Thus, the resistance, R, should be chosen to create a critically or overdamped waveform. (Figure 2) This must be balanced with the worker's need to minimize the time necessary to maintain contact the capacitor. Once the resistance value is selected, the peak current can be derived from the system voltage and Ohm's Law: I = V/R. The instantaneous power must then be calculated to ensure that the resistor selected can dissipate the energy. The resistor selected should withstand the total energy without excessive heating or damage. This requires knowledge of the duty cycle for the ground stick.

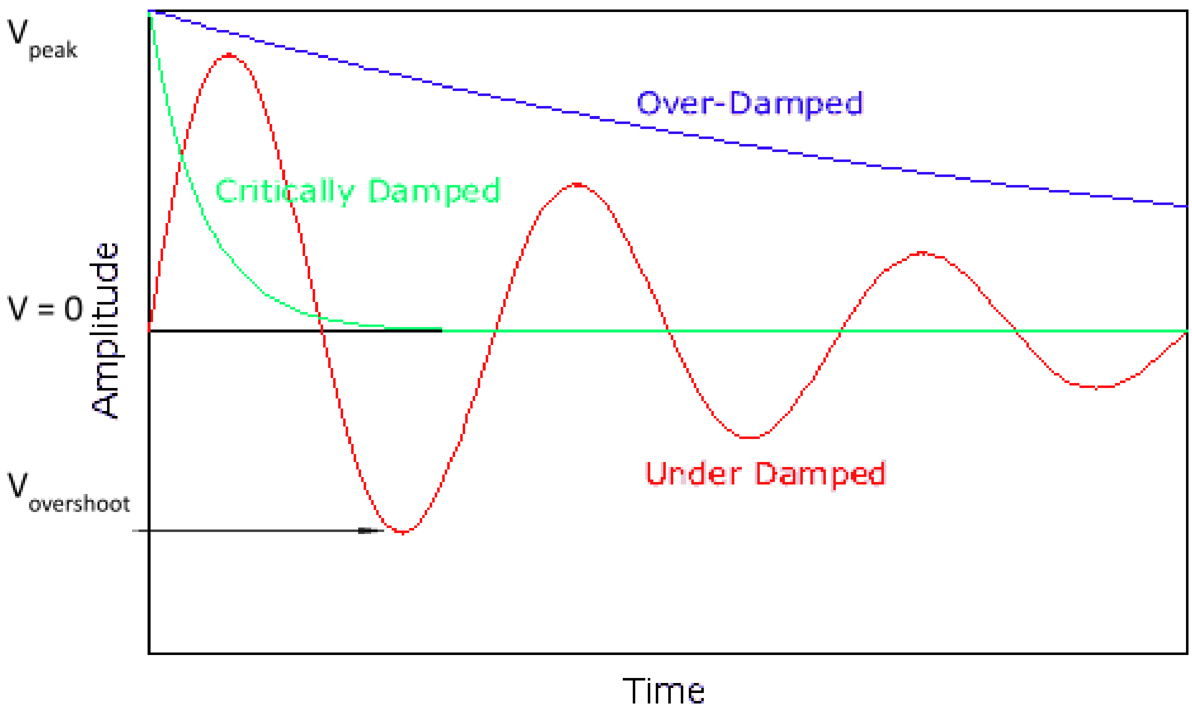


Figure 2. Damping of a capacitor discharge.

The resistor should be chosen to keep the peak discharge current under 500 A, to avoid excess impulse magnetic forces on the cable and connections.

4.5 Ground Stick Cable Requirements

The ground stick cable should be finely stranded to provide adequate flexibility. The cable should be designed with a transparent sheath to protect the cable from mechanical damage and contaminants. The sheath is to protect the cable and may not be sufficient to protect personnel from hazardous voltages and this should be considered in the procedures and training to use the ground stick. The cable must be sized to protect the cable and its sheath from thermal damage from the energy transferred through the ground stick cable. The cable terminations should be compression connectors or lugs, sized for the cable size and stranding type.

Note: For a shorting stick, the cable sheath insulation should be rated to the maximum capacitor-to-capacitor voltage and the maximum floating system to ground voltage.

4.6 Ground Stick Connector Requirements

The connector(s) terminating the cable must be selected to accommodate the cable diameter and the calculated peak current. For the connection of the cable to the stick a robust permanent connection (crimped) should be used. The connection means for the cable at the equipment should follow good engineering practices. Temporary connectors such as alligator clips or C-clamps should be avoided for energies above 1000 joules. Connectors should provide for visual inspection of the termination integrity.

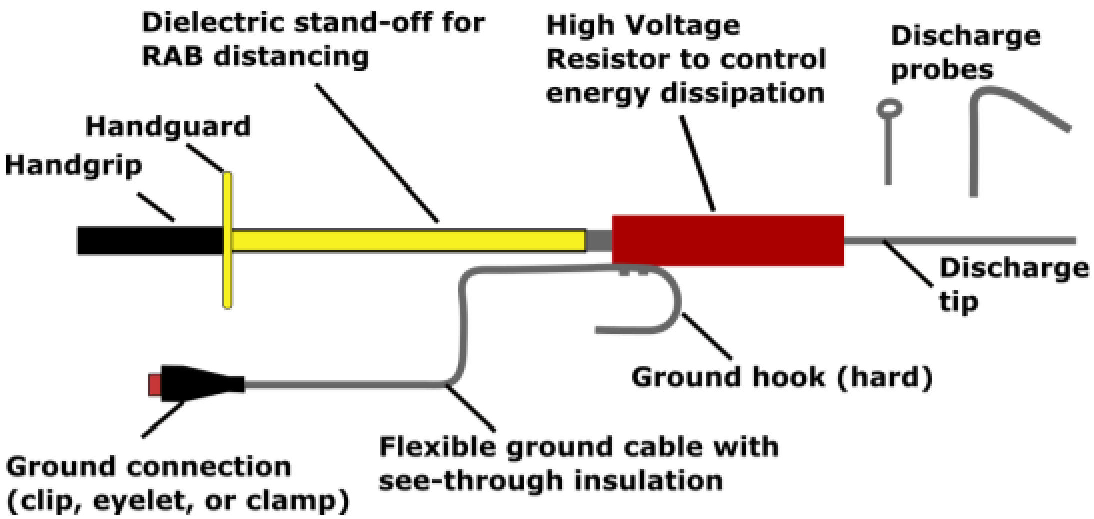


Figure 3. Diagram of a typical ground stick.

4.7 Identification Labeling

Minimum permanent labeling should include a unique equipment identifier, voltage rating and testing expiration and the following information should be readily available to include: ground sticks should be labeled for maximum voltage and testing expiration date. In addition, soft ground sticks should be labeled for stored energy and duty cycle. Examples of “readily available to the worker” would either be to label the stick directly with serial number and test expiration date labeled directly on the stick with a linked reference document in the case that tracking is managed through a database.

The labeling method should not impact the voltage, energy or power ratings of the device.

5 Inspection and Acceptance Testing

5.1 Initial Inspection and Evaluation of the Ground Stick

The initial inspection should be performed upon receipt, after repair, and the first time the stick is used for a specific application. The initial inspection and evaluation should consist of the following steps:

(1) Verify that the design and ratings of the ground stick are suitable for the application and that the ground stick is labeled appropriately.

(2) Verify that the length of the stick from the handguard to the nearest conducting component (e.g., cable connection) is sufficient to keep the user outside the Restricted Approach Boundary for all intended applications, unless otherwise approved by the AHJ or ESA.

(3) Verify that the shaft, contact probes, resistor, terminations, and cable of the ground stick are undamaged and free from visible defects (see 4.1)

(4) Verify that the resistor meets the value determined in the design document for the specific application, both from labeling and by measuring the resistance.

(5) Verify that the cable measures less than 0.1 ohm from the stick to termination.

(6) Verify, using manufacturer-provided documentation, that dielectric testing has been completed and that the stick meets the requirements of the application, or have in-house dielectric testing performed to ensure that the stick meets the voltage rating. Consult ASTM F711 for guidance. Dielectric testing should occur every two years at a minimum or whenever the dielectric strength is in question.

5.2 Ground Stick inspection daily or before each use

Inspect the components of the device for damage and visible defects:

- Label determining voltage rating, and dielectric test within the last two years
- Handle
- Hand guard
- Shaft
- All fasteners and connections in place and secure
- No damage to cable or transparent insulator
- Solid connection to a contact point visibly bonded to one of the capacitor terminals
- No dirt, oil, or damage to the components
- Resistor (soft ground stick) is in good working order and of the proper value

Remove the ground stick from service if the inspection fails. Repair or replace as necessary.

6 Ground Stick Use and Safe Work Practices

6.1 Stored Energy Hazard Thresholds

(1) Appropriate controls shall be applied where any of the following thresholds are exceeded: (2021 NFPA 70E) From Figure 1, these thresholds are exceeded in the yellow (3.2), red (3.3), and maroon (3.4 classes). Less than or equal to 100 volts and greater than 100 joules of stored energy,

(2) Greater than or equal to 100 volts and greater than 1.0 joule of stored energy,

(3) Greater than or equal to 400 volts and greater than 0.25 joules of stored energy.

Controls may include any of the following: engineering controls to automatically remove energy (e.g., bleeder resistor), actuated systems to discharge the capacitors (e.g., a dump system), permanent voltage indicating devices, portable contact meters for zero energy verification, and/or ground sticks (the subject of this best practice).

Note: Ground sticks should NOT be used for energy removal above a stored energy of 100 kJ (classes 3.4). After remote energy removal has been verified for systems above 100 kJ, ground sticks should be applied as a visual verification to workers that the system is in Mode 0, the Electrically Safe Work Condition.

Similarly, ground sticks should be left in place for all safing procedures, regardless of energy, as a visual indication of a Mode 0 state, unless drain wires or other approved visible shorts are approved by the AHJ/ESA.

6.2 Performing a Risk Assessment for Capacitors

Before any procedure to achieve an electrically safe work condition (to safe the system) a risk assessment must be performed to identify and manage the thermal, shock, and arc blast hazards, and to choose the appropriate controls, including PPE. See the 2021 or 2024 NFPA Article 360.4(B) for details. Accessing capacitors may be challenging and might contribute to the likelihood of making accidental contact or mistakes, due to poor lighting or capacitor placement within the equipment. Equipment and environmental conditions are additional factors that should be taken into account when performing a risk assessment. Figure 4 is an example of such a small system.

Some level of PPE eye protection is almost always used due to possible sparks, and hearing protection is required for entry at energies above the hearing protection boundary.

Dielectric gloves are not required if the hands are outside of the RAB. If the AHJ/ESA approves the use of a ground stick where the hands are inside of the RAB, dielectric gloves might be specified to be worn. However, note there is NO dielectric glove rated above 40 kV (class 4), plus, the higher classes of gloves (3 and 4) are very cumbersome and make holding the shaft of the ground stick difficult. During a risk assessment, some AHJs argue that the hands are separated from the probe by a distance from the probe to the hand guard, and the likelihood of exposure to a shock hazard is extremely low.

Arc-rated PPE is not required for the safing of capacitors as staying outside of the RAB or lung collapse boundary typically keeps the worker outside of any calculated Arc Flash Boundary. A risk assessment will verify this general conclusion for the specific cases.

Workers should not be allowed within the Lung Collapse Boundary, as there is no available PPE for the acoustic shock hazard.

See the 2021/2024 NFPA 70E for details on the selection of PPE for the safing of capacitive stored energy.

Figure 4. Two capacitors embedded in a system.

The hazard classification tables and Risk Evaluation flow charts from EFCOG Best Practice #252 Hazard Identification & Risk Assessment Figures, Tables & Charts, are useful in assisting personnel with responsibilities for performing a risk assessment, particularly when multiple electrical waveforms are found in a system. The hazard classification tables were formerly in the DOE Electrical Safety Handbook (2013 edition). The Best Practice #252 has improved upon the tables (adding a Risk column) and several Risk Evaluation flow charts and information specifically meant for performing Risk Assessment of electrical hazards. One should be familiar with Best Practice #252 and experienced with performing Risk Assessment prior to using the tables and figures. Contact an SME or your ESA or AHJ for how to use the Risk Assessment tables prior to attempting to perform a risk assessment on a system with multiple wave forms or hazardous capacitance. Selected Tables and Figures have been provided for convenience in the Chapter 8 of this Best Practice.

6.3 Worker Qualification and Training

A ground stick user is required to be a qualified electrical worker (QEW) including appropriate on-the-job training (OJT). The AHJ and equipment SME should be involved in the OJT and approval of the worker for using a ground stick on the system by going through the detailed requirements of the specific system. The worker should perform a demonstration of proficiency (DOP) on the specific ground stick and its application. If the work is conducted less frequently than annually, an annual DOP is required for a worker to stay qualified.

6.4 Operation

Soft grounding is required above 1000 J (NFPA 70E Annex R.11.4). When using a soft ground stick, calculate the decay time to get the energy below 1000 Joules before placing hard grounding:

$$\tau = RC$$

$$V(t) = V_p \, e^{-t/\tau}$$

$$E = \frac{1}{2} C V^2$$

Solve for V_{1000J}=sqrt(2E/C)

Td=-ln(V_{1000J}/Vp)*τ

where:

E = target energy (Joules) = 1000J

V_{1000J} = voltage (Volts) at which the energy is reduced to 1000J.

τ=time constant(sec)

R=discharge path resistance (Ohms) = stick resistor value

C=total capacitance (Farads)

T_d=discharge time (wait time) (sec)

V_p=peak voltage (Volts)

Ensure that hands are placed behind the hand guards. Keep the entire body out of the RAB. Ensure the stick ground cable is at least one RAB distance away from all body parts and well connected to a ground shared with the capacitor to be discharged (Figure 5). Touch the tip of the soft ground stick to the capacitor discharge point. Ensure contact is made for enough time to drop the energy below 1000 Joules. These time calculations should be provided in the work procedure. Then follow the soft ground stick contact with a hard ground stick contact to drain the remaining energy (see Figure 6).

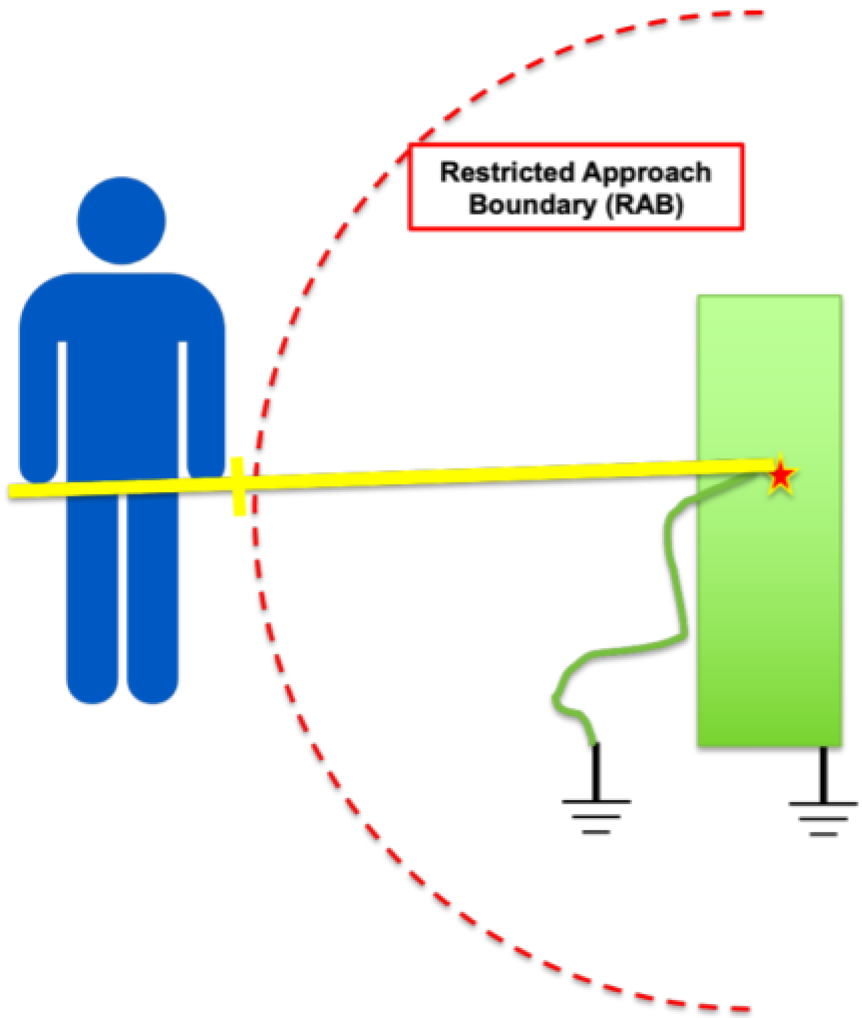


Figure 5. Diagram of using a ground stick.

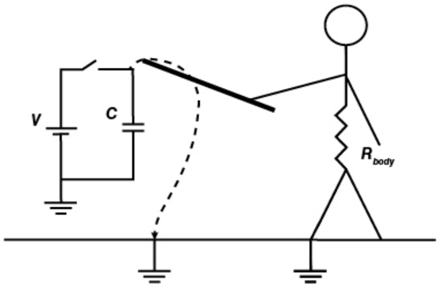
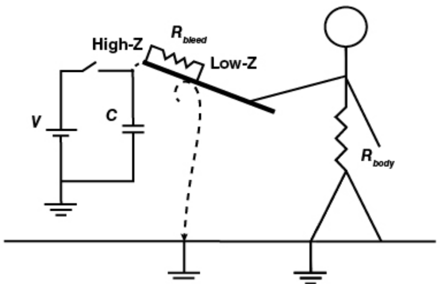
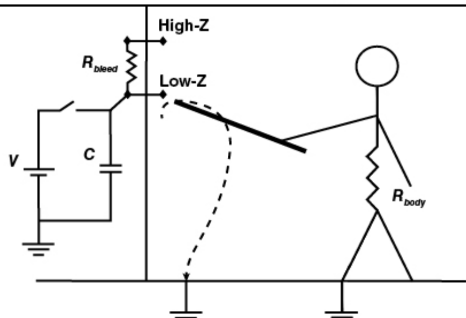
	**Hard grounding:** An insulating stick with a grounding tip is used to discharge a capacitor between its two terminals and then to ground.
	**Soft grounding 1:** An insulating stick with a mounted resistor is used to perform a controlled discharge of the capacitor charge using the High-Z tip first. Then, after the prescribed wait time, hard grounding is applied with the second (Low-Z) tip that bypasses the resistor.
	**Soft grounding 2:** An insulating stick with a grounding tip is first applied to the High-Z point to perform a controlled discharge of the capacitor. Then, after the prescribed wait time, the grounding tip is applied to the Low-Z point to bypass the resistor and hard-ground the capacitor.

Figure 6. Procedures for using a ground stick.

6.5 Application of Drain Conductor after Discharge

Following verification of a complete discharge of stored energy, the ground stick(s) must remain in place on the capacitor terminals to prevent any capacitor recharging. If the capacitor in isolated from the system, or is intended to be transported, stored, or disposed of, a drain wire should be applied between all capacitor terminals. The drain wire (s) is applied by a QEW while a zero-energy state is maintained by another QEW holding the ground stick on the terminals, by a ground stick left hanging on the terminals, or by an approved engineered system maintaining a zero-energy state.

The drain wire should be a bare wire of sufficient size so as not to be broken or knocked loose during subsequent activities, and attached in a way that it will maintain contact.

Figure 7 illustrates the safing of a 1 MJ capacitor module. At least 4 levels of engineering controls were implemented to assure the module is discharged before the two soft shorting/ground sticks are applied by the two workers on the right. The worker on the left is preparing to attach a drain wire across the module, which will be left in place during the work procedure.

Figure 7. Example attaching a drain wire. Two workers on the right are holding soft shorting/ground sticks across a 1 MJ bank, while the worker on the left approaches with a drain wire.

6.6 *Safing a Damaged Capacitor*

One of the most challenging problems in capacitor safety is when the capacitor is damaged. The damage may be obvious, such as in Figure 8, or may not be visible. Signs can include an abnormal noise during operation, bulging of the case, or a change in operational behavior.

The state of the capacitor may not be known. A worst case is when a terminal open circuits inside the case, leaving charge that can't be removed from the outside with normal methods. This situation is potentially very hazardous. Work should be stopped and appropriate subject matter experts consulted. Risk assessment should be conducted considering all possible failure modes and states of the capacitor. A unique procedure with potentially additional protective measures will likely be required.

Figure 8. A failed capacitor.

7 Examples of Safing Capacitors

The following examples illustrate some possible scenarios for safing capacitors. They are not all inclusive, each process is unique to the system design. These examples are intended to start with simple work and progress towards more complex systems.

7.1 Safing an isolated capacitor

Figure 9 is an example of a capacitor that is isolated and not installed in a system. This should only occur (a) if it was received in shipping without a drain wire (shouldn't happen), (b) it was discovered in storage or in a laboratory setting without a drain wire (not supposed to happen), or (c) it was just removed from a system and it was difficult to place a drain wire during removal of the connections.

The probe tip must be able to contact both capacitor terminals simultaneously to short the capacitor and bring it to ground potential. In some cases, the probe tip may need to be custom built to reach across the two terminals, or two ground sticks may be needed, or a pair of shorting sticks that are also grounded.

The next step will be to place a drain wire between the two terminals.

Some observations, which should be a part of a risk assessment, and documented:

(a) This capacitor looks like a two terminal capacitor that may be isolated from the case. Although there is a very small case capacitance to ground, it is negligible, in this case. Touching the case with the ground stick will verify this. Once the drain wire is in place the capacitor case can't recharge, since the dielectric from the case to ground is air, and air does not have dielectric memory, i.e., can't recharge.

(b) This is about a 10 kV capacitor (should be a part of the risk assessment) and the length of the ground stick to the hand guard is sufficient. The dielectric gloves seen in this example are not required if the hand guard is outside the RAB.

(c) This capacitor is on the order of 10s kJ. Eye protection is required for sparks and hearing protection may be required.

(d) There is no arc flash hazard or lung collapse hazard

Figure 9a

Figure 9b

Figure 9. Example 1. Shorting a two-terminal, isolated capacitor with a hard ground stick.

Figure 10 is another example of an isolated capacitor that needs to be safed and a drain wire applied.

In this example a single stand-alone capacitor with exposed terminals needs to be safed for storage or disposal. The following procedure is used to safe the capacitor (Figure 9a):

Figure 10a. Example 2. An isolated, unsafe capacitor.

1. Determine the operating parameters of the capacitor:
   220 microFarad, max Voltage 600 Volts
   This results in an energy of $\frac{1}{2}CV^2$ = 39.6 Joule

2. Given this energy, it is safe to use a hard ground stick on this capacitor. Eye protection should be used, no hearing or arc flash PPE is required. A ground stick with 0.3 m (1 ft) will keep the worker’s hands outside of the RAB. No shock protection is required, the ground stick serves that purpose.

3. Using a properly rated ground stick connect the two terminals and short them together (Figure 9b).

Figure 10b. Applying the probe of a hard ground stick across the two terminals.

4. Once the capacitor is safely discharged, immediately place a bare copper wire, as a drain wire, around the two terminals ensuring they stay shorted out. Use at least a 14-gauge uninsulated wire for the task (Figure 9c).

Figure 10c. Capacitor with a drain wire in place between the two terminals.

7.2 Safing a single capacitor in piece of equipment.

Figure 11 is an example of a single capacitor installed in a chassis. The capacitor is small, 450 VDC, less than 10 J.

Although there is a bleeder resistor between the two capacitor terminals, single bleeder resistors can fail and can’t be used to determine a safe condition. A hard ground stick must be applied across the two terminals and a drain wire applied before working in this chassis.

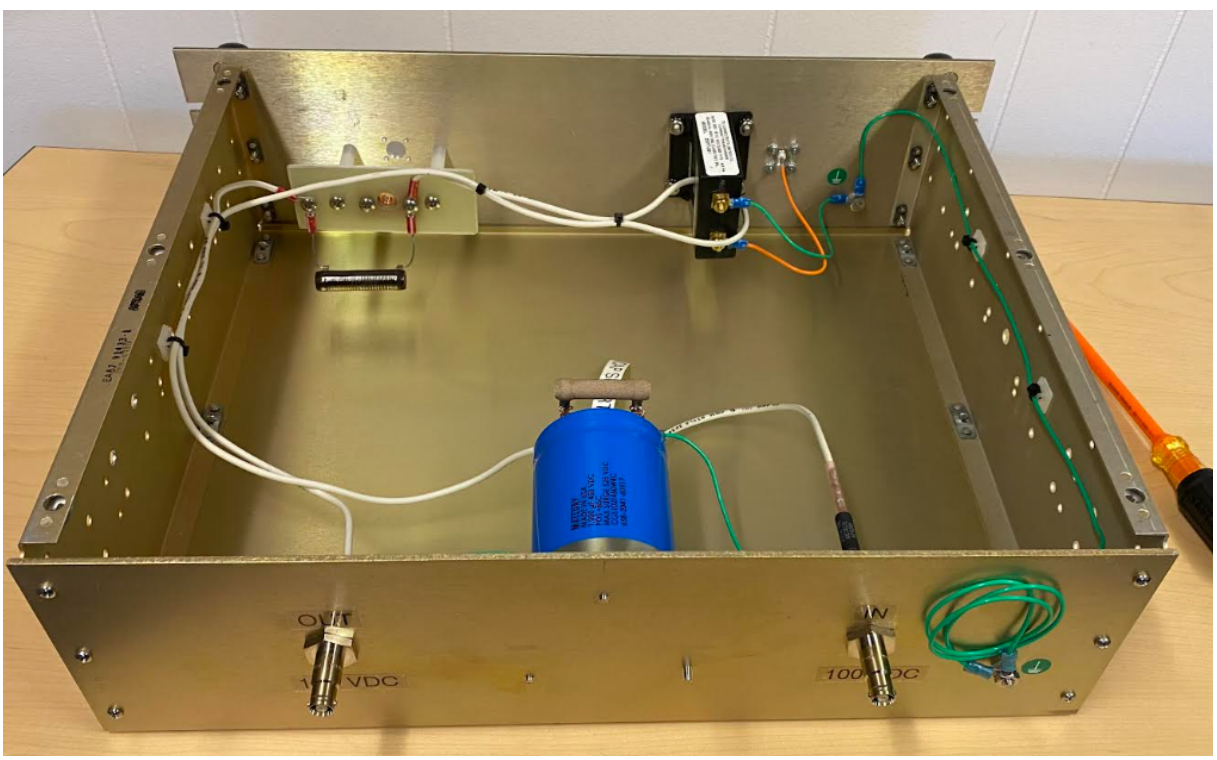


Figure 11. A single capacitor in a chassis.

7.3 Safing a capacitor embedded in a system

Figure 12 is an example of two capacitors installed in a system. The purpose of this example is to illustrate the complications of difficult-to-access capacitors in an unknown circuit geometry.

First, two electrolytic capacitors can be seen in the lower right corner of the photo. Sometimes it is difficult to read the parameters on the capacitors, in which case the information needed for a risk assessment must be obtained from the manual schematics or the manufacturer.

Second, it may be impossible to determine the circuit configuration (i.e., schematic) by visual inspection. In this case, the two capacitors seem to be in a center-tapped, series configuration, with two terminals tied together by the metal buss plate, and a red lead on one capacitor, and a black lead on the other one.

Without a schematic, it is impossible to tell if any terminal of either capacitor is grounded. Thus, one has to assume that they are floating and each capacitor must be discharged separately. A ground stick may be used to discharge two terminals of the left capacitor (buss plate to red-wire terminal) and then immediately discharge the two terminals of the right capacitor (buss plate to black-wire terminal). Two drain wires must then be applied.

Even though this simple system appears (from the view presented) to only have two capacitors, complications include: (a) can't read the capacitor parameters, (b) can't determine circuit configuration by visual inspection only, (c) limited space to apply ground sticks and drain wires, and (d) there are two capacitors to be managed separately.

The key point is that a risk assessment and development of a procedure should be done by someone very familiar with the system, or able to gather the knowledge to understand it.

Figure 12. Two capacitors embedded in a system.

7.4 Multi-section Capacitor

Some capacitor packages may have multiple capacitors in a single enclosure. Figure 13 in an example of a multi-section capacitor with fluid cooling - typically used for high power applications like resonant converters.

Figure 13. Six capacitors in a single enclosure.

Two possible methods to safe this example would be to use 6 ground sticks, although it would be cumbersome to manipulate six, and to not knock on off while applying the others.

Another option would be to design a special probe that could contact all six terminals.

It is important to realize that all capacitor safing procedures are not identical and design, risk assessment, and a procedure may be unique to the situation.

7.5 Distributed capacitance in cables or other parts

A discrete capacitor is a component designed for the purpose of providing capacitance for filtering, oscillation, or energy storage. The discrete capacitor is in a dedicated enclosure and is labeled with the capacitance value (typically milli- or micro-Farads). Example of discrete capacitors have been shown above.

But capacitance exists whenever any two conductive surfaces at two different voltages are in proximity, such as parallel plates, or coaxial cable. Often the capacitance is in pF or nF per square meter, or per unit length of coax cable. For medium voltages this may result in stored energies of mJ up to J of energy. However, since energy scales as V squared, for higher voltage, in the 10s to 100s of kV, the stored energies can reach 10s to 100s of J and be a substantial shock hazard.

Examples include: (a) a room-sized metal box biased at 750 kV, (b) a 10 m coax cable at 300 kV for a transmission electron microscope (Figure 14), and(c) a 50 m coax cable at 200 kV for connection to and x-ray source. All three examples have very dangerous or lethal stored energies. Another example is the high-voltage dc testing of medium voltage underground coaxial distribution cables, which may be 100s m long.

Although there be capacitance at the source (the dc power supply) and the load, the capacitance of the coax cable is often overlooked and must be analyzed for risk to the workers, especially when disconnecting such cable.

Procedures must be developed to assure discharge of the stray capacitance while preventing a shock. On occasion these procedures may seem to bring a worker's hands well within the RAB, but the key is to have a grounded shield between the HV terminal and the worker as the cable is discharged.

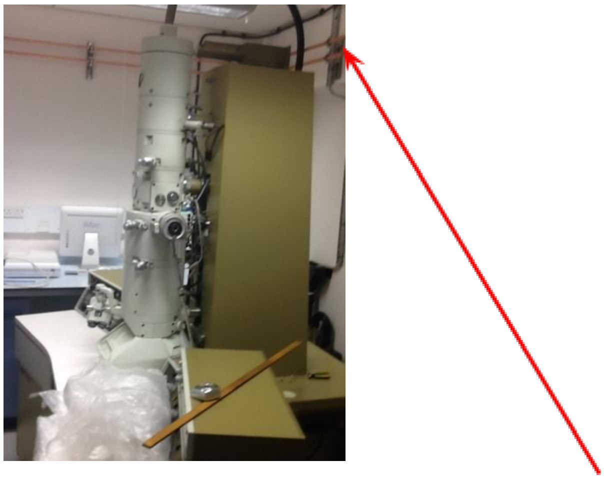


Figure 14. Transmission electron microscope, 300 V high-voltage coaxial cable.

7.6 Series/Parallel Capacitor Configurations (Voltage Multipliers, Marx Banks)

Voltage multipliers and Marx banks use series-parallel capacitor configurations and should only be discharged and made safe for others to work on after having a risk assessment completed and reviewed by two separate equipment SME's to reduce the likelihood of human error when addressing the sequencing of steps being performed while placing the equipment into an electrically safe work condition and to continually perform real time risk assessment. The capacitor elements and failure modes may not be readily apparent. This best practice is NOT TO BE USED to discharge specific equipment and the information provided below is meant to briefly describe some of the hazards and challenges associated with these equipment configurations.

Compact Marx circuits are used in a research environment for portable x-ray generation. Marx circuit for pulsed x-ray generation are available for a total voltage output from 150 kV to 1.5 MV. A Marx circuit works by charging multiple capacitors in parallel and then quickly switching them into a series configuration to add the voltage of all of the stages. In the simple circuit in Figure 15, three capacitors are charged to 30 kV and then switched to be in series. A 150 kV output Marx might have 10 sections charged to 15 kV, giving a series circuit voltage of 150 kV. A 1.2 MV output Marx might have 40 sections charged to 30 kV, to give a final output voltage of 1.2 MV.

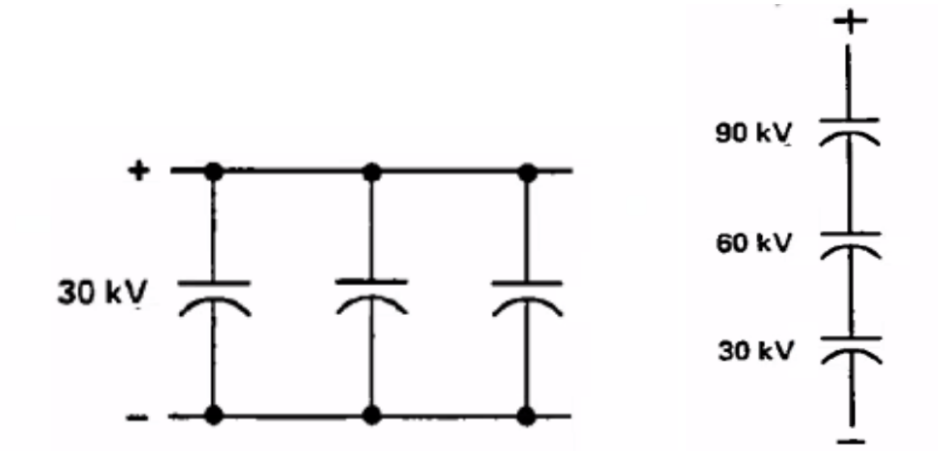


Figure 15. 3 capacitors charged to 30 kV, switch to 90 kV in series.

Compact Marx units are compact by constructing them from potted (encased in a molded compound) sections. The internal elements include the capacitors and parallel charging inductors or resistors. The individual components can't be accessed, nor can damage be seen.

The individual modules making up the stack may consist of a single capacitor and spark gap or may include more than one capacitor per module and include multiple external contact points per module. Figure 16 is an example of 10 potted modules.

Figure 16. example of a small Marx stack of 10 modules

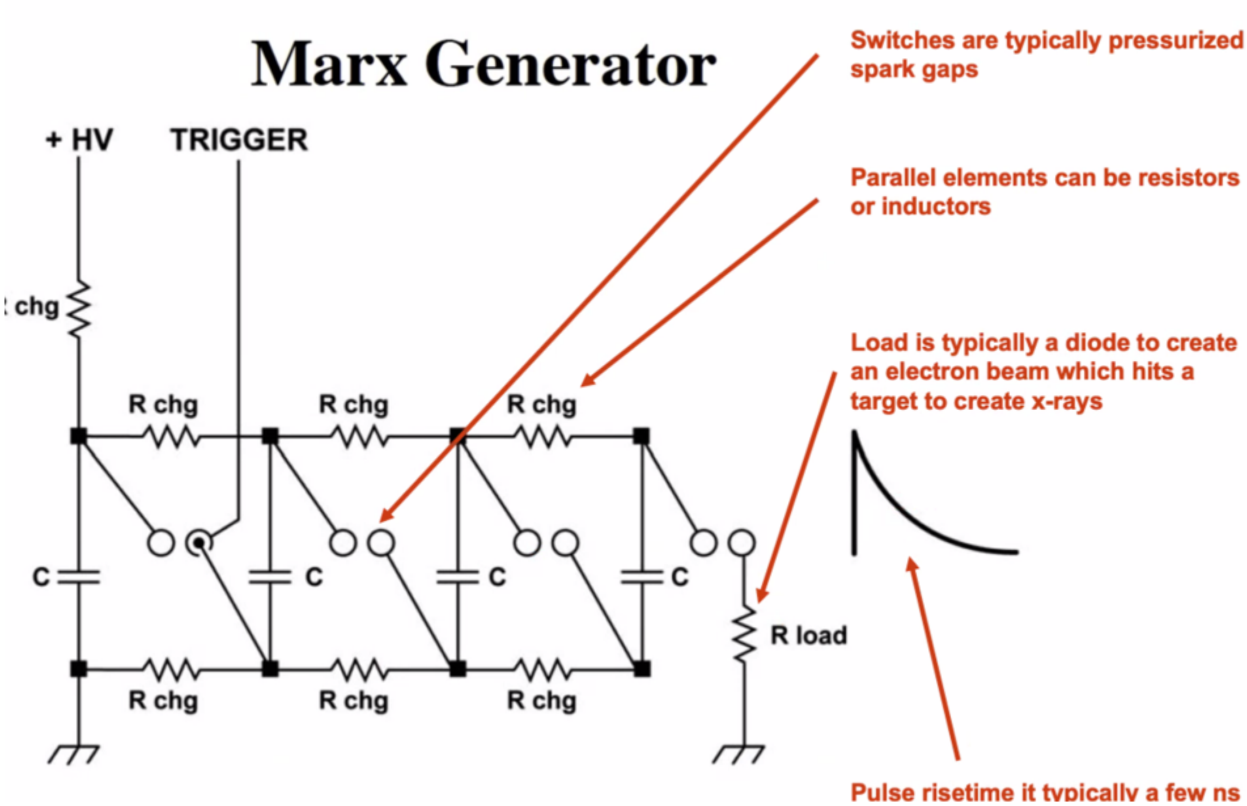


Figure 17. Circuit of a resistor charged, 4-stage Marx.

Figure 17 is an example of a complete Marx circuit with 4 capacitors being charge in parallel through the resistor ladder network. When the 4 spark gaps are triggered (switched on to be a short circuit) the 4 capacitors appear in series as the Marx "erects" to create a high voltage output. In a typical compact Marx, the resistors and capacitors are all embedded in a solid caste dielectric and can NOT be seen or accessed. The only access points to the internal components are the spark gaps.

There are failure modes where an internal resistor or connection fails, leaving one or more capacitor elements charged.

Working on Marx circuits is uniquely hazardous and requires extensive training and experience to work safely.

There have been numerous incidents and accidents at several DOE and DOD research labs on Marx circuits.

7.7 Safing discrete capacitors installed in a system

This is an example of safing HV components in a complex system and is appropriate for use in training.

Discrete capacitors installed in a system, such as the research apparatus in the Neutralized Drift Compression Experiment NDCX II experimental set up at LBNL uses a combination of dc power supplies capable of supplying 0.15MV of acceleration voltage to ions. The electronics equipment is powered from 120V AC to provide high voltage DC with varying output voltages from 40 kV for acceleration electrode power supply up to 130-kV DC. The system is capable of operating at 150kV DC with 142 Joules of stored energy available.

Figure 18. Photograph depicting the HV enclosure (cage) with custom grounding devices. HV dome can be seen through the front of the interlocked cage doors.

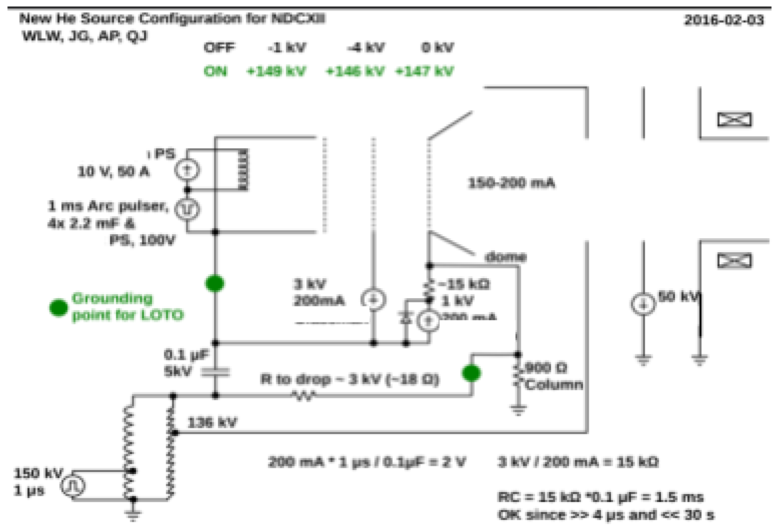


Figure 19. Simplified Electrical Schematic depicting sources of electrical energy and grounding points.

Common tasks that the physicists and mechanical technicians perform that could potentially expose themselves to hazardous electrical energy would be replacing/swapping out the ion source; accessing the HV dome to connect/disconnect a laptop and other measuring device for remote monitoring of injection tests and accelerator performance. Performing the risk assessments for the various tasks, requires understanding and adequately describing both the complete work scope, and hazard(s) identified (via Hazard Classification Tables). LBNL also uses Modes of Work as part of the risk assessment process. Using the hierarchy of controls the following were developed for this equipment:

1. Elimination: Removing the hazard entirely (not possible); however, as technology changes the group does perform yearly walkdowns and discussions regarding the possibility of elimination and/or substitution with equipment incapable of producing dangerous electrical hazards.

2. Substitution: Replacing a severe hazard with a less severe hazard. In the past some of the DC power supplies were replaced with those whose outputs were less hazardous.

3. Engineering Controls: Installing guards inside the HV dome to decrease the likelihood of a potential shock hazard due to dropping tools while making adjustments inside the equipment or making accidental contact with line power and stored energy connection points.

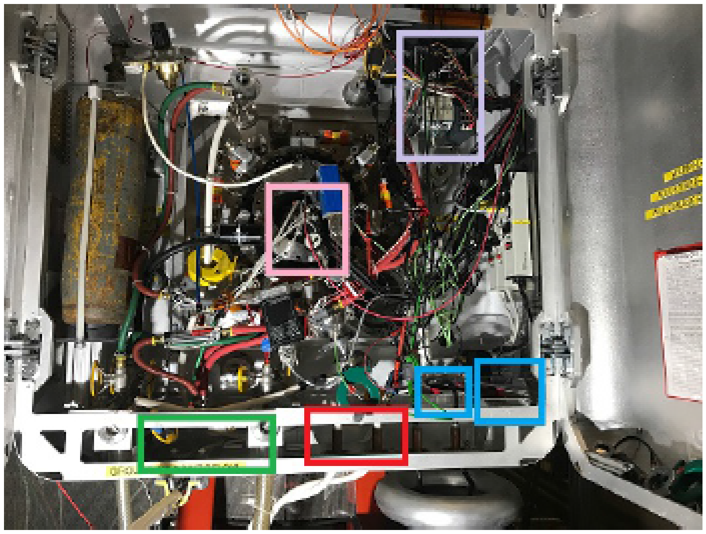


Figure Injector: Electronics adjustment points (in purple box), Ion source area/connections (in pink box), 120 V AC connections inside dome (in blue box), 130 kV pulsed DC connections inside dome (in red box), Grounding point connections (in green box)

Figure 20. Identification of potential electrical hazards and work scope activities to aid work package development and understanding.

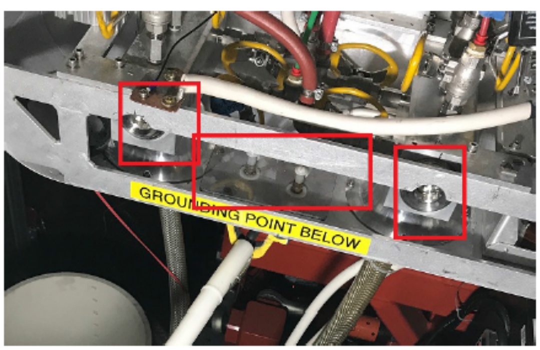


Figure 21a

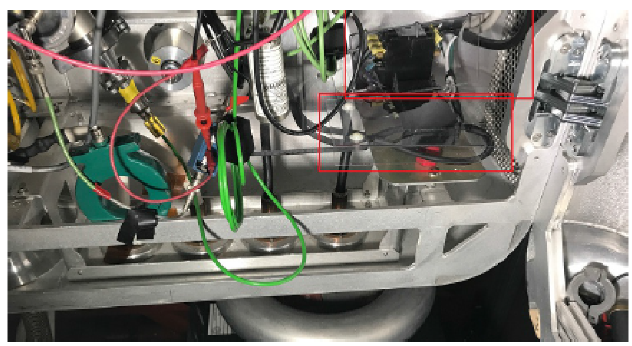


Figure 21b

Figures 21a & 21b Examples of protective enclosures/guards (Engineered Controls)

4. Awareness: Educating researchers, mechanical technicians, engineers and others on the hazards by labeling the equipment, describing approved hazards and controls, providing training and requiring OJT, and providing resources to respond to questions that arise as a result of conditions found in the field. Fixed Retractable barricade tape keeps workers from getting closer than a safe distance to the hazards; signage attached to the barricade tape notifies every

one of the hazards and specifies the controls in place to protect workers and provides a POC for access.

5. Administrative Controls:

   (a) Developed formal work control procedures with specific worker's authorizations, operations procedures, Complex LOTO and equipment specific procedures that identify complete scope of work for which the hazards/risks had been identified and the controls to be used. Requirements that include specific QEW level and tasks for which they are trained and qualified. Limiting the QEW pool that performs this work to staff Physicists permanently assigned to the apparatus and group; and only allowing others to join the LOTO after it has been executed and remains in place. Additionally, Electrical Safety Work Procedures have been created for infrequent tasks, as the situation arises, that include collaboration from SME, Electrical Safety, Engineering to gather documents, review potential failure modes, determine necessary sequencing and tools to use considering equipment location, person(s) interaction, emergency response sequence and Line Management authorization.

   (b) Equipment operation/maintenance status board near the Equipment Control Station with an equipment log.

6. Personal Protective Equipment: Providing QEWs with the appropriate PPE, tools to ensure they can perform LOTO and all needed tasks with the correct tools and equipment and have a LOTO station near the installation where workers store LOTO locks, tags, hasps, etc.

7. Reducing likelihood of Human Error: Including Figure 21a and 21b in the equipment specific LOTO procedure to emphasize location of potential hazards and the Engineering Controls used. These photographs are also embedded into other work control and procedure documents. Additional labeling has also been provided to prevent errors associated with Look Alike equipment.

Accessing the HV Dome to install equipment monitoring devices, requires that the system be placed in an electrically safe work condition due to the potential risk of electrical shock and thermal burns to personnel. LBNL uses an equipment specific Complex LOTO procedure that includes all of the steps needed to ensure stored energy has been discharged and cannot become re-charged during the course of the work inside the dome. The LOTO procedure begins by directing workers to perform a visual condition inspection of the ground dissipation devices (ground cable, stick, contact point, ground cable connection point), and provides a directive to NOT proceed if any item is in question along with who to contact to get the condition(s) resolved.

Each Lab or facility needs to have written procedures that clearly describe the necessary sequential steps to mitigate all of the hazards for the scope of work. Additional elements may be added to procedures to assist with reducing errors and omissions, including equipment labeling using unique equipment identifiers, photographs, limiting the quantity of personnel allowed to perform the tasks, etc. The ground sticks used on this apparatus were custom made for this experiment by a well-known manufacturer. Specific instructions regarding the placement of each device are included in the LOTO procedure along with photos as depicted in Figures 22a and 22b.

12	Using the grounding stick hanging on the left side of the ground cage door (with the ball on the end), place the ball end of the grounding rod in the 3 ball assembly mounted just underneath the HV dome to the left labeled "GROUNDING POINT BELOW". Confirm that the grounding stick handle is not resting on the injector pulser tank. If the grounding stick is seated properly, the handle will support itself horizontally. This step grounds the HV dome and the variac power leads.	

Figure 22a. Example of having steps with photos on the equipment specific LOTO procedure including instructions and displaying Ground Stick equipment ID.

13	Using the second grounding stick hanging on the right side of the grounding cage, touch the railing on the top of the dome and hang the ground hook on the railing on the left side of the dome (so that the dome doors can be opened). The grounding point is labeled "Grounding hook ATAP-GH-047".	

Figure 22b. Example of showing each ground stick placement instructions and photo into the equipment specific LOTO procedure to reduce human error.

The energy dissipation points and devices with equipment specific identification numbers are also called out at the beginning of the LOTO procedure within the Energy Isolation Checklist on front page as seen in Figure 23b

Energy dissipation devices

#	Equipment Descriptor	Dissipation Point	Stored Energy Type	Magnitude	PPE	Device ID Number	Device
1	NDCX-II Injector HV dome variac power leads. (below dome)	GROUNDING POINT ATAP-GH-046	Capacitors	150 kV / 142 J	Minimum PPE and Hearing Protection	ATAP-GH-046	Ground Hook
2	NDCX-II Injector (top of dome)	Grounding hook ATAP-GH-047	Capacitors	150 kV / 142 J	Minimum PPE and Hearing Protection	ATAP-GH-047	Ground Hook

Figure 23. Excerpt from the approved LOTO procedure regarding the ground sticks and PPE to be worn while dissipating energy as approved by the AHJ for Safe Work Practices.

The LOTO locks and ground stick devices are applied by a Qualified Electrical Worker that is task qualified on the apparatus. The devices remain in place for the duration of the tasks included within the scope of work on the procedure; the doors of the HV Dome enclosure are not opened until after this step has been completed, and all LOTO locks have been applied. Workers not involved in the execution of the LOTO who have a need to access the LOTO safe zone to perform work, must be LOTO trained and briefed on the hazards and controls by the LOTO Person in Charge before being allowed to join the LOTO with their personal red LOTO lock and LOTO tag.

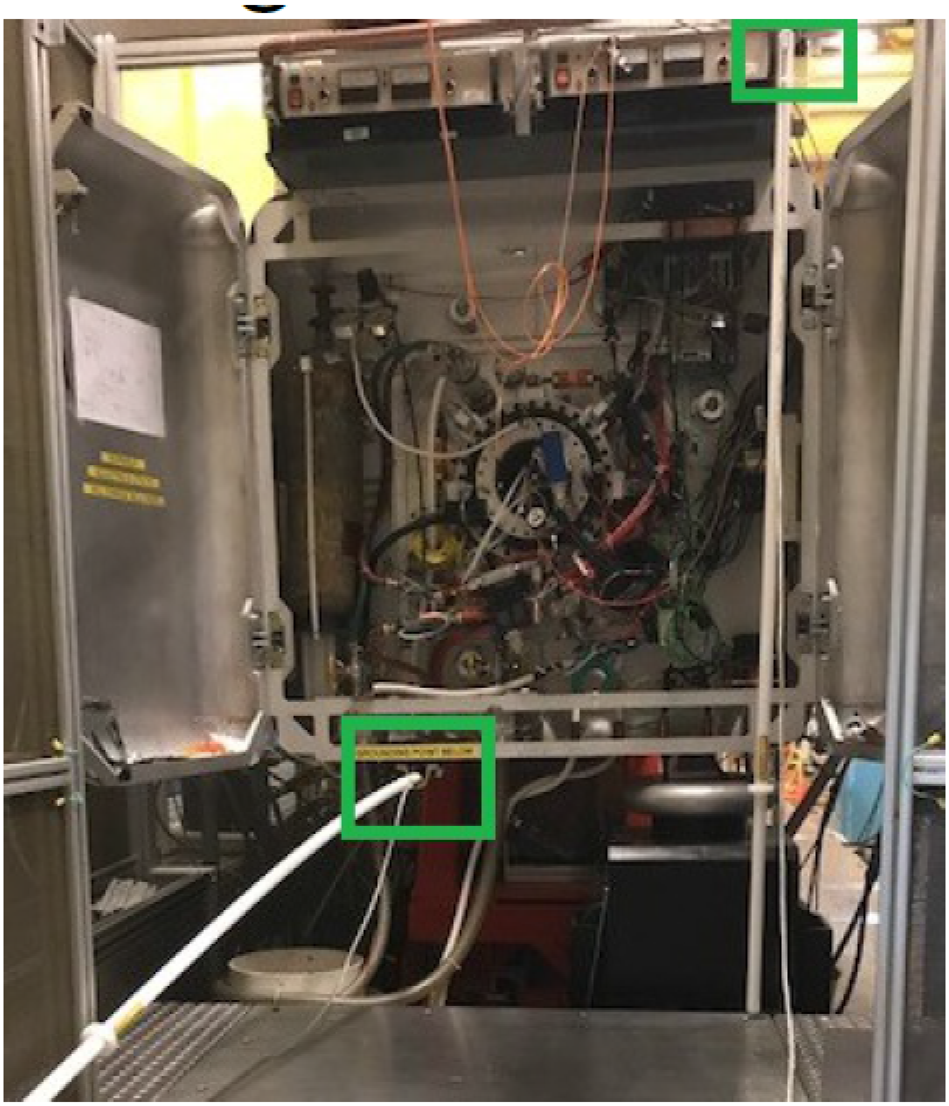
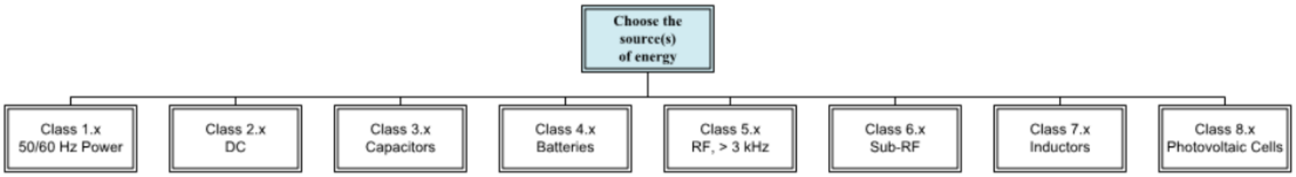


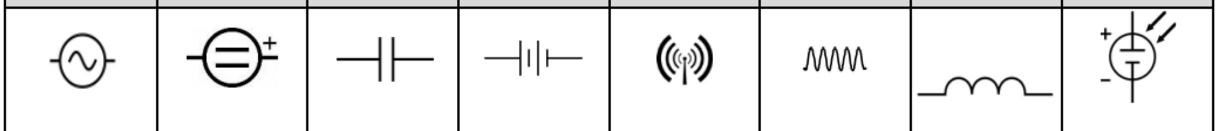
Figure 24. Example of Ground Sticks remaining in place while in an Electrically Safe Work Condition.

NDCX-II High Voltage dome with its two permanently installed ground sticks in the appropriate positions to ensure stored energy has been dissipated and cannot re-accumulate. The one on the bottom left has a ball configured on the end and is placed on the dome variable transformer power leads. The one on the top right of the dome uses a hook attachment. A simplified electrical drawing indicating where the grounding points are with relation to the system is provided in Figure 19. The handles include hand guards and are of sufficient length for the worker to get into position without crossing the 3'10" Restricted Approach Shock Protection boundary for 150 kV.

Similar tools and tables that have been presented throughout this document were used to perform the risk assessment for the experimental apparatus known as NDCX-II. SMEs in pulse power, physics and this installation, LOTO and Electrical Safety collaborated to develop the appropriate controls based on the work scope, specific apparatus, and field conditions and potential failure modes.

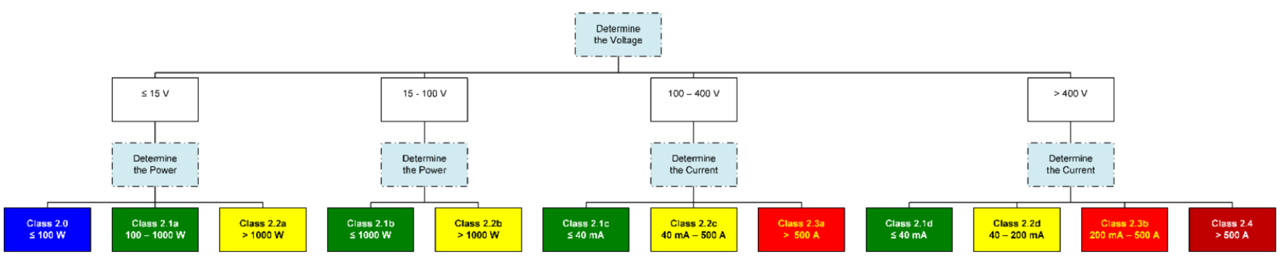
8 Electrical Energy Hazard Classifications EFCOG



Class 1.x	Class 2.x	Class 3.x	Class 4.x	Class 5.x	Class 6.x	Class 7.x	Class 8.x
							
50/60 Hz power	DC	Capacitors	Batteries	RF	Sub-RF	Inductors	Photovoltaic Cells
See Fig. 1-7	See Fig. 1-8	See Fig. 1-9, Fig. 1-10	See Fig. 1-11	See Fig. 1-12	See Fig. 1-13	Future Updates	Future Updates

NOTE: Throughout the following charts and tables, threshold numbers are ≤ and >, unless indicated otherwise. For example, ≤50 V is not an AC shock hazard, >50 V is an AC shock hazard.

Figure 25. Complete Electrical Hazard Classification System - 8 Major Classes of Energy



Notes on use:

1. The voltage is the DC voltage.
2. Power is available short-circuit power.
3. Current is available short-circuit current.

Figure 26. Hazard Class 2.x, DC

Class	Mode	Risk (Section 4.5.1)	Electrical Worker(s)	Training	Work Control	PPE
2.0 ≤15 V, ≤100 W	All	Low	Alone	None	None	None
2.1a,b,c,d ≤100 V, ≤1 kW or >100 V, ≤40 mA	All	Low	Alone	Non-Energized	None	None
2.2a,b ≤15 V, >1 kW or 15 - 100 V, >1 kW	0	Low	Alone	Non-Energized[1]	None	None
	1	Low	Alone	Energized, DC[2]	None	Insulated tools, gloves, eye protection
		Moderate	Two Person[3]	Energized, DC[2]	YES	Insulated tools, gloves, eye protection
		High	Safety Watch	Energized, DC[2]	YES	Insulated tools, gloves, eye protection
	2	Moderate	Two Person[3]	Energized, DC[2]	YES	Insulated tools, gloves, eye protection
		High	Safety Watch	Energized, DC[2]	YES	Insulated tools, gloves, eye protection
	3[4]	Moderate	Two Person	Energized, DC[2]	YES, EEWP	Insulated tools, gloves, eye protection
		High	Safety Watch	Energized, DC[2]	YES, EEWP	Insulated tools, gloves, eye protection
2.2c 100 - 400 V, 40 mA - 500 A	0	Low	Alone	Non-Energized[1]	None	None
	1	Low	Alone	Energized, DC[2]	YES	Shock Risk Assessment[5]
		Moderate	Two Person[3]	Energized, DC[2]	YES	Shock Risk Assessment[5]
		High	Safety Watch	Energized, DC[2]	YES	Shock Risk Assessment[5]
	2	Moderate	Two Person[3]	Energized, DC[2]	YES	Shock Risk Assessment[5]
		High	Safety Watch	Energized, DC[2]	YES	Shock Risk Assessment[5]
	3[4]	Moderate	Two Person	Energized, DC[2]	YES, EEWP	Shock Risk Assessment[5]
		High	Safety Watch	Energized, DC[2]	YES, EEWP	Shock Risk Assessment[5]
2.2d >400 V, 40 - 200 mA	0	Low	Alone	Non-Energized[1]	None	None
	1	Low	Alone	Energized, DC[2]	YES	Shock Risk Assessment[5]
		Moderate	Two Person	Energized, DC[2]	YES	Shock Risk Assessment[5]
		High	Safety Watch	Energized, DC[2]	YES	Shock Risk Assessment[5]
	2	Moderate	Two Person[3]	Energized, DC[2]	YES	Shock Risk Assessment[5]
		High	Safety Watch	Energized, DC[2]	YES	Shock Risk Assessment[5]
	3[4]	Moderate	Two Person	Energized, DC[2]	YES, EEWP	Shock Risk Assessment[5]
		High	Safety Watch	Energized, DC[2]	YES, EEWP	Shock Risk Assessment[5]
2.3a 100 - 400 V, >500 A	0	Low	Alone	Non-Energized[1]	None	None
	1	Moderate	Two Person	Energized, DC[2]	YES	Shock and Arc-Flash Risk Assessments[5]
		High	Safety Watch	Energized, DC[2]	YES	Shock and Arc-Flash Risk Assessments[5]
	2[6]	Moderate	Two Person	Energized, DC[2]	YES	Shock and Arc-Flash Risk Assessments[5]
		High	Safety Watch	Energized, DC[2]	YES	Shock and Arc-Flash Risk Assessments[5]
	3[4]	High	Safety Watch	Energized, DC[2]	YES, EEWP	Shock and Arc-Flash Risk Assessments[5]
2.3b >400 V, 200 mA - 500 A	0	Low	Alone	Non-Energized[1]	None	None
	1	Moderate	Two Person	Energized, DC[2]	YES	Shock Risk Assessment[5]
		High	Safety Watch	Energized, DC[2]	YES	Shock Risk Assessment[5]
	2[6]	Moderate	Two Person	Energized, DC[2]	YES	Shock Risk Assessment[5]
		High	Safety Watch	Energized, DC[2]	YES	Shock Risk Assessment[5]
	3[4]	High	Safety Watch	Energized, DC[2]	YES, EEWP	Shock Risk Assessment[5]
2.4 >400 V, >500 A	0	Low	Alone	Non-Energized[1]	None	None
	1	Moderate	Two Person	Energized, DC[2]	YES	Shock and Arc-Flash Risk Assessments[5]
		High	Safety Watch	Energized, DC[2]	YES	Shock and Arc-Flash Risk Assessments[5]
	2[4]	High	Safety Watch	Energized, DC[2]	YES	Shock and Arc-Flash Risk Assessments[5]
	3[4]	High	Safety Watch	Energized, DC[2]	YES, EEWP	Shock and Arc-Flash Risk Assessments[5]

1. LOTO training is required for any worker who places a personal locking device to control hazardous energy while performing work.
2. DC = Training on unique electrical hazards in the laboratory including DC sources, capacitors, inductors, transients, magnetic forces, potential gradients, and induced voltages and currents, as applicable.
3. Mode 2 in Classes 2.2a, b, and c may be performed alone, if proper dielectric gloves are worn, or if other approved protective equipment is used.
4. This mode of work should be avoided.
5. Perform shock and/or arc-flash risk assessment(s) per NFPA 70E.
6. DO NOT move probes while energized.

Figure 27. Control Table for Work in Hazard Class 2.x, DC

Class	Mode	Risk (Section 3.3.3)	Electrical Worker (s)	Training	Work Control	PPE	Energy Removal
3.1a ≤100 V, ≤100 J	All	Low	Alone	Electrical Hazard Awareness	None	None	NA
3.1b ≤1 J 100–400 V	All	Low	Alone	Electrical Hazard Awareness	None	None	NA
3.2a ≤100 V 100 J–1 kJ	0	Low	Alone	Electrical Hazard Awareness[1]	None	None	
	1	Low	Alone	Qualified Electrical Worker, DC[2,9]	YES	Eye, No Jewelry	Hard Ground Stick
		Moderate	Two Person[3]	Qualified Electrical Worker, DC[2,9]	YES	Eye, No Jewelry	Hard Ground Stick
		High	Safety Watch	Qualified Electrical Worker, DC[2,9]	YES	Eye, No Jewelry	Hard Ground Stick
	2	Moderate	Two Person[3]	Qualified Electrical Worker, DC[2,8]	YES	Eye, No Jewelry	
		High	Safety Watch	Qualified Electrical Worker, DC[2,8]	YES	Eye, No Jewelry	
	3[5]	Moderate	Two Person	Qualified Electrical Worker, DC[2]	YES, EEWP	Eye, No Jewelry	
		High	Safety Watch	Qualified Electrical Worker, DC[2]	YES, EEWP	Eye, No Jewelry	
3.2b 100–400 V 1–100 J	0	Low	Alone	Electrical Hazard Awareness[1]	None	None	
	1	Low	Alone	Qualified Electrical Worker, DC[2,7,9]	YES	Shock Risk Assessment[4]	Hard Ground Stick
		Moderate	Two Person[3]	Qualified Electrical Worker, DC[2,7,9]	YES	Shock Risk Assessment[4]	Hard Ground Stick
		High	Safety Watch	Qualified Electrical Worker, DC[2,7,9]	YES	Shock Risk Assessment[4]	Hard Ground Stick
	2	Moderate	Two Person[3]	Qualified Electrical Worker, DC[2,7,8]	YES	Shock Risk Assessment[4]	
		High	Safety Watch	Qualified Electrical Worker, DC[2,7,8]	YES	Shock Risk Assessment[4]	
	3[5]	Moderate	Two Person	Qualified Electrical Worker, DC[2,7]	YES, EEWP	Shock Risk Assessment[4]	
		High	Safety Watch	Qualified Electrical Worker, DC[2,7]	YES, EEWP	Shock Risk Assessment[4]	
3.3a ≤100 V 1–100 kJ	0	Low	Alone	Electrical Hazard Awareness[1]	None	None	
	1	Moderate	Two Person	Qualified Electrical Worker, DC[2,9]	YES	Eye, No Jewelry	Soft Ground Stick
		High	Safety Watch	Qualified Electrical Worker, DC[2,9]	YES	Eye, No Jewelry	Soft Ground Stick
	2	Moderate	Two Person	Qualified Electrical Worker, DC[2,8]	YES	Eye, No Jewelry	
		High	Safety Watch	Qualified Electrical Worker, DC[2,8]	YES	Eye, No Jewelry	
	3[5]	High	Safety Watch	Qualified Electrical Worker, DC[2]	YES, EEWP	Eye, No Jewelry	
3.3b 100–400 V 100 J–100 kJ	0	Low	Alone	Electrical Hazard Awareness[1]	None	None	
	1	Moderate	Two Person	Qualified Electrical Worker, DC[2,7,9]	YES	Shock Risk Assessment[4]	Soft Ground Stick
		High	Safety Watch	Qualified Electrical Worker, DC[2,7,9]	YES	Shock Risk Assessment[4]	Soft Ground Stick
	2	Moderate	Two Person	Qualified Electrical Worker, DC[2,7,8]	YES	Shock Risk Assessment[4]	
		High	Safety Watch	Qualified Electrical Worker, DC[2,7,8]	YES	Shock Risk Assessment[4]	
	3[5]	High	Safety Watch	Qualified Electrical Worker, DC[2,7]	YES, EEWP	Shock Risk Assessment[4]	
3.4a ≤100 V >100 kJ	0	Low	Alone	Electrical Hazard Awareness[1]	None	None	
	1	Moderate	Two Person	Qualified Electrical Worker, DC[2]	YES	N/A to be done remotely	Remotely
		High	Safety Watch	Qualified Electrical Worker, DC[2]	YES	N/A to be done remotely	Remotely
	2[6]	High	Safety Watch	Qualified Electrical Worker, DC[2]	YES	N/A to be done remotely	
	3[5]	High	Safety Watch	Qualified Electrical Worker, DC[2]	YES, EEWP	N/A to be done remotely	
3.4b 100–400 V >100 kJ	0	Low	Alone	Electrical Hazard Awareness[1]	None	None	
	1	Moderate	Two Person	Qualified Electrical Worker, DC[2]	YES	N/A to be done remotely	Remotely
		High	Safety Watch	Qualified Electrical Worker, DC[2]	YES	N/A to be done remotely	Remotely
	2[6]	High	Safety Watch	Qualified Electrical Worker, DC[2]	YES	N/A to be done remotely	
	3[5]	High	Safety Watch	Qualified Electrical Worker, DC[2]	YES, EEWP	N/A to be done remotely	

[1] LOTO training is required for any worker who places a personal locking device to control hazardous energy while performing work.
[2] DC = Training on unique electrical hazards in the laboratory including dc sources, capacitors, inductors, transients, magnetic forces, potential gradients, and induced voltages and currents, as applicable.
[3] Mode 2 in Classes 3.2a, and b may be performed alone, if proper dielectric gloves are worn, or if other approved protective equipment is used.
[4] Perform shock risk assessment per NFPA 70E, keep hands outside of Restricted Approach Boundary or wear appropriate dielectric PPE.
[5] This mode of work should be avoided.
[6] This mode of work should be avoided or done remotely.
[7] The use of dielectric PPE for shock protection requires dielectric PPE training per OSHA 1910.132(f) including demonstration of competency.
[8] The use of test instruments (meters) requires training per NFPA 70E 110.2 including demonstration of how to use the device to verify the absence of voltage.
[9] The use of ground sticks requires training to demonstrate the worker's ability to use a ground stick safely.

Notes on use:

1. PPE "Eye" means proper eye protection, either goggles or a face shield, for higher energies.
2. PPE "No Jewelry" means no jewelry on the hands (e.g., rings, watches) and no dangling jewelry or other objects (e.g., badge).
3. Column "Energy Removal" is the method used to discharge lower-energy capacitors, or apply a safety ground on higher-energy capacitors.
4. "Energy Removal" remotely means using engineering methods to discharge and verify the capacitors without worker exposure (e.g., a capacitor remote discharge system).
5. Performing Mode 2 remotely means using sensors and instruments that are placed during a Mode 0 condition, then observed from a safe location during Mode 2 work.

Figure 28. Control Table for Work in Hazard Class 3.x, Capacitors, ≤400V

Class	Mode	Risk (Section 4.5.1)	Electrical Worker(s)	Training	Work Control	PPE	Energy Removal
3.0–ESD	All	Low	Alone	None	None	None	
3.1c–ESD Haz Loc	All	To Be Determined, refer to explosive safety SME.					
3.1d >400 V, ≤0.25 J	All	Low	Alone	Non-Energized	None	None	
3.2c >400 V, 0.25 - 50 J	0	Low	Alone	Non-Energized[1]	None	None	
	1	Low	Alone	Energized, DC[2]	YES	Shock Risk Assessment[4]	Hard Ground Stick
		Moderate	Two Person	Energized, DC[2]	YES	Shock Risk Assessment[4]	Hard Ground Stick
		High	Safety Watch	Energized, DC[2]	YES	Shock Risk Assessment[4]	Hard Ground Stick
	2	Moderate	Two Person	Energized, DC[2]	YES	Shock Risk Assessment[4]	
		High	Safety Watch	Energized, DC[2]	YES	Shock Risk Assessment[4]	
	3[5]	Moderate	Two Person	Energized, DC[2]	YES	Shock Risk Assessment[4]	
		High	Safety Watch	Energized, DC[2]	YES, EEWP	Shock Risk Assessment[4]	
3.3c >400 V, 50 - 1000 J	0	Low	Alone	Non-Energized[1]	None	None	
	1	Moderate	Two Person	Energized, DC[2]	YES	Eye, Ear, Shock Risk Assessment[4]	Hard or Soft Ground Stick
		High	Safety Watch	Energized, DC[2]	YES	Eye, Ear, Shock Risk Assessment[4]	Hard or Soft Ground Stick
	2[6]	Moderate	Two Person	Energized, DC[2]	YES	N/A to be done remotely	
		High	Safety Watch	Energized, DC[2]	YES	N/A to be done remotely	
	3	Do not do this mode of work.					
3.3d >400 V, 1 - 10 kJ	0	Low	Alone	Non-Energized[1]	None	None	
	1	Moderate	Two Person	Energized, DC[2]	YES	Eye, Ear, Shock Risk Assessment[4]	Soft Ground Stick
		High	Safety Watch	Energized, DC[2]	YES	Eye, Ear, Shock Risk Assessment[4]	Soft Ground Stick
	2[6]	Moderate	Two Person	Energized, DC[2]	YES	N/A to be done remotely	
		High	Safety Watch	Energized, DC[2]	YES	N/A to be done remotely	
	3	Do not do this mode of work.					
3.4c >400 V, >10 kJ	0	Low	Alone	Non-Energized[1]	None	None	
	1	Moderate	Two Person	Energized, DC[2]	YES	N/A to be done remotely	Remotely
		High	Safety Watch	Energized, DC[2]	YES	N/A to be done remotely	Remotely
	2[6]	High	Safety Watch	Energized, DC[2]	YES	N/A to be done remotely	
	3	Do not do this mode of work.					

1. LOTO training is required for any worker who places a personal locking device to control hazardous energy while performing work.
2. DC = Training on unique electrical hazards in the laboratory including DC sources, capacitors, inductors, transients, magnetic forces, potential gradients, and induced voltages and currents, as applicable.
3. Mode 2 in Classes 3.2a, and b may be performed alone, if proper dielectric gloves are worn, or if other approved protective equipment is used.
4. Perform shock risk assessment per NFPA 70E, keep hands outside of Restricted Approach Boundary or wear appropriate dielectric PPE.
5. This mode of work should be avoided.
6. This mode of work should be avoided or done remotely.

Notes on use:

1. PPE “Eye” means proper eye protection, either goggles or a face shield, for higher energies.
2. PPE “No Jewelry” means no jewelry on the hands (e.g., rings, watches) and no dangling jewelry or other objects (e.g., badge).
3. Column “Energy Removal” is the method used to discharge lower-energy capacitors; or apply a safety ground on higher-energy capacitors.
4. “Energy Removal” remotely means using engineering methods to discharge and verify the capacitors without worker exposure (e.g., a capacitor remote discharge system).
5. Performing Mode 2 remotely means using sensors and instruments that are placed during a Mode 0 condition, then observed from a safe location during Mode 2 work.

Figure 29. Control Table for Work in Hazard Class 3.x, Capacitors > 400 V