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Reducing/Eliminating ESD Hazards During PYRO Operations

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REDUCING/ELIMINATING ESD HAZARDS DURING PYRO OPERATIONS

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ABSTRACT

Several safety concerns have occurred during pyro operations at 30% or lower RH in the OPF area based on the increase of electrostatic discharge (ESD). These concerns targeted the safety of personnel, flight hardware and ground support equipment (GSE). Two proposed methods considered to control ESDs during pyro operations at 30% or lower RH are 1) the use of an ionizer blower and 2) to increase the moisture content. In order to demonstrate that the ionizer is effective in neutralizing static charge, a series of experimental runs were conducted in the Electrostatics Laboratory located in the Operations & Checkout (O&C) Building at NASA KSC. I served as the NASA KSC PYRO Systems Engineering representative as well as a laboratory research assistant to Dr. Rupert Lee from NASA KSC Failure Analysis and Physical Testing Laboratory who was in charge of performing the experiment (Job #: KSC-MSL-0331-2000-00-00). The effectiveness of the ionizer blower was evaluated based upon the time lapse of a charged metal plate from initial 1000 to 400 volts. These variables were studied: distance, RH, and angle of attack. A full factorial experiment ($2^3 = 8$) was conducted. Since we did not have a statistical analysis program, such as SAS available, calculations were done manually based on the method of "ANOVA" (ANalyis of VAriances), but R^2 (fitness of curve) was not obtained. As conjectured, distance was found to be the major influencialvariable. Therefore, we concluded that the best possible combination of situations would be to position the ionizer blower as close as possible and facing directly into the charged plate. This scenario resulted in the quickest discharge rate, which would be the most beneficial during pyro operations below 30% RH. The second method of increasing the moisture content in the work environment through a modification of the OPF ECS current configuration appeared to be dependent on budget constraints and currently not planned to be modified. Finally, some recommendations are discussed such as to test the ionizer in an actual field experiment with a mockup pyro connector and a technician with all the NASA KSC Safety-compliant PPE to assess the realistic effectiveness of the ionizer blower.

GENERAL ORDNANCE OPERATIONS

Mechanical Operation The term "mechanical" refers to all operations where the pyro devices are hand-held, installed/removed as a single unit device or as part of an assembly where no electrical connections/disconnections are performed. Some of the pyro devices involving mechanical installation are the Avionics Bay Firex, NLG Strut Thruster, MLG/NLG Uplock Release Thruster, MPM guillotine/jettison, Ku Band Antenna guillotine/jettison pyro assemblies, devices with Faraday Caps on and are not removed during installation, and separation nuts (8 installed on each SRB/MLP hold down post location assembly and 2 located in the Aft structural attachments between the Orbiter & ET).

Electrical Operation The term "electrical" refers to all operations where electrical connections/disconnections are performed on pyro devices. These operations are usually performed during open pin (exposed pin to the environment) during mating/demating of pyro connectors. The pyro system is intimately related to the electrical system consisting of all the wiring, cabling, interconnects, power supply, and additional electrical interfaces.

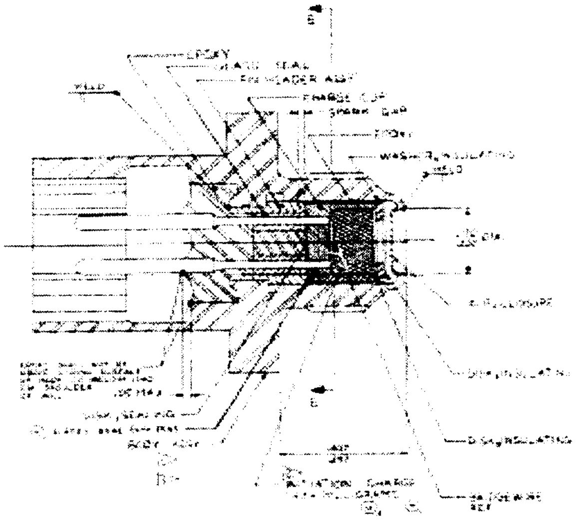
NASA STANDARD INITIATOR (NSI)

The NASA Standard Initiator (NSI) is one of two types of Electro-Explosive Devices (EED) used in the STS Program. This and the Orbiter Docking System (ODS) pyros are the only approved EEDs for the Space Shuttle. NSIs are category "A" explosive devices.

A category "A" explosive device is that which by expenditure of its own energy, or because it initiates a chain reaction of events, causes injury or death to people or damage to equipment. They are designed for a minimum probability of initiation by static electricity and are used in Orbiters for all pyro system initiation except for the crew emergency escape systems.

NSIs contain 2 electrical contacts, which lead to a bridgewire that is surrounded by 0.114 grams of granular mixture of Zirconium Potassium Perchlorate ($ZrKClO_4$). An NSI transforms electrical energy into explosive energy. Specifically, they have the following characteristics:

1) The bridgewire is a 0.002" diameter stainless steel (304 Nilstain) with a resistance of 0.95 to 1.15 Ω. The bridge distance of 0.118" results in a circuit resistance of 1.05 ± 0.10 Ω.
2) An electrical current of 3.5 to 5 amps will heat the bridgewire to 600 °F and cause ignition.
3) Output pressure of 650 ± 125 psi in a 10cc closed volume.
4) Will not fire if subjected to 1 amp for 5 minutes.
5) Can auto-ignite if subjected to temperatures in excess of 400 °F.
6) An airtight thin stainless steel end closure welded to the cartridge will contribute shrapnel when the NSI detonates.



Although NSIs are used mainly for initiating other secondary/high explosive pyros such as NSI Detonators, NSI Booster Cartridges, NSI Pressure Cartridges, and Linear Shape Charges (LSC), they have enough power to be used alone in some other Orbiter systems such as in the Crew Module Firex System, MPM Guillotine, and Aft Gas Samplers. An expended NSI will have a hole in the end where the explosive charge was located, and an unexpended NSI will have a smooth end cap with no visible hole.

NSI Detonator An NSI Detonator is a category "A" explosive device, and consists of an NSI threaded into a detonator housing containing additional explosive mixtures. The NSI acts on the detonator's Lead Azide (PbN_6) primer/accelerator, which in turn acts on the detonator's Cyclotrimethylene Trinitramine (RDX) high explosive. Detonators will produce a 0.040"-dent in a steel block. An unexpended detonator has a protrusion on its end. This protrusion is not present after the detonator is expended. NSI detonators, NSI boosters, and NSI pressure cartridges all have wrench flats for installation and removal.

Electrostatic Protection in NSIs The NSI used today is based on a design from the Apollo era called the Apollo Standard Initiator. One of the design changes that the NSI incorporated was electrostatic protection. Electrostatic safety is achieved in two ways. The NSI utilizes the spark gap/air gap method, and also the ordnance cavity is electrically isolated from ground.

Spark gaps are located in the electrical connector cavity where arcing is not dangerous. The design scheme is to provide as high an internal breakdown voltage in the ordnance area and as low an external spark gap breakdown voltage as possible. Providing a spark gap between the pins and case involves the electrical breakdown of air dielectric. Electrical breakdown in an air gap happens after the onset of voltage on the pins. If voltage is applied to the pins an ionization process starts and a short time later, in the order of μ-seconds, the spark jumps from pin to case.

The dielectric strength specification for the NSI is that it shall withstand an AC voltage of 200±10 volts for 60 seconds between the case and the pins shorted together. The leakage current shall not exceed 500 μ-amperes. The initiator shall not ignite nor otherwise be degraded. Isomica discs are installed at the top surface of the propellant and are secured in place with an epoxy impregnated washer or sealing tape as an electrically insulating feature. The metal disk welded in place across the output end is for hermetic sealing.

As a design consideration dielectric specifications calling for no breakdown pins to case to 1500 volts AC can compromise the design of the external spark gap and thus compromise electrostatic safety while at the same time adding nothing to functional reliability over the 500 volts DC specifications.

Electrostatic specifications state that the EED shall not function when a 500-pF capacitor charged to 25,000 volts is discharged from pins to case. A human on average is the equivalent of 300 pF. NSIs are designed with a "no fire current" and "no fire power". That requirement specifies that all NSIs will not fire nor be degraded with 1 amp/1 watt applied for 5 minutes. According to Test Report TR82-106 "Verification of Electrical Firing System Compatibility with NSI-1's on Appendage 2" dated July 22, 1982, it appeared that the NSI-1 required ~40 millijoules of energy to fire, provided this energy was delivered fast enough.

A typical energy analysis for a human follows:

Capacitance of an average human is 300 pF. Maximum allowable voltage is 350 volts during pyro operations, which result in a calculated energy of 18.3 μ-joules. A calculated value of 16,300 volts is required for an average human to produce 40 millijoules. At 16,000 volts a human would have the same amount of energy that as a minimum is known to have ignited an NSI.

Failure mode in which an NSI would fire are:

1. A manufacturing defect with the NSI spark gap.
2. Static generation around the NSI at a level >16,000 volts.
3. Failure of the wriststat to dissipate static.
4. Voltage potential not measured with a volt scanner.
5. Technician in some way does not touch the connector backshell when connecting/disconnecting NSIs.
6. Technician reaches to the NSI in a way to touch one of the pins and the spark current goes from pin through bridge wire then to ground.

SAFETY PROCEDURES AND REQUIREMENTS USED DURING ELECTRICAL PYRO OPEERATIONS

NSIs are designed to be relatively insensitive to static electricity and RF radiation (the two NSI connector pins may act as antenna to RF energy) as compared to other EEDs, however they can still be initiated by either of these forms of energy if a high enough level exists. Incorrect usage of meters or other energy sources may cause NSIs to be inadvertently initiated. Therefore, during pyro operations the following NASA/KSC safety practices and procedures must be followed.

KHB 1710.2 KENNEDY SPACE CENTER SAFETY PRACTICES HANDBOOK

This is the governing document for safety at NASA/KSC. This handbook, which is Revision D dated November 1998, establishes and specifies safety policies and requirements during design, operations and maintenance activities at NASA Kennedy Space Center and areas of jurisdiction under KSC. These requirements identify and minimize the hazards to personnel and property associated with daily industrial operations. It is intended to assure the completion of the task to the safest possible manner with maximum efficiency.

This manual is divided into seven chapters ranging from general information, weather, personnel, control areas, operational safety, unique hazardous facilities requirements, and use of plastic films and adhesive tapes in Space Shuttle/Payload Processing areas.

The remainder of this manual contains eleven annexes dealing with OSHA requirements, NASA KSC safety and requirements document, National Electric Code, and NASA safety policy for pressure vessels and pressurized systems, among others.

Of specific interest applicable to Pyro Systems and Pyro operations, there are two main annexes:

Annex D. KSC Supplement to NFPA 70–National Electric Code

This section discusses all sources of static electricity discharges controls to avoid unsafe situations. It outlines specific procedures for grounding of personnel, flight hardware, tools, equipment, materials, grounding during hoisting of flight hardware, and three-phase power connections.

All personnel should wear grounding devices when handling or working within 5 ft of open grain, handling EEDs when Faraday Caps or Shorting Plugs are removed, also when firing line extension cables are connected to EEDs. When using legstats or conductive shoes, personnel should stand on a conductive surface. Resistance checks shall be performed prior to operations.

The Orbiter shall be grounded and wheels chocked inside the OPF platforms. Payloads or canisters containing explosives or hazardous fluids shall be grounded to facility ground upon arrival at the facility/handling mechanism.

Pneumatic tools used on hardware containing EEDs, within 10 ft of open grain, or in petroleum/oil/lubricant areas shall be fitted with a conductive air supply hose or connected to facility ground. All materials in contact with open grain shall be grounded. Conductive plastic sheeting (velostat) shall be grounded to common ground with railcar prior to installation.

Annex F. KSC Supplement to NSS-1740.12-NASA Safety Standard for Explosives, Propellants, and Pyrotechnics

This section discusses the Relative Humidity (RH) requirements and Explosive requirements.

Relative Humidity (RH) The RH shall be recorded prior to start and every 4 hrs during operations. When $RH \leq 50\%$, if personnel is not wearing grounding devices then personnel should be verified $\Delta V < 350$ volts, and electrostatic scanning shall be done <1hr during operations and every time new equipment, personnel, or hardware are introduced into the work area. **When $RH \leq 30\%$, operations involving open grain except SRB segments, and EEDs with Faraday Caps removed or firing circuits exposed, shall not be permitted.**

For SRB segment processing when RH=30%-10%: Electrostatic scanning shall be done at 10-min intervals if propellant is exposed, and 30-min interval if propellant is covered. Operations shall not continue if $\Delta V \geq 350$ volts measured on segment case of segments with propellant or equipment and personnel within 5 ft of open grain.

When segment has end rings with shipping covers installed; if electrostatic scan readings >1kv then stop operations (do not continue unless readings <1 kv). If scan readings on case of covered propellant > 4kv then notify safety and evacuate personnel from area at least 500-ft radius. If RH<10% then SRB segment processing shall not be permitted.

General Explosives Requirements

EEDs must be classified as category A or category B, handled only in approved areas and by certified personnel only, and under control of the explosive storage area supervisor. For operations requirements, facility doors and openings shall be closed during electrical connection/disconnection of pyro devices. Controlled switching and RF silence shall also be in effect during these operations or during the removal of Faraday Caps/Shorting Plugs of pyro devices.

RF Transmission

Cell phones and pagers in VHF & UHF shall not transmit within 20 ft of flight hardware or equipment containing EEDs. Mobile, KSC-controlled radio transceivers shall not transmit within 50 ft. Unapproved radios shall not transmit within 600 ft.

S&As Rotation

For S&A devices pin removal, 2 firing inhibits shall remain when removing an S&A safing pin. Rotation of the S&As during ground testing and processing shall be performed with the ETA or CDF disconnected from the S&A or at the point of terminus. All the rotation testing shall be done prior to firing circuit electrical connection. If firing circuits must be connected during rotation test, safety assessment shall be provided to assure no hazardous condition exists. Rotation testing of S&As (except SRB ignition) with only the initiators electrically connected shall be done with a minimum clearance of 10 ft.

SRB ignition S&As shall not be rotated in the VAB. S&A rotation during Phase 1 or 2 lightning warnings shall be prohibited. Faraday Caps shall remain on EEDs when installing/removing the S&A.

Orbiter Hatch T-Handle explosives

The pyro activation T-handle enclosure lock shall be available at each landing and TAL site and shall be installed ASAP after Fwd Assessment Team inspection. The lock shall not be removed during processing until the T-6 BDA clear for the start of ET tanking. A pyro engineer shall control the T-handle enclosure whenever is unlocked unless the lock is removed and transported to an approved explosive storage facility. Whenever the T-handle enclosure is unlocked, safety pip pins shall remain installed in the hatch and cabin vent T-handles.

The following SSV (Orbiter, ET/SRB, and Orbiter-installed Payload) explosive operations and safeguard requirements shall be followed from OMI S5009, Part I, through launch:

1) During OMI S5009 Part I, all vehicle and GSE explosive items, except the Range Safety initiators, Range Safety CDF, and the SRM Ignition S&A control cables, shall be connected.

2) Prior to any explosive connection, functional tests shall be performed on critical MEC PIC circuits.

3) After completion of the functional tests, the MEC Critical Commands shall be disabled and the SSV and GSE PIC racks shall be powered down.

4) In parallel with the subsequent pad clear, the active version of TCS sequence VFC81 shall be replaced with a dummy version (Rev. 0) in the C10 console and any hot spare console that is loaded with C10 software. Console dumps shall be performed to verify that VFC81 Rev. 0 is loaded in both consoles.

5) After the PIC resistance tests, the SRBs shall be remotely powered-down. The MECs shall be powered-down After SCO ingress.

6) After the SRBs are powered-down, the following safeguards shall be in effect:

- VFC81 Rev. 0 shall remain loaded at C10 and the hot spare(s).
- MEC Critical Commands shall remain disabled.
- GOAL programs capable of firing PICs, except SRSS PICs, shall not be activated.

- SRB power shall be applied for instrumentation reads only, except in OMI S0024. Pre-launch Propellant Loading, OMI S5009 Part II, and OMI S007 Launch Countdown.

7) OMI S5009, Part II, shall be performed in the following sequence:

- SSV powered up for the Range Safety Open Loop Test, flight code insertion and the Closed Loop Test.
- SRBs, ET, OV, and MEC power removed, power off stray voltage checks performed, and the SRSS NSIs, SRSS CDF, and SRM Ignition S&A control cables connected.
- SRM Ignition S&A safing pins removed.
- SSV and GSE PIC resistance tests performed.
- All S&As rotated to the armed position.
- SRBs remotely powered-down.
- MECs powered-down, After SCO ingress.
- S&As physically inspected to verify they are in the safe position.

8) After the SRBs are powered-down, the following safeguards shall be in effect:

- VFC81 Rev. 0 shall remain loaded at C10 and the hot spare(s).
- MEC Critical Commands shall remain disabled.
- GOAL programs capable of firing PICs, except SRSS PICs, shall not be activated.
- SRB power shall be applied for instrumentation reads only, except in OMI S0024. Pre-launch Propellant Loading, OMI S5009 Part II, and OMI S007 Launch Countdown.

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- SRBs, ET, OV, and MEC power removed, power off stray voltage checks performed, and the SRSS NSIs, SRSS CDF, and SRM Ignition S&A control cables connected.
- SRM Ignition S&A safing pins removed.
- SSV and GSE PIC resistance tests performed.
- All S&As rotated to the armed position.
- SRBs remotely powered-down.
- MECs powered-down, After SCO ingress.
- S&As physically inspected to verify they are in the safe position.

10) After completion of explosives Part II (S&A hookup), the fwd skirts and ET/IT doors shall be controlled.

11) After SRB final power-down in OMI S5009 Part II, the following safeguard restrictions shall be in effect in addition to those in effect for Part I:

- GOAL programs capable of arming/firing SRSS PICs, or arming SRSS or SRM Ignition S&A devices, shall not be activated.
- SRSS vehicle power shall remain off.

12) If OMI S5009, Part III is performed, the restrictions for Parts I and II shall apply.

13) The Orbiter shall be powered down for disconnection of live drag chute explosives.

14) Orbiter power-down or controlled switching is not required when connections/disconnections are made to pyro circuits that are shorted or isolated from the Orbiter electrical system.

GSOP 5400 USA® GROUND SAFETY OPERATING PROCEDURES Vol. 1 HANDBOOK

This document, which is a Revision C dated January 20, 2000, written per KHB 1710.2 Kennedy Space Center Safety Practices Handbook, is intended to identify and minimize the hazards associated with ground processing and integration operations. This document provides the requirements for safety of USA® operations personnel in designated areas of KSC. It outlines the applicability, responsibilities, safety monitoring, and implementation of safety responsibilities.

GSOP 5400 Section 2.10 paragraph 2.10.1 requires an RH>30% for general STS and payload operations where EED firing circuits are exposed. At RH<30% operations involving explosives, except SRB processing, will cease. More specific, all operations where NSIs and ODS pyros are electrically disconnected, or exposed for testing, or reconnected will not be permitted where RH<30%.

Appendix G, Space Shuttle Vehicle (SSV) Ordnance Operations and Safeguards

This section discusses the safeguards governing the installation, connection, verification, and safety procedures to prevent inadvertent firing of SSV ordnance. The specific information provided by this appendix, and pertaining to pyro devices around the SSV is exactly the same outlined in the previous handbook.

Lightning policy as it is outlined in GSOP 5400 for major hazardous operations such as ordnance operations for phase 1, shall not begin, and for phase 2, if already in progress shall be terminated and secured.

ELECTRICAL PYRO OPERATING PROCEDURES

For electrical pyro operations, the proper safety controls must be established per WAD procedures. Electrical work with pyros is the most hazardous and the most critical. Inadvertent initiation or failure of initiation at the proper time depends greatly upon the quality of work in this portion of a pyro task.

For all hazardous portions of pyro operations, the task team leader (Pyro Engineer) is required to give a pre-task briefing. The importance of pre-task briefings cannot be overemphasized. This is the point when the task should be summarized with specific coverage given to safety issues, hardware concerns, and paper status. Also, expected duties of each person within the task team should be reviewed. Team communication and professional interaction is extremely important at this early stage in a successful, safe operation. All personnel involved in the commencing task should be present for the briefing including QC/QA.

Prior to initiating the task, all non-essential personnel must be cleared from a 10-ft radius of pyro electrical operations. Also, if applicable, this clear applies to the affected pyro device if it's in an area different from the electrical work (i.e. pyro interrupt box connectors require clear of middeck along with clears around Ku, gear uplocks, strut thruster, and Fwd Sep Bolt). All essential personnel are required to wear blue-collar flame retardant coveralls or nomex bunny suits (clean room only). RF silence is required in OPF bay and safety radios are to be kept a minimum of 20 ft away from the electrical connectors. Also, Fire/Rescue and Emergency Medical Personnel are required to be notified to be on standby for the pyro operation. As part of RF silence, no lightning advisories can be in effect prior to starting.

Prior to any electrical connection of pyros, all possible sources of energy must be verified to be isolated or turned off (controlled switching). This protects both personnel and the hardware from inadvertent initiation. To ensure no energy source is on, either orbiter power must be off, or an interruption in the pyro circuit is required prior to reaching the PIC circuitry (i.e. pyro interrupt boxes installed for forward separation bolt connection). Each task involving electrical connections will call for some verification of being isolated from energy sources. For any pyro disconnection, power down is required or controlled switching is required. Power down or controlled switching provides protection to personnel and hardware in that it ensures no accidental test configuration that would send energy to the pyro device while personnel are working in that area.

A second verification of no stray energy source in the pyro circuitry, a power-off stray voltage test is performed prior to any and all pyro NSI and ODS pyro connections. This test requires use of a stray voltage test meter. This test should be performed within five minutes of the planned actual connection to the NSI. If the time duration is longer prior to connection, another stray voltage test should be performed. For NSI's, the maximum allowable DC or AC voltage is 50 millivolts. For ODS pyros, the maximum allowable DC or AC voltage is 20 millivolts. These allowable voltages are more than 100 times lower than the minimum "All-Fire" voltage level required to initiate these devices.

Also, to ensure the flight connection will be properly shielded from RF energy, verification is also made with the stray voltage meter in the way of a shield-to-ground check. The shielding of all pyro wires is terminated at each RF connector backshell. The shield-to-ground test requires less than one ohm resistance between the connector backshell and orbiter structure. After all verifications, the stray voltage meter is disconnected from the orbiter connector.

Next, in preparation for handling a live NSI (or ODS) pyro connector, don a wriststat. Connect the wriststat ground clip to orbiter structure or an adjacent orbiter connector backshell. Next, perform a resistance check using a Simpson DVOM between the wearer and wriststat ground clip or orbiter structure. The resistance between the wearer and wriststat ground clip/orbiter structure must be between 10kΩ and 1 MΩ (10,000 Ω and 1,000,000 Ω). The purpose of the wriststat is to alleviate any voltage potential/electrostatic charge between the wearer and the pyro connector. The resistor within the wriststat limits the energy current to a non-harmful level in a case where the voltage potential difference is high. After this wriststat verification, turn off the Simpson DVOM and remove from the area. This meter has the ability to initiate or degrade NSI's and ODS pyros if the conductors are accidentally touched with the meter leads.

After the task team is fully ready and everyone is in position, only a grounded technician is allowed to handle any open pin pyro device including firing line extension cables connected to EEDs. The grounded technician should hold the pyro connector or wire harness backshell with one hand and remove the Faraday Cap or safing plug with the other hand. Holding the connector/backshell ensures two things: obviously this prevents twisting of a connector/wire harness, and secondly this provides another ground path (in addition to the wriststat) between the technician and the pyro device, thus preventing any electrostatic discharge. Once the pyro pins are exposed, inspect to verify no deformations, no bent pins, no contamination, and o-ring is in place at bottom of rubber cushion. If contamination exists (usually originating from gold plating being removed as normal wear and tear when pins and sockets are mated/demated), use an acid brush and compressed air to remove contaminants. Isopropyl alcohol can also be used but a 20-minute waiting time is required to allow all alcohol to flash off prior to final connections.

Next, after inspections of the connectors to be mated are complete, mate the connectors. Verify good connections by identifying three bayonet-locking pins are visible through the connector barrel-locking ring. Once mated, the pyro is safed and the wriststat is not required any longer (unless other pyro connections in same area are being made). Before leaving this connection, inspect wires to verify no damage or defects, verify backshell and strain relief tang are not loose, and verify wire routing is such that no tight bends or interference with other hardware exists.

In some electrical connections, an "upstream" break point test location is used to verify downstream connections are correct and intact. For example, after the Forward Separation Bolt pyros are connected, a resistance check is made "upstream" at the FLCA pyro interrupt boxes to measure resistance down through the ship harness, connector just mated at the Fwd Sep Bolt, and across the NSI bridgewire. Typical resistance is approximately 1.25 to 1.75 Ω. To perform a resistance check on NSI or ODS pyro bridgewires, only one type meter is allowed for use: the Valhalla 4314A. The output energy of this meter is more than 100 times lower than the "All fire" energy level for these pyros. Other meters such as the Simpson DVOM, Keithly 580, Honeywell, and even other model number Valhalla meters have sufficient energy output when measuring resistance to fire orbiter electro-explosive devices (EEDs). The safety controls for resistance checks are the same as described earlier in this section for electrical connections. The safety clear area includes both the location around the pyro device being tested, and the "break" location in the pyro circuit from where the resistance test will be made.

SAFETY TERMS AND DEFINITIONS

Orbiter Power Down

Required when mating live pyro connectors unless circuit is isolated from PIC card (within "black boxes"). EXAMPLE - All pyros isolated from FLCAs may be connected without power down if Pyro Interrupt Boxes are installed. The purpose is to keep any energy source that could cause inadvertent initiation away from pyro device connectors. EXAMPLE - Energized black box next to pyro connector could have sufficient energy to initiate EED if contacted with connector.

Controlled Switching (or Power Down)

The purpose is the same as outlined in the previous term. EXAMPLE - Test Operations switch throws requiring FLCAs/MECs may affect circuits that energize PIC cards/pyro initiation. Controlled Switching definition - No flight vehicle/element or GSE commands issued, no switches or circuit breakers operated on flight elements or GSE electrically connected to the flight elements. Safety requirement for demating live pyro connectors unless circuit is isolated from PIC card as outlined in previous example.

RF Silence

The purpose is to prevent the two NSI connector pins from acting as an antenna to RF energy. Energy from handheld radios or other RF transmitters can be enough for inadvertent pyro initiation. Doors closed. Hand-held radios off within OPF bay. RF Beacon in OPF Bays 1 and 2. No beepers. No AC powered electrical motors (i.e. fans) or heat producing equipment (i.e. soldering irons) within 10 ft of open connector pyros.

Wriststats

Don Wriststat and verify resistance between wearer and wriststat ground clip. Then attach ground clip to designated structural ground location and verify resistance between wearer and structure. The purpose is to remove any voltage potential between personnel and orbiter pyro connectors. Wriststats will bleed off any unwanted electrostatic energy. Resistor in wriststat will limit the static electricity current dissipation.

Resistance between wearer and ground clip, and between wearer and orbiter structure should be between 10kΩ and 1 MΩ. Wriststat verification precedes every step where pyro connectors are mated/demated or Faraday Caps/Shorting Plugs are removed (all operations where pyro pins are exposed).

Clear Area

A 5 to 10-ft clear area is typically required in the area of electrical connections. Expanded areas are sometimes required around the envelope where inadvertent activation of a pyro system could cause injury to other personnel. EXAMPLE - Drag chute electrical connections require clear area of entire rotating swing platforms and floor area to OPF exterior door (per GP-1098). 10-ft clears do not go through floors, walls, ceilings, or platforms.

CURRENT PROBLEMS WITH ECS EQUIPMENT DURING LOW RH AMBIENT CONDITIONS

ORBITER PROCESSING FACILITY ENVIRONMENTAL CONTROL SYSTEM (OPF ECS)

The OPF ECS is used primarily for Space Shuttle Orbiter purge operations. The OPF ECS consists of four individual airflow ducts that are connected to the Forward, Payload Bay, Aft, and Cabin interface ducts of the Orbiter. The OPF ECS allows for the operator to control flow rate and air temperature through these ducts. The air entering the ducts is de-humidified and filtered with a High Efficiency Particle Accumulator (HEPA) and Carbon filters.

A typical OPF ECS air process starts with outside ambient air entering the OPF ECS through an inlet filter. The air is drawn through this filter via a centrifugal compressor blower, which compresses and moves the air. Then the air goes through the cooling coil were the air is de-humidified to **no more than 37 grains of moisture/lb of dry air** per OPF ECS ICD requirements. After the air is de-humidified, it enters the mixing/manifold chamber were it is mixed and distributed to the four purge ducts: FWD, PLB, AFT, and Cabin. Then each circuit controls the purge airflow rate and temperature. Finally, the purge air is filtered and exits the OPF ECS via the ECS duct system. This filtered air enters the Orbiter through the LO2 T-0 for the FWD, PLB, and AFT circuits and through the white room for the Cabin circuit.

Based on the current design and assuming ambient conditions of 50 °F and 50% RH, it can be calculated from psychrometric equations that the delivered Orbiter purge air at 65 °F would be 29% RH and thus **prohibit pyro operations**. The Pad ECS is similar in design and operation to the OPF ECS except for one major difference: The Pads ECS have humidifiers in the AFT, PLB, and Cabin circuits, which will raise the humidity and allow pyro operations during low ambient humidity days.

Before 1996, the RH level was measured by a "squirrel cage" type RH monitoring device that measured the OPF Bay humidity for pyro operations in the OPF. However, these measurements were misleading since they did not reflect accurately the actual RH value inside the area within the Orbiter where pyro operations were performed. Typically the

OPF High Bay humidity is above 30% RH. It was not until the 1996-1997 time frame when the first hand-held RH meters were used. At that time, a discrepancy was discovered: the RH level inside the work area and specifically around pyro devices, would drop below 30% although the High Bay RH level was above 30%.

In order to prevent possible mission delays and to assess safety of personnel and flight hardware during pyro operations, USA® Pyro Engineering Dept 5532 USK-251 submitted a Safety Variance Request (the latest was from December 11, 1999 to January 31, 2000. Currently there have been 4 variances requested: 1997, 1998, 1999, and 2000) in which the affected TOPs were V5032.002, V5032.003, V5032.004, and V5032.005. Some of the impacts discussed in the request were the interruption of pyro operations when RH<30% producing a hazardous situation for personnel and flight hardware, and lengthy delays in the order of weeks and major milestones would be affected, including launch.

The requests were approved for pyro operations for RH<30% and specified that the potential hazards remained at an "acceptable level of risk" based on the following rationales: Nomex/Blue-collar coveralls and wriststats shall be used and verified to be common with wearer and ground clip/Orbiter structure, Pyro Engineering/TTL shall brief personnel of increased hazards at Low RH levels, electrostatic scanning shall be performed on all personnel, tools and equipment within a 5-ft radius prior to disconnect and at 10-minute intervals, and finally, operations shall stop if RH≤10%.

ELECTROSTATIC DISCHARGE (ESD) PRINCIPLES AND BACKGROUND INFORMATION

High electrical potentials on surfaces can result in uncontrolled ESD. The dissipation of energy associated with ESD can cause ignition of solid propellants, explosives and flammable/combustible materials, cause damage to or inadvertent actuation of electronic devices/systems, and shock experienced by personnel. Shock to personnel causes involuntary muscle reaction, which can result in injury or flight hardware/equipment damage.

When an insulated person is charged, the charge will distribute itself in such a way that all points on the person have the same voltage with respect to ground. This implies that the charge will be densely located on areas close to the ground. For a standing person who is not actually leaning against a wall, the shortest distance is through the soles and the floor covering. Consequently, most of the charge will be located on the soles of the feet and by induction bind an equally large, opposite charge in a conducting layer or the floor. The capacitance of a person can be determined by using equation:

$$C = (\varepsilon_r \varepsilon_0) A/d$$

Where:

ε_r is the relative permittivity or dielectric constant of the insulator.

$\varepsilon_0 = 8.85 \times 10^{-12}$ (F)(m^{-1}), is the vacuum permittivity, which is a fundamental constant.

A is the area of the soles.
d is the effective thickness of the soles plus the insulating floor covering.

For a typical person, $A \cong 300\ cm^2$, $d = 5$ to 10 mm, $\varepsilon_r = 4$ to 10. This leads to a capacitance of about 100 to 300 pF. If the parameters A, d and ε_r are actually determined for a given person, and if the capacitance is also measured directly, the value estimated by this equation will normally be about 60 to 70% of the measured value, indicating that this fraction of the total charge is on the feet.

Under normal circumstances, atmospheric air is considered a good insulator, and a charged insulated or insulating body will lose its charge slowly when surrounded by air. The reason for this is that air, as a rule, contains very few charged particles or ions, which by being attracted to the charged body might neutralize its charge. The "natural" air ions are formed primarily by radioactive radiation.

Ionization causes an electron to be knocked off an air molecule, O_2 or N_2, leaving the molecule as a singly, positively charged elementary ion, which within a fraction of a second will attract 10 to 15 molecules, mostly H_2O, forming a molecular cluster called a positive air ion.

The electron will almost immediately attach to an uncharged oxygen molecule and thus form a negative elementary ion. The negative elementary ion will also attract about 8 to 12 H_2O molecules to form a negative air ion. This ionization process will create, under normal circumstances, only a small number of ion pairs (about 5 to 10 ion pairs per cm^3 per sec.), but the production rate will increase very markedly if the electric field strength in the air exceeds a critical value, the breakdown field strength, E_b, which at atmospheric pressure has the value of $E_b \cong 3 \times 10^6$ v/m.

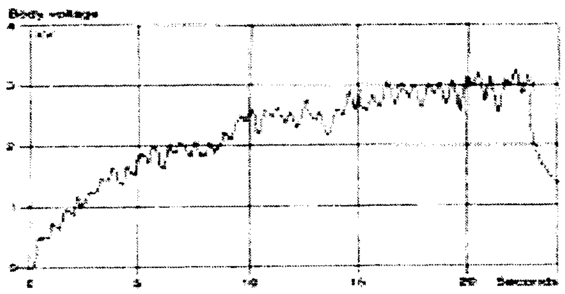
When the electron gets knocked off a neutral molecule by natural ionization, and if this happens in an electric field, the electron will move and be accelerated. If the accelerating field strength exceeds E_b, the electron may, before it collides with a molecule, gain a kinetic energy sufficiently large to enable it to ionize the molecule. This process is called ionization by collision. The process will take place in the whole region where the field strength exceeds E_b and will give rise to an electrical discharge, in other words, a transport of charge by the ions being moved by the field.

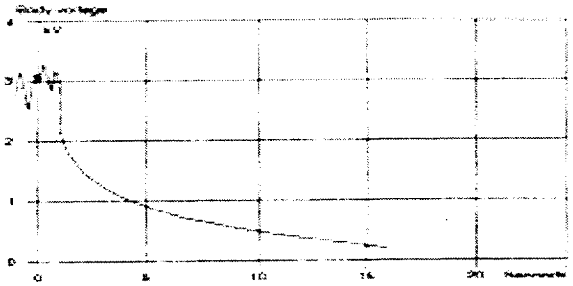
Many of the static electric problems are connected with a charged person and the possibility of spark discharge from the person creating an ignition hazard when explosive vapor-air mixtures may be present in the working environment.

If we consider charging by walking only, we can easily estimate an acceptable upper limit for the grounding or decay resistance for the person. If a body voltage $\mathbf{V_m}$ can be tolerated, walking across a floor with a step rate **n** (s^{-1}), and a charge transfer $\mathbf{\Delta q}$ (C), the maximum acceptable grounding resistance $\mathbf{R_m}$ is given by

$$R_m = V_m / n\Delta q$$

The maximum permissible value V_m of the body voltage depends upon the working environment. If for instance, the atmosphere contains explosive mixtures of vapors with known minimum ignition energy W_{min}, V_m has to be smaller than the explosion-safe voltage V_{es}. In the figure that follows, two graphs show a typical voltage buildup and dissipation (charging/discharging) in two different scenarios, one walking across an insulated floor (top graph) and the other standing still (bottom graph).





<u>Types of discharges</u>

There are three types of electrical discharges such as Corona Discharge, Brush Discharge, and Spark Discharge.

Out of these three types, **Spark Discharge** is the best-known type of electric discharge and is reserved for the discharge between two conductors at different potentials. In a spark, ionization takes place along and the charge is transferred through a narrow channel between the two conductors. In this channel most of the energy stored in the field between the conductors will be dissipated. If the partial capacitance of the two conductors is C and their potential difference is V, the energy W dissipated in the discharge is given by

$$W = (1/2)\, CV^2$$

Because the discharge channel is very narrow and short and the discharge as a whole very fast, the energy density of a spark discharge can be very high, making the <u>spark discharge the most incendive</u> (ability of an electrical discharge to start an ignition or explosion in a gas/vapor or dust/vapor mixture) <u>of all types of discharges</u>.

The human body can precipitate an electrostatic discharge hazard when the material is initiated by electrical discharges less than 0.015 joules.

Electrical Properties of ionized air

In any solid or liquid material, the charge, mobility, and concentration of possible charge carriers are constant at constant temperature as long as electrical breakdown does not take place. In a metallic conductor, the charge carriers are electrons with a concentration characteristic for the metal in question; in a semiconductor the carriers may be holes. But the carriers are always there to yield a current, when a field is applied. The conductivity γ (Unit is $\Omega^{-1}m^{-1}$)

$$\gamma = \mathbf{nqk}$$

where **n** is the charge carrier concentration, **q** is the charge, and **k** is the mobility, can be ascribed a constant value during the decay. However, the situation is not simple when a gas is the current-carrying medium. Gases inherently contain no or very few non-paired charges that can be moved independently by an electric field to cause a net current. Gases in general and, more specifically, atmospheric air can be ionized. Atmospheric ions, however, differ from the charge carriers in other media in several ways.

The concentration of air ions will change with time and location because of processes like recombination with other, oppositely charged ions, combination with particles, and plate out (deposition of airborne particulates by diffusion or aided by an electric field) on surfaces, or simply because the actual field-induced neutralization process may deplete the air of ions faster than they are re-supplied by the ionizing device.

Explosive Mixtures of Gases and Powders

Explosions may occur not only in vapor-gas mixtures, but also, in clouds of dusts or powders. The minimum ignition energy for a vapor-gas mixture depends on the nature and concentrations of the vapor and the gas, but it is more complicated for powders. Whereas mixtures of vapors and gases in closed environments are normally homogeneous with the vapor concentration being the same throughout the whole mixture, the concentration of powder particles in a cloud may vary from point to point, making the determination of minimum ignition energy very difficult.

The ignition energy depends on grain size of the powder involved. Generally, it takes more energy to start an explosion in a cloud of powders than in an explosive vapor-gas mixture. The minimum ignition energies for vapors in atmospheric air are lower than 1 mJ, but powders will require a minimum of 10 to 100 mJ to start combustion.

We can assume that any electrical discharge disseminating less than 0.2 mJ in the atmosphere is not incendive. For a capacitive system with a typical capacitance of 300 pF, this means that an "explosion-safe" voltage V_{es} is given by

$$V_{es} = (2W_{min}/C)^{1/2}$$

So $V_{es} \cong 1100$ to 1200 v. It should be stressed that this safe-voltage level refers only to explosion risks. When dealing with electronic ESD problems, the acceptable levels are often considerably lower. This safe-voltage level only applies to insulated conductors, as voltage cannot be meaningfully determined for an insulating material.

MEANS OF CONTROLLING ESD AT RH<30%

To reduce the potential for ESD, proper bonding and grounding must be employed and personnel must understand bonding/grounding reduces voltage potentials on conductive materials. Non-conductive materials (i.e., wood, paper, glass, plastics, etc.) must be eliminated, properly selected or be treated for the particular application and use. Voltage potentials on surfaces are commonly induced from friction (rubbing or sliding) but can be reduced by the simple act of separating two dissimilar materials.

ESD is not normally a concern when RH>50%. Moisture in the air will act as a high resistance bleeder, dissipating voltage potentials on the surface before they can build up to a level of about 350 volts and result in ESD. A few materials (i.e., Teflon, vinyl, etc.), however, do not absorb moisture, will not bleed-off readily even in environments RH>50% and should be avoided where ESD is a concern.

Environments where RH<50% require special attention. Operations where RH<30% should be carefully assessed and avoided when possible. Voltages, especially on large surfaces, should be dissipated using a high resistance resistor (100kΩ to 1 MΩ) in series with the ground wire until the charge is eliminated before going direct to ground.

Grounding of conductors

The basic rule of fighting electricity is to ground all conductors that might possibly become charged or exposed to induction from other charged objects, such as insulated charged conductors, which can produce energetic spark discharges.

The grounding must include all conducting objects, machinery and main structures including each part of piping, tubing system, containers, and fixed and moving parts. A direct connection to the ground is not necessary as long as all conducting parts are interconnected, so that no voltage differences or bonding occurs.

Grounding people

Due to the insulating properties of footwear and floor coverings, a person may constitute a capacitive system, with his/her own capacitance in the range of a few hundred pF and with a leakage resistance ranging from almost zero to maybe 10^{14} to 10^{15} Ω or more. This problem might be resolved by use of protective fire-retardant coveralls and wriststats or other type of clothing.

Blue-collar Coveralls/Nomex Coveralls

(Safety requirement per GP-1098). Both Personal Protective Equipment (PPE) are used at NASA KSC and provide excellent resistance to static electricity buildup. Cotton in blue-collar coveralls retains moisture and does not allow static buildup. Nomex coveralls have similar characteristics and are used for clean-room type environments. They provide protection against momentary flashes of high heat or fire. Blue-collar coveralls are made out of 100% cotton cloth impregnated with a proprietary chemical that allows the cloth to meet NASA KSC flammability requirements. Westex Corporation manufactures the particular cloth under the trade names Proban and Indura. It is used for civilian industry for protection against short duration flash fires and electrical arcing. Both Proban and Indura have undergone extensive testing by the NASA KSC Test Laboratory and consistently satisfy ESD and flammability requirements. Flame retardant clothing such as the blue-collar coveralls does not mean that the clothing will not burn; it just means that the clothing will self-extinguish within a specified time limit when the heat source is removed.

Wriststats

This device consists of a band or chain made of metal similar to an expandable watchband, and conductive plastic or fibers, connected to ground by a strap, either made of solid conductive plastic or of multistrand wire. Normally the strap includes a series of safety resistor of 1 MΩ for minimizing the shock from accidentally touching a live wire while being tied to ground via the strap.

There are some problems associated with the wrist straps though, intermittent skin contact with loose-fitting bands, bad skin contact caused by excessively dry skin or too much body hair, or sluffing of the band material, resulting in contamination of components.

Ionization: Removal of ions from the Air

An air ion is an unstable structure and consequently has a limited lifetime. It may be moved to some surface where it may be neutralized. It may combine with oppositely charged ions or particles and hence cease to exist as an ion. Or a small ion may combine with aerosol particles and then either be neutralized or become a large ion; in both cases it again no longer exists as a small ion. The rate of combination is proportional to the concentration of the species involved. The inverse relation between conductivity and particle concentration can be used as an indicator of the particle level in the air.

Ionizers

Any ionization process in air starts with the removal of an electron from a neutral molecule. The necessary energy may be delivered to the molecule from a colliding particle or from a quantum of electromagnetic radiation energy. Only two ionization methods are in practical technical use: radioactive ionization and field ionization.

In Field Ionization, if air is exposed to an electric field, ions will move in the field and collide with neutral molecules after having traveled the mean free path characteristic for the ions. However, even at the highest possible field strengths, the energy of the ions at the end of their mean free path is not high enough to release an electron.

Controlled field ionization is normally achieved by creating the necessary high field strength in front of a set of conducting electrodes in the form of sharp points or thin wires, by keeping the electrodes at a high potential (≅2-20 kv) with respect to some suitable counter electrode, which may even be the walls of the room. Discharge conditions are different for positives and negative voltages. The positive voltage necessary to start ionization under given geometrical conditions is about 30% higher than the corresponding negative voltage.

Types of Ionizers

Ionizers for neutralizing static charges were first put to practical use in the textile, printing, and plastic industries. In most cases these ionizers were bar shaped and mounted parallel with and at a short distance from charged sheets of material. There are several types of ionizers: ionizer bars, passive ionizer, electrical ionizer, radioactive ionizer, ion blower, whole-room ionization, and unipolar ionizer.

Radioactive ionizers

In a radioactive ionizer the radioactive source is placed upon a base material and covered with an extremely thin protective layer, often made out of gold. The ionizer is mounted such that the radiation is directed towards the space immediately in front of the charged material. When dealing with relatively low levels of static charges and specifically at hard-to-reach places, radioactive ionizers are very handy.

They do not require electrical installation and they cannot cause potential harmful electrical discharges. Their limitation lies in the fact that at high charge levels, one has to use impractically high (radio) activities or the neutralization process will take too long.

Usually radioactive ionizers utilize an α-active nuclide with a half-life of about half a year. Thus the active material is replaced at regular intervals, and the device does not remain unchecked for extended periods of time.

INVESTIGATION OF PROPOSED MEANS OF CONTROLLING ESD AT RH<30%

On February 16, 1999, there was a meeting between NASA Safety, NASA Materials Test Laboratory representatives, USA® Pyro Engineering, and NASA Pyro Systems Engineering. In that meeting it was proposed the use of ionizers during ordnance connections/disconnections with NSIs during conditions of RH<30%. During that discussion, it was identified that a Safety Hazard Analysis should be performed assuming the worst-case scenario, i.e.- SSV on the Pad and inadvertent initiation of the Aft Separation Bolts with personnel in the Orbiter Aft compartment. It was concluded that the NASA Material Test Laboratory should conduct tests with the ionizer before a decision could be made on the proposed ionizer concept. The meeting resulted with USA Pyro Engineering taking an action item to formally task the NASA Material Test Lab to perform the ionizer test in conditions of less than 30 % RH.

Even though variance approvals have been implemented in most of the pyro operations in and around the Orbiter, two extra avenues can be considered to add to the required "safety umbrella" even when RH<30%, and perhaps as low as RH≤10%. One avenue is to increase the moisture content in the air and the other is to ionize the surrounding air by use of a radioactive ionizer-blower combination as outlined in the following guidelines:

1. Post-flight pyro safing where the verification of expended pyros is required, and removal/installation of Faraday Caps and/or Shorting Plugs and connecting NSIs to PIC cabling may proceed with an area ionizer directed at the connector in work.
2. NSI operations involving pin probes, and adapter cabling shall not be permitted.
3. Russian category EED operations with Faraday Caps removed or firing circuits exposed shall not be permitted.
4. All personnel shall wear clean, nomex or blue-collar coveralls with long sleeves and long legs.
5. All personnel within 5 ft shall wear wriststats reading 10kΩ to 1 MΩ of resistance.
6. Work-related paperwork should remain 5 ft from work area.
7. Personnel should avoid activities that produce static charges.
8. Electrostatic of the work area within 5 ft of the EED will be performed with a maximum allowable of 350 volts at all times.

IONIZER EXPERIMENT/TEST

The experiment was conducted at the Electrostatics Laboratory located in Room 2275 on the 2nd Floor of the Operations & Checkout (O&C) Building at NASA KSC, which is managed by Dr. Carlos I. Calle and Dr. Raymond H. Gompf. Mr. Douglas Kraft from USA® Pyro Engineering arranged for Dr. Rupert Lee from NASA KSC Failure Analysis and Physical Testing Laboratory to be in charge of performing the experiment (Job #: KSC-MSL-0331-2000-00-00. Title: "ESD Testing of Nuclear Ionizers". Description: To demonstrate that the ionizer is effective in neutralizing static charge). I served as the NASA KSC PYRO Systems Engineering representative as well as a laboratory research assistant to Dr. Rupert Lee.

INSTRUMENTATION AND EQUIPMENT

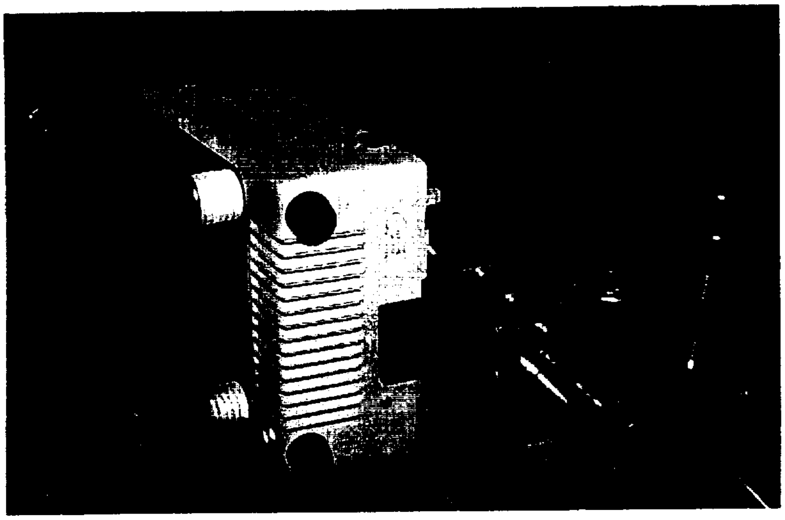
Charged Plate/Probe Assembly Model 268A-1

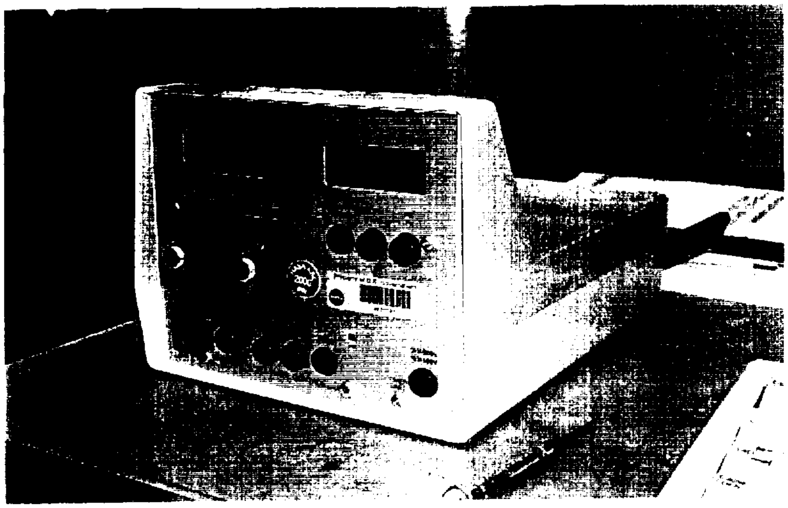
A charged plate analyzer Model 268A-1 (manufactured by Monroe Electronics Inc. Lyndonville, NY 14098) will be used to conduct the experiment. The assembly is composed of two separate components connected by a 10-ft cable. The top part with the attached plate contains the field meter portion of the instrument and was placed inside a Plexiglas™ box. To separate the two components, we released the two over-center latches near the rear of the unit and lifted at the rear of the top section.

A ¼-20-threaded receptacle is provided inside of the top section for convenient tripod mounting. Two foldout legs are provided underneath the bottom of the control unit to elevate the front of the cabinet to permit easy viewing of the meters. The control panel is a unit of 6 *3/4*" high, 6 *3/4*" wide, and 9 *1/2*" and weighs 5 lbs. Switches on the front panel are alternate action push-push type with the exception of the three used for "plate control". These are mechanically interlocked so that only one function can be selected at a time.

Controls are grouped by function. Three pushbutton switches directly beneath the "PLATE VOLTAGE" meter relate to meter range and function. Three switches at the lower center of the panel labeled "PLATE CONTROL" affect the charge/discharge condition of the plate. The "HV" control knobs, the "HV ON" indicator and the "POLARITY" pushbutton switch relate to the polarity and magnitude of the initial charge voltage on the plate. The "TIMER LIMIT" switch sets the start/stop voltage limits for the timer. The "OUTPUT" BNC connector on the back panel allows an oscilloscope or recorder to be connected to the output of the field meter. The signal here is 1/1000th of the actual voltage on the plate regardless of the settings of the meter range and function switches.

The charged plate is a standard tripod mount plate of 6" X 6" with a capacitance rated for a total discharge test circuit in the plate of 20 ± 2pF. The plate self-discharge is less than 10% of set voltage within 5 minutes below RH = 50% at 25 °C. As far as the power supply is concerned, ±7500 volts maximum output, ±1000 volts/±5000 volts charging of isolated plate available, adjustable from < ±1000 to > ±5000 volts.





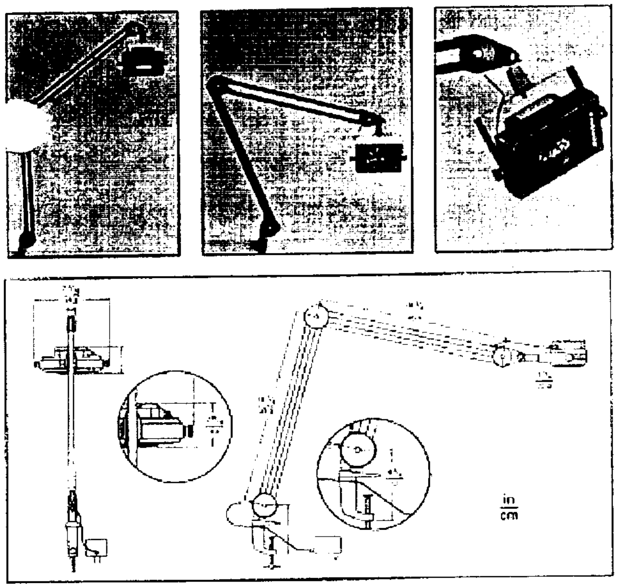
Ionmaster™ Ionizer NRD Model 4060

The Ionmaster™ (Serial Number: SN36330) blower from NRD is a lightweight unit equipped with an articulated arm and a bracket for attachment to the blower, compact and a reliable source of ions for static control. The blower bracket contains four slots were four small metallic grill-like (sealed cartridge) plates (Model 2U500, manufactured on May, 2000 by NRD, Inc. Grand Island, NY 14072) containing the radioactive material 500uCi Po210 sit and are held in position by a plastic closure.

This unit is designed to remove static charge that cannot be controlled by conductive or grounding methods. This apparatus delivers balanced ionized air. The ions are kept in continuous balance by the unit's internal α-energy source. The α-energy source, which is contained safely in the sealed cartridges, poses no risk to personnel, and requires no calibration. The Polonium 210 source is replaced annually.

The radiation emitted from the Polonium 210 element is called α radiation and is harmless externally. Alpha rays travel through air very rapidly to a maximum distance of

1 *3/8*' in still air, but have no power to penetrate the skin. In general, each person in the U.S. receives an average of 80 millirems of radiation from natural sources and about 100 millirems from man-made sources. As the rays travel through air, they produce ionization, and this ionized air is the one that dissipates static charges. The greatest ionization occurs at the end of their path.

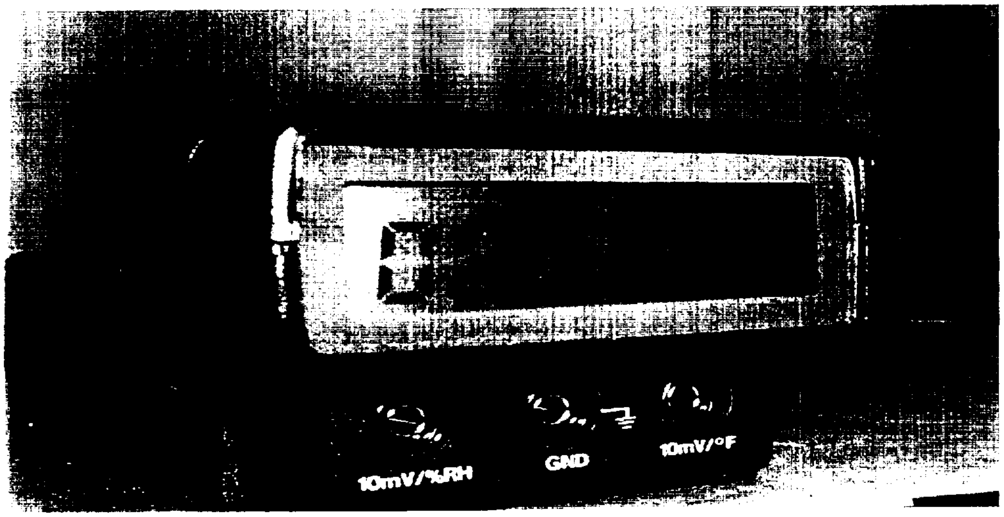


Plexiglas™ Test Chamber

A transparent Plexiglas™ box was used as the test chamber that housed the ionizer blower, the charge plate analyzer, and the relative humidity probe. The Plexiglas™ box 62" long, 31" high, 31" deep, and 5/8" thick is usually used as an electromagnetic Physics testbed mounted on top of a 33" high, 31" wide, and 72" long table. It has a flow meter valve installed on the outside near the test entrance and outfitted with tubing going inside supplying compressed breathing air (dm/dt) to regulate relative humidity.

Digital Ω Omega™ Thermo-Hygrometer

A Digital Ω Omega™ Thermo-Hygrometer with probe was used to record the required percentage of relative humidity and temperature inside the test chamber. The probe was attached to the ionizer's movable arm away from the blower and without contacting any metallic or non-metallic parts.



EXPERIMENTAL/TEST PROCEDURE

For the purposes of studying one of the two proposed alternate methods to eliminate ESD during pyro operations at RH<30%, which is the main objective of this final project, the experimental procedure took the following sequence:

The sequence started by verifying that the ionizer would work under the conditions required for the experiment. After carefully reading and understanding the operator's manuals for both the replacement of ion cartridges into the ionizer blower and the charged plate analyzer section respectively, we conducted a set of four experimental runs. We measured the distance between the charged plate and ionizer blower, recorded the relative humidity and temperature, and oriented the charged plate with respect to the ionizer blower. Also, we identified the time and amount of compressed breathing air (inspected by SGS and contained in "K" Bottles, spec: SES-0073-6.3-29 with a purity of 21.4% O_2) needed to achieve the desired relative humidity.

The charged plate was wiped cleaned with Isopropanol and its polarity was maintained at "+" setting as specified in the operator's manual. When running in the 1000-100 volt regime, the decay rate (timing) stopped below 300 volts. The same situation occurred in the 5000 - 500-volt range where the decay rate stopped at 1.7 sec when the voltage reached 3000 volts. Also, in the region of 1000-100 volts, the decay rate continued indefinitely in the order of ~200 sec. These occurrences prompted Dr. Rupert Lee to contact Monroe Electronics Inc. on August 17, 2000 at 11:00 AM EST to report the charged plate behavior at those voltage regimes. For that reason we decided to arbitrarily set up the voltage to 1000 – 400 v and 1000 – 300 v.

The opening of an existing orifice for venting and the installation of grounding wire for the charge plate, ionizer blower, and stands to a common ground was done to neutralize the remaining ion pairs in the test chamber, which produced a longer charging/discharging rates indicating that equilibrium was not completely achieved as it was observed with some experimental runs. Also, after placing 4 Engelhard/Desiccite 25™ 16 Units Type I desiccant bags into the test chamber to speed up the drying process, it was verified that the decay rate was shorter as expected.

Two plate orientations were used, direct impingement (charged plate perpendicular to ionizer blower flow, high 90°) and horizontal (charged plate parallel to ionizer blower flow, low 0°). The ionizer blower remained at a fixed position while the charge plate was allowed to move freely at different distances (near and far as we denoted them), which depended on the size of the experimental chamber.

EXPERIMENT/TEST RESULTS

As stated earlier, we conducted 4 preliminary experimental runs to verify the following parameters: the charged plate control panel properly working at the voltage range specified by the manufacturer, RH meter probe position inside the test chamber, ionizer blower positioning and minimum/maximum distance from charged plate inside the test chamber. During these experimental runs, it was noticed that some air ion pairs remained inside the chamber after each charging/discharging session and did not permit equilibrium conditions to re-establish, producing longer rates. In order to correct this situation, all stands and metallic parts were grounded to a common ground, the charged plate was wiped-clean with Isopropanol, and venting of the chamber was achieved to obtain faster charging/discharging rates.

Once all the experimental setup was properly chosen, a total of 21 experimental runs were conducted whose results are shown below:

Ionizer Experiment for August 18, 2000	
Position = Direct Impingement (90°)	
Distance = 33.02 cm / 13 in	
Relative Humidity RH = 30%	
Temperature = 21 °C / 70 °F	
Voltage Setup (v) = 1000 - 400	
Average Decay Rate = 2.0 sec	
Exp. Run#	Decay Rate (sec)
1	2
2	2
3	2
4	2
5	2
6	2
7	2
8	2
9	2
10	2

Ionizer Experiment for August 21, 2000	
Position = Direct Impingement (90°)	
Distance = 33.02 cm / 13 in	
Relative Humidity RH = 20%	
Temperature = 21 °C / 70 °F	
Voltage Setup (v) = 1000 - 400	
Average Decay Rate = 2.5 sec	
Exp. Run#	Decay Rate (sec)
1	2
2	2
3	2
4	3
5	3
6	2
7	3
8	3
9	3
10	2

Ionizer Experiment for August 28, 2000	
Position = Direct Impingement (90°)	
Distance = 33.02 cm / 13 in	
Relative Humidity RH = 10%	
Temperature = 22 °C / 72 °F	
Voltage Setup (v) = 1000 - 400	
Average Decay Rate = 2.2 sec	
Exp. Run#	Decay Rate (sec)
1	2
2	2
3	2
4	2
5	2
6	2
7	2
8	3
9	2
10	3

Ionizer Experiment for August 16, 2000	
Position = Direct Impingement (90°)	
Distance = 33.02 cm / 13 in	
Relative Humidity RH = 31% - 29%	
Temperature = 22 °C / 72 °F	
Voltage Setup (v) = 1000 - 500	
Average Decay Rate = 3.4 sec	
Exp. Run#	Decay Rate (sec)
1	4
2	3
3	4
4	4
5	4
6	3
7	3
8	3
9	3
10	3

Ionizer Experiment for August 16, 2000	
Position = Direct Impingement (90°)	
Distance = 33.02 cm / 13 in	
Relative Humidity RH = 31% - 29%	
Temperature = 22 °C / 72 °F	
Voltage Setup (v) = 1000 - 400	
Average Decay Rate = 11.6 sec	
Exp. Run#	Decay Rate (sec)
1	2
2	14
3	22
4	15
5	16
6	13
7	10
8	9
9	8
10	7

Ionizer Experiment for August 28, 2000	
Position = Direct Impingement (90°)	
Distance = 55.88 cm / 22 in	
Relative Humidity RH = 10%	
Temperature = 22 °C / 72 °F	
Voltage Setup (v) = 1000 - 400	
Average Decay Rate = 6.1 sec	
Exp. Run#	Decay Rate (sec)
1	6
2	6
3	6
4	6
5	8
6	6
7	6
8	5
9	6
10	6

Ionizer Experiment for August 30, 2000	
Position = Direct Impingement (90°)	
Distance = 55.88 cm / 22 in	
Relative Humidity RH = 30%	
Temperature = 21 °C / 70 °F	
Voltage Setup (v) = 1000 - 400	
Average Decay Rate = 7.1 sec	
Exp. Run#	Decay Rate (sec)
1	8
2	9
3	6
4	6
5	6
6	7
7	8
8	8
9	7
10	6

Ionizer Experiment for August 30, 2000	
Position = Direct Impingement (90°)	
Distance = 55.88 cm / 22 in	
Relative Humidity RH = 30%	
Temperature = 21 °C / 70 °F	
Voltage Setup (v) = 1000 - 300	
Average Decay Rate = 12.2 sec	
Exp. Run#	Decay Rate (sec)
1	13
2	9
3	9
4	10
5	8
6	11
7	16
8	16
9	11
10	13

Ionizer Experiment for August 18, 2000
Position = Horizontal Position (0°)
Distance = 33.02 cm / 13 in
Relative Humidity RH = 30%
Temperature = 21 °C / 70 °F
Voltage Setup (v) = 1000 - 400
Average Decay Rate = 3.6 sec

Exp. Run#	Decay Rate (sec)
1	4
2	3
3	3
4	4
5	4
6	4
7	4
8	3
9	3
10	4

Ionizer Experiment for August 29, 2000
Position = Horizontal Position (0°)
Distance = 33.02 cm / 13 in
Relative Humidity RH = 20%
Temperature = 22 °C / 72 °F
Voltage Setup (v) = 1000 - 400
Average Decay Rate = 3.6 sec

Exp. Run#	Decay Rate (sec)
1	3
2	4
3	3
4	4
5	4
6	4
7	3
8	4
9	4
10	3

Ionizer Experiment for August 28, 2000
Position = Horizontal Position (0°)
Distance = 55.88 cm / 22 in
Relative Humidity RH = 10%
Temperature = 22 °C / 72 °F
Voltage Setup (v) = 1000 - 300
Average Decay Rate = 21.9 sec

Exp. Run#	Decay Rate (sec)
1	23
2	20
3	21
4	27
5	22
6	22
7	22
8	27
9	16
10	19

Ionizer Experiment for August 30, 2000
Position = Horizontal Position (0°)
Distance = 55.88 cm / 22 in
Relative Humidity RH = 30%
Temperature = 21 °C / 70 °F
Voltage Setup (v) = 1000 - 400
Average Decay Rate = 7.6 sec

Exp. Run#	Decay Rate (sec)
1	6
2	8
3	8
4	9
5	9
6	6
7	8
8	7
9	8
10	7

Ionizer Experiment for August 29, 2000
Position = Horizontal Position (0°)
Distance = 33.02 cm / 13 in
Relative Humidity RH = 20%
Temperature = 22 °C / 72 °F
Voltage Setup (v) = 1000 - 300
Average Decay Rate = 4.9 sec

Exp. Run#	Decay Rate (sec)
1	4
2	5
3	4
4	5
5	5
6	5
7	5
8	5
9	5
10	6

Ionizer Experiment for August 29, 2000
Position = Horizontal Position (0°)
Distance = 33.02 cm / 13 in
Relative Humidity RH = 10%
Temperature = 22 °C / 72 °F
Voltage Setup (v) = 1000 - 400
Average Decay Rate = 3.8 sec

Exp. Run#	Decay Rate (sec)
1	4
2	4
3	4
4	4
5	4
6	3
7	3
8	3
9	5
10	4

Ionizer Experiment for August 30, 2000
Position = Horizontal Position (0°)
Distance = 55.88 cm / 22 in
Relative Humidity RH = 30%
Temperature = 21 °C / 70 °F
Voltage Setup (v) = 1000 - 300
Average Decay Rate = 10.0 sec

Exp. Run#	Decay Rate (sec)
1	8
2	12
3	12
4	7
5	12
6	10
7	11
8	11
9	8
10	9

Ionizer Experiment for August 29, 2000
Position = Horizontal Position (0°)
Distance = 55.88 cm / 22 in
Relative Humidity RH = 6%
Temperature = 21 °C / 70 °F
Voltage Setup (v) = 1000 - 400
Average Decay Rate = 16.3 sec

Exp. Run#	Decay Rate (sec)
1	15
2	16
3	15
4	19
5	21
6	13
7	14
8	16
9	17
10	17

<table>
<tr><td colspan="2">Ionizer Experiment for August 29, 2000</td></tr>
<tr><td colspan="2">Position = Horizontal Position (0°)</td></tr>
<tr><td colspan="2">Distance = 33.02 cm / 13 in</td></tr>
<tr><td colspan="2">Relative Humidity RH = 20%</td></tr>
<tr><td colspan="2">Temperature = 22 °C / 72 °F</td></tr>
<tr><td colspan="2">Voltage Setup (v) = 1000 - 300</td></tr>
<tr><td colspan="2">Average Decay Rate = 5.2 sec</td></tr>
<tr><td>Exp. Run#</td><td>Decay Rate (sec)</td></tr>
<tr><td>1</td><td>6</td></tr>
<tr><td>2</td><td>6</td></tr>
<tr><td>3</td><td>4</td></tr>
<tr><td>4</td><td>5</td></tr>
<tr><td>5</td><td>5</td></tr>
<tr><td>6</td><td>5</td></tr>
<tr><td>7</td><td>5</td></tr>
<tr><td>8</td><td>5</td></tr>
<tr><td>9</td><td>6</td></tr>
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<tr><td colspan="2">Ionizer Experiment for August 29, 2000</td></tr>
<tr><td colspan="2">Position = Horizontal Position (0°)</td></tr>
<tr><td colspan="2">Distance = 55.88 cm / 22 in</td></tr>
<tr><td colspan="2">Relative Humidity RH = 20%</td></tr>
<tr><td colspan="2">Temperature = 21 °C / 70 °F</td></tr>
<tr><td colspan="2">Voltage Setup (v) = 1000 - 400</td></tr>
<tr><td colspan="2">Average Decay Rate = 16.3 sec</td></tr>
<tr><td>Exp. Run#</td><td>Decay Rate (sec)</td></tr>
<tr><td>1</td><td>16</td></tr>
<tr><td>2</td><td>18</td></tr>
<tr><td>3</td><td>17</td></tr>
<tr><td>4</td><td>16</td></tr>
<tr><td>5</td><td>14</td></tr>
<tr><td>6</td><td>17</td></tr>
<tr><td>7</td><td>16</td></tr>
<tr><td>8</td><td>19</td></tr>
<tr><td>9</td><td>15</td></tr>
<tr><td>10</td><td>15</td></tr>
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<table>
<tr><td colspan="2">Ionizer Experiment for August 29, 2000</td></tr>
<tr><td colspan="2">Position = Horizontal Position (0°)</td></tr>
<tr><td colspan="2">Distance = 55.88 cm / 22 in</td></tr>
<tr><td colspan="2">Relative Humidity RH = 6%</td></tr>
<tr><td colspan="2">Temperature = 21 °C / 70 °F</td></tr>
<tr><td colspan="2">Voltage Setup (v) = 1000 - 300</td></tr>
<tr><td colspan="2">Average Decay Rate = 21.7 sec</td></tr>
<tr><td>Exp. Run#</td><td>Decay Rate (sec)</td></tr>
<tr><td>1</td><td>20</td></tr>
<tr><td>2</td><td>27</td></tr>
<tr><td>3</td><td>17</td></tr>
<tr><td>4</td><td>19</td></tr>
<tr><td>5</td><td>21</td></tr>
<tr><td>6</td><td>21</td></tr>
<tr><td>7</td><td>23</td></tr>
<tr><td>8</td><td>26</td></tr>
<tr><td>9</td><td>24</td></tr>
<tr><td>10</td><td>19</td></tr>
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<table>
<tr><td colspan="2">Ionizer Experiment for August 29, 2000</td></tr>
<tr><td colspan="2">Position = Horizontal Position (0°)</td></tr>
<tr><td colspan="2">Distance = 55.88 cm / 22 in</td></tr>
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<tr><td colspan="2">Temperature = 21 °C / 70 °F</td></tr>
<tr><td colspan="2">Voltage Setup (v) = 1000 - 300</td></tr>
<tr><td colspan="2">Average Decay Rate = 20.6 sec</td></tr>
<tr><td>Exp. Run#</td><td>Decay Rate (sec)</td></tr>
<tr><td>1</td><td>21</td></tr>
<tr><td>2</td><td>21</td></tr>
<tr><td>3</td><td>18</td></tr>
<tr><td>4</td><td>23</td></tr>
<tr><td>5</td><td>18</td></tr>
<tr><td>6</td><td>21</td></tr>
<tr><td>7</td><td>20</td></tr>
<tr><td>8</td><td>20</td></tr>
<tr><td>9</td><td>22</td></tr>
<tr><td>10</td><td>22</td></tr>
</table>

Ionizer Experiment for August 28, 2000	
Position = Horizontal Position (0°)	
Distance = 55.88 cm / 22 in	
Relative Humidity RH = 10%	
Temperature = 22 °C / 72 °F	
Voltage Setup (v) = 1000 - 400	
Average Decay Rate = 18.8 sec	
Exp. Run#	**Decay Rate (sec)**
1	17
2	27
3	21
4	18
5	21
6	23
7	19
8	13
9	14
10	15

DATA ANALYSIS

From the experimental runs, it appeared that **the distance** from the charged plate to the ionizer blower **is the major player** of all three variables considered (i.e. Relative Humidity, distance, and angle) in this experiment.

The graph displayed at the bottom of the analysis section, is intended for depicting the interaction effect of the three variables simultaneously studied in the experiment whose meaning is given by the statistical analysis of the experimental data. The results pattern indicated a factorial design, three factors tested at two levels, i.e. # of experiments = $2^3 = 8$. The statistical analysis process used to analyze this experimental data is called "ANOVA" (ANalysis Of VAriances).

Low Distance = near (33.02 cm / 13 in)

High Distance = far (55.88 cm / 22 in)

Low RH = 10%

High RH = 30%

Low Angle = 0° (Horizontal Plate)

High Angle = 90° (Direct Impingement)

Low = "0" and "-"

High = "1" and "+"

AVG = Average of 10 experimental values (no round off and with no decimal point)

In the following chart numbers 1 - 8 in the first column are the average values of 10 experimental data.

	A	B	C	AVG
1	0	0	0	3.8
2	1	0	0	18.8
3	0	1	0	3.6
4	1	1	0	7.6
5	0	0	1	2.2
6	1	0	1	6.1
7	0	1	1	2
8	1	1	1	7.1

Single Independent Variables

A = Distance

B = RH

C = Angle

In the following chart, **AB, AC, BC, and ABC** represent the combined interaction of 2 and 3 single independent variables.

** Number 4 here represents the number of differences or changes in the experimental conditions.

	A	B	C	AB	AC	BC	ABC
1	-3.8	-3.8	-3.8	3.8	3.8	3.8	-3.8
2	18.8	-18.8	-18.8	-18.8	-18.8	18.8	18.8
3	-3.6	3.6	-3.6	-3.6	3.6	-3.6	3.6
4	7.6	7.6	-7.6	7.6	-7.6	-7.6	-7.6
5	-2.2	-2.2	2.2	2.2	-2.2	-2.2	2.2
6	6.1	-6.1	6.1	-6.1	6.1	-6.1	-6.1
7	-2	2	2	-2	-2	2	-2
8	7.1	7.1	7.1	7.1	7.1	7.1	7.1
Sum	28	-10.6	-16.4	-9.8	-10	12.2	12.2
**Sum/4	7	-2.65	-4.1	-2.45	-2.5	3.05	3.05

This chart represents the 4 paired scenarios where the distance changed from near to far. The first set (1,2), represents the combined effect of low RH and low angle. The second set (3,4), high RH and low angle. The third set (5,6), low RH and high angle. The last set (7,8), high RH and high angle. The graph below represents the average between shortest and farthest distance in each set.

	A	B	C	AVG
1	0	0	0	3.8
2	1	0	0	18.8
3	0	1	0	3.6
4	1	1	0	7.6
5	0	0	1	2.2
6	1	0	1	6.1
7	0	1	1	2
8	1	1	1	7.1

(3.8 + 18.8) / 2 = 11.3

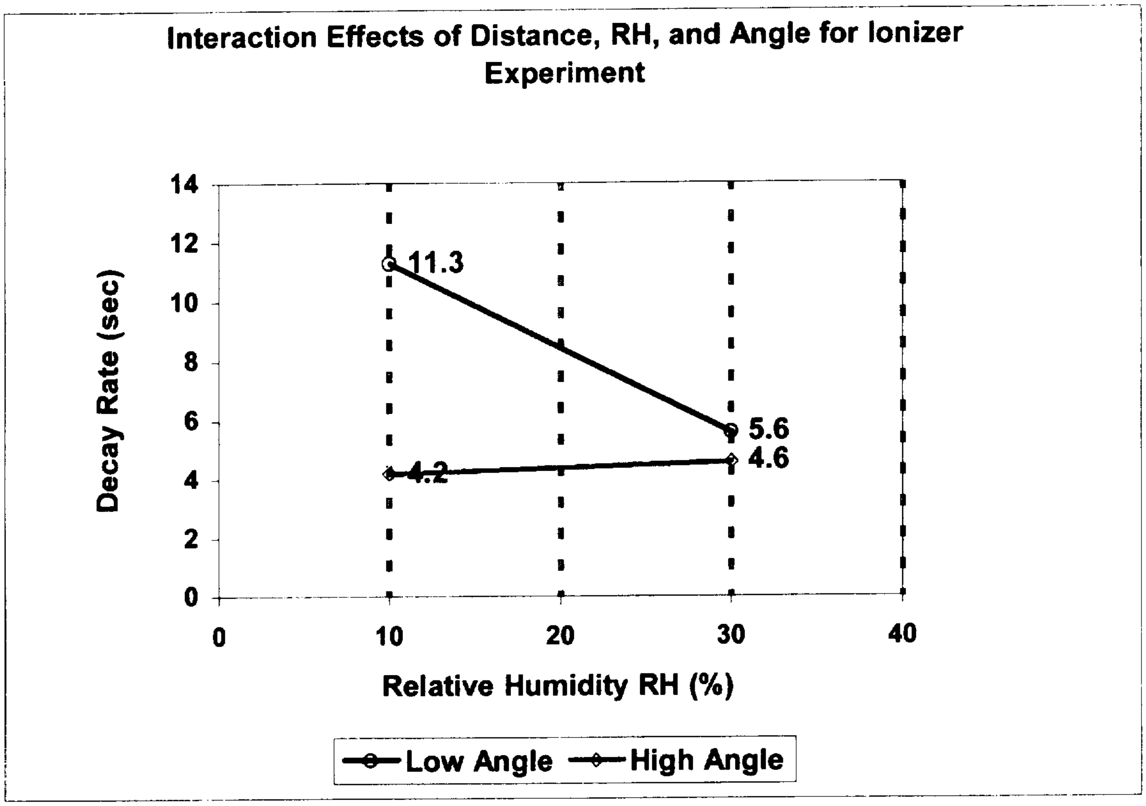
11.3 - 5.6 = 5.7

(3.6 + 7.6) / 2 = 5.6

(2.2 + 6.1) / 2 = 4.2

4.6 - 4.2 = 0.2

(2.0 + 7.1) / 2 = 4.6



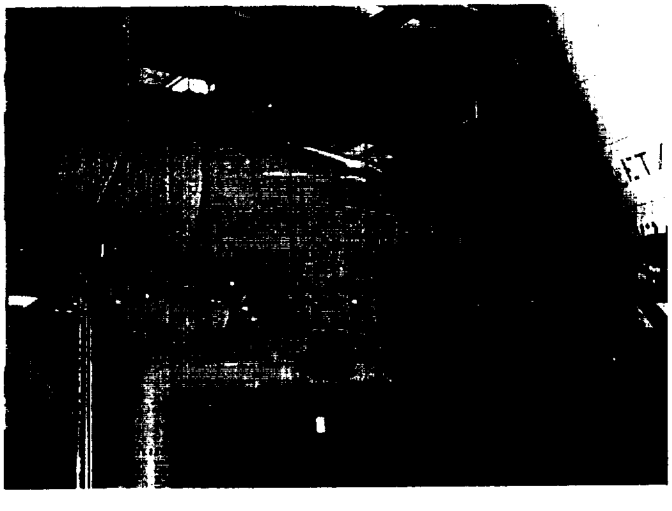
A further analysis of these experimental data would involve the use of a statistical software package which, would fall beyond the scope of the purpose for this experiment since a more complete variable analysis would involve the following interaction sequence: T_{ABC} = Average of the experimental values + main effect of **A** + main effect of **B** + main effect of **C** + interaction effect of **AB** + interaction effect of **BC** + interaction effect of **AC** + interaction effect of **ABC** + experimental error (how good this model fits the experimental data).

INCREASE OF MOISTURE CONTENT IN WORK AREA

The proposed alternative to allow for pyro operations to continue while RH≤30%, is in fact, to raise the humidity level above 30%. This task would require a modification of the OPF ECS configuration, similar to the ECS humidification modification at Pad B. The Pad B ECS has the ability to control the RH to the AFT, PLB, and Cabin purge circuits individually. The system consists of a humidifier, boiler, associated water piping, control valves, controllers, and sensors. The system has the capability of controlling the RH of the purge air going to the Orbiter above 30% while maintaining the maximum specific moisture of no more than 37 grains of moisture per pound of dry air. Although this method would work, it has two downsides: 1) this method could not be implemented at DFRC due to the fact that the Portable Purge Unit could not be outfitted with such a scheme, and 2) the modification would be costly as shown below.

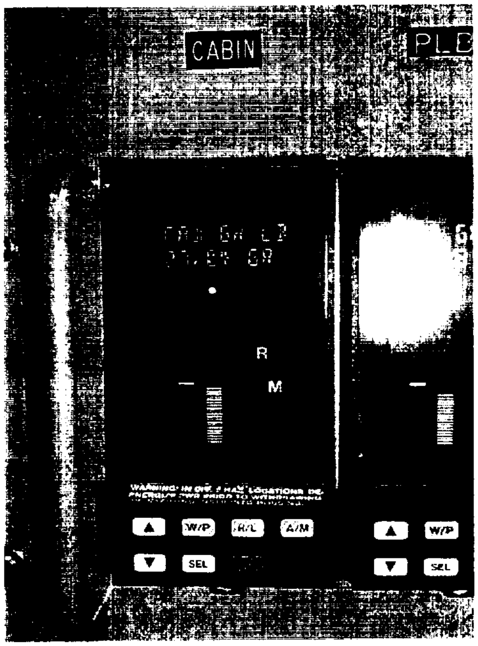
The approximate cost break down for the modification of one OPF ECS is as follows (in U.S. Dollars):
Two Required Sensors = \$300.00 each
Humidifier = \$2,500.00
Humidifier Chamber = \$1,500.00
Steam Generator (Boiler) = \$3,000.00
Piping and Control Valves = \$1,500.00
Water Softener = \$2,600.00
Design Costs = \$5,000.00
Two Foxboro Controllers = \$250.00 each
Labor = \$4,000.00
Burden (Contractor Profit) = 1.8% of Parts and Labor
Estimated Total = \$24,000.00

If this modification would be implemented to all three OPF ECSs, the total cost would be approximately \$72,000.00.



Dehumidifier already installed at Pad 39-B

Boiler Assembly at Pad 39-B



Humidifier Controller for the ECS at Pad 39-B

RECOMMENDATIONS FOR FUTURE ACTIONS

Some experimental issues and preliminary findings about ESDs and pyros were discussed with Dr. Raymond Gompf, a NASA adjunct consultant in the Research Area at the O&C Building and Mathematics Professor at Brevard Community College (BCC). He pointed out that the ionizer used in the experiment was not designed for pyro operations, rather we were just using it for testing purposes, and for future testing, we should contact the vendor to ask if they manufacture ionizers for pyro operations. Also some other small and important details such as how fast the technician is moving, body fat, weight, height, protective equipment, etc. can make a difference when handling EEDs at low RH levels, since these factors can trigger an inadvertent spark.

Future testing calls for a simulation on an OPF-like Pyro operation with RH<30% using the ionizer to verify that the voltage drops down to about 350 volts. This could be performed using wriststats, fire retardant coveralls, and personnel grounding. The key to provide electrostatic protection lies on timing because the faster the breakdown or switching time of the protective device after onset of applied electrostatic voltage, the better the protection will be.

Another possibility is to extend the experimental setup to a field experiment in the real environment of the OPF with a bigger ionizer blower and try to obtain some data. Perhaps in this realistic setting, we may have different variables to consider within the OPF. However, if further testing does not satisfy the safety community, then budgeting for modifications to the OPF ECS must be considered. Also, to solve the low RH problem at DFRC a portable dehumidifier may be considered. Of course, the portable dehumidifier must go through the proper testing and analysis before such a device could be used in the Orbiter.

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