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ESD Hazards Associated with CO₂ Refrigeration

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Abstract

Apparent malfunctions of two Trajectory Sensing Signal Generators (TSSGs) were observed during B61-3/4/10 trajectory arming tests at the Pantex Weapons Evaluation Test Laboratory (WETL). On two subsequent occasions, the TSSG used in the B83 bomb developed single-channel failures during tests at WETL. It was concluded that the failures were related to the electrostatic discharge (ESD) hazard associated with the use of a Thermotron® liquid carbon dioxide (CO₂) refrigeration system. It was demonstrated that during temperature conditioning, the case of the TSSG can acquire a substantial electrostatic charge as a result of triboelectric processes. A series of tests was performed to identify the charging mechanisms associated with liquid CO₂ refrigeration systems and a quantitative assessment of the ESD hazard was made. The conclusions and recommendations derived in these tests were summarized in a *Significant Finding Investigations Closeout*. The purpose of this report is to provide formal documentation for, and elaboration on, issues addressed in the *Findings*.

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ESD Hazards Associated with CO₂ Refrigeration

1.0 Introduction

The Trajectory Sensing Signal Generator (TSSG) is a bomb component whose function is to sense either radial or axial acceleration and subsequently generate proper arming signals. In October 1991, apparent malfunctions of two TSSGs, both MC2948s, were observed during B61-3/4/10 trajectory arming tests at the Pantex Weapons Evaluation Test Laboratory (WETL). In both cases, a unique signal generator malfunctioned at the time of stronglink closure. The cause of the apparent TSSG malfunctions was attributed to an electrostatic charge accumulation on isolated circuits in the test bed during temperature conditioning to cold.¹ This charge was believed to have been dumped into the tester at stronglink closure.

Subsequently, on two occasions the TSSG (model type MC3072) used in the B83 bomb developed single-channel failures during tests at WETL. As in the previous case, the components were temperature conditioned to -35°F prior to centrifuge tests. Again, after an extensive investigation, it was concluded that the failures were related to the electrostatic discharge (ESD) hazard associated with the use of a Thermotron® liquid carbon dioxide (CO₂) refrigeration system.² It was demonstrated that during temperature conditioning, the case of the TSSG can acquire a substantial electrostatic charge as a result of triboelectric processes. Accordingly, steps were taken to dissipate this charge as it was generated to decrease the potential for ESD-induced damage to components during cold temperature conditioning.

A series of tests was performed to identify the charging mechanisms associated with liquid CO₂ refrigeration systems and a quantitative assessment of the ESD hazard was made. In addition, ESD control measures were devised and changes to test operating procedures for the WETL Thermotron were proposed. A modification to the gas injection inlet on the cold conditioning chamber was found to be only moderately effective in reducing the charge acquired by the TSSG case. However, the charge accumulation can be reduced to a negligible value simply by connecting the TSSG case to the facility ground.

The conclusions and recommendations derived in these tests were summarized in a *Significant Finding Investigations Closeout*.² The purpose of this report is to provide formal documentation for, and elaboration on, issues addressed in the *Findings*. Historical background, theory, test procedures, conclusions, and recommendations are covered in the sections that follow. In the interest of completeness, elaboration on the rationale behind proposed modification of the CO₂ injection system is appended.

1.1 Test Cycle Overview

After the parachute and the nuclear components have been removed from a weapon by Mason & Hanger, the weapon is reassembled, placed inside a plastic bag with desiccants, and delivered to Sandia for testing. The first stop is in the system test area. Here, primary and secondary tests are conducted on the assembled weapon; during the tests the weapon is located inside a large environmental test box. During the primary tests, the weapon batteries, squibs, and detonators are fired. During the secondary tests, the weapon batteries are replaced with power supplies in the test equipment. Many of the tests are conducted at ambient temperature conditions; however, the tests also may be conducted at hot or cold temperatures.

¹ Newell, R. A., (367) "Investigation of Apparent B61 TSSG Malfunctions at Cold Temperature," Memo to Distribution, November 14, 1991.

² *Significant Finding Investigations*, SFI 92-04-B83-02 and SFI 92-16-B83-05; (closeout), October 22, 1993.

After system tests are completed, the fire set, junction box, and TSSG are removed from the weapon and placed inside a plastic bag with desiccants for storage, pending centrifuge testing. When the centrifuge tests are conducted, the hardware is removed from the plastic bags and placed inside an environmental box for this phase of the testing. In the case of the B61, the fire set, junction box, and TSSG are placed in the box; only the TSSG is placed in the box in B83 tests. The W80 is also subjected to cold conditioning. However, individual components are not conditioned to cold. Instead, the complete warhead is placed into an environmental test box. During this test sequence the unit is first temperature cycled (either hot, cold, or ambient) and then placed on a centrifuge where it is monitored while undergoing acceleration tests. Finally, the components are removed from the box, placed in a plastic bag, and returned to Mason & Hanger.

Thermal Cycling. The temperature within the box is established by means of a circulating flow of temperature-conditioned, gaseous CO₂ which is injected into and exhausted from the box through short lengths of non-conducting tubing, 4 inches in diameter. The temperature of the gas is cycled, typically between -65°F and +160°F under the control of a Thermotron. High temperatures are obtained by heating the gas by means of resistor heating coils. The basic cooling principal used in the Thermotron is the Joule-Thomson effect in which liquefied carbon dioxide at high pressure is expanded adiabatically through a small orifice to a low pressure, resulting in a decrease in temperature of the gas. Temperature control is established by a complex servo system, which determines the length of time that cooling and heating are on during each of a consecutive train of variable timing intervals.

Environmental Box Configuration. Figure 1 is a schematic representation of the QU1659 environmental box used for temperature cycling. The component under test, in this case the MC2948 (TSSG for the B61), is held in place during the test by solid foam support blocks. The external box, which is 24 by 18 by 20 inches on the outside, surrounds an inner box. Both boxes are electrically conducting and are separated by a layer of thermal insulation. Three jacks provide electrical access to the component under test. Electrical continuity between boxes is ensured by means of a screw that penetrates both boxes. (The screw was added after the ESD incidents were observed.)

Figure 1. Environmental Test Box with Weapon Components (B61)

2.0 Experimental Procedure

The experimental procedure was designed primarily to identify the charging mechanism, and to quantify the amount of charge acquired by the TSSG during cold conditioning. In the Joule-Thomson expansion process, under certain conditions of temperature and pressure there is a flash separation in

pressure, the exhaust is composed of about 47% dry ice and 53% gas by weight.³ Therefore, it can be assumed that CO₂ gas and particulate having various sizes coexist in the input to the environmental test chamber in roughly equal portions by weight. In addition, there is present in the stream additional particulate of various sizes consisting of condensed and frozen water vapor derived from the ambient atmosphere. A number of experimental studies have shown that this particulate produces an electric charge when it impinges on a metallic surface. Presumably, particles of carbon dioxide acquire a negative charge when they collide with a metallic surface, leaving the surface with a positive charge. A preliminary investigation of the charging phenomena was conducted in the Electromagnetic Analysis and Test Department ESD Laboratory. The experiments are described in the Appendix.

Figure 2 shows the experimental arrangement used to monitor the case voltage attained by the MC3072 during temperature conditioning. In this arrangement, the MC3072 is held in place during the test by a foam insert (QU1745). An insulated thermocouple, thermally bonded to the case of the component under test, provides an electrical feedback signal to the Thermotron control circuit. Connection to the Thermotron can be made through either J1 or J2, which are multiple pin connectors. The MC3072 case is connected to a field sensing plate through jacks J1 and J1A. The plate voltage, and, therefore, the TSSG case voltage, is measured by means of a MONROE model 245 fieldmeter, which provided an analog readout. A vibrating reed sensor with a phase-synchronized detector ensures a drift-free measurement. A direct-current variable-voltage source was used for calibration.

Figure 2. Environmental Box with TSSG (B83)

³ Lindsey, J. S., 1992, "Carbon Dioxide," *Encyclopedia of Science and Technology*, 7th ed., Vol. 3, (New York: McGraw-Hill) 220-221.

The equivalent electric circuit of the cold conditioning box is shown in Figure 3. It should be noted that C2 represents the capacitance of the box with respect to the facility ground, assuming that both the box and the movable cart, which supports the box, are electrically isolated from the facility ground. C2 is in parallel with the series combination of C1, the capacitance of the box with respect to the cart, and C3, the capacitance of the cart with respect to the facility ground. The indicated values of the capacitance were determined by iteratively solving the three simultaneous nonlinear algebraic equations representing the three possible series-parallel capacitive equivalents between the three lower terminals taken two at a time. The actual capacitance between any two terminals was measured by means of a BK-Precision® model 820-capacitance bridge. The capacitance between the TSSG case and the box was measured directly using the same instrument.

A PROSTAT® model PRS-800 megohmmeter was used to obtain the resistance values indicated in Figure 3. R1 represents the resistance of the insulating pad between box and cart, and R3 represents the resistance of the insulating rubber wheels of the cart. The resistance of the foam surrounding the TSSG is represented by R4.

The two characteristic intrinsic time constants of interest are given by the products $R4 \cdot C4$ and $R1 \cdot C1$, nominally, 10 seconds and 0.1 second, respectively. The time constant is the length of time required for a charge on a capacitor to decay to a value of $1/e$ of the original charge, where e is the Napierian base. Because most physical operations, for example, moving the cart between the Thermotron and centrifuge, require at least a minute, the principal capacitance of concern is C4, the capacitance between the TSSG case and the cold conditioning box.

Figure 3. Cold Conditioning Box Equivalent Circuit

A strip chart recorder, connected to the analog output of the electric field meter, was used to obtain Figure 4, which shows the voltage buildup of the TSSG case (C4 on Figure 3) versus time resulting from exposure to CO₂. Injection occurred at approximately 12-second intervals. Charging is indicated by the fast rise portion of the sawtooth. After each pulse of gas, the charge on the case decays, approximately in an exponential fashion, with the decay constant consistent with the $R4 \cdot C4$ product. The charging is not uniform; some pulses are more effective in charging, presumably due to variation in the amount of charging particulate from pulse to pulse. The decay time is determined by the product of the intrinsic capacitance of the TSSG and the leakage resistance of the surrounding foam. The voltage attained by the case is, roughly, inversely proportional to the duration of the interval between pulses.

Of greater interest than the fine charging structure shown in Figure 4 is the macro charging phenomena associated with long duration exposure to cold CO₂ injection. Measurements were made of the TSSG case voltage over cold-conditioning runs lasting over one hour. A number of runs were made with different grounding configurations.

For the first configuration, the box and cart were "floating," that is, ungrounded. Figure 5 shows the TSSG case voltage with respect to facility ground versus time as the temperature, measured by a thermocouple in contact with the case, was lowered. The temperature decreased linearly with time from

Figure 4. TSSG Case Voltage Versus Time (CO₂ injection at approximately 12-second intervals)

70°F to -35°F in about 100 minutes, that is, about 1 degree per minute. During the first sixty minutes, the voltage increased exponentially to a peak value of 600 volts. A reasonable fit to the charge build up is given by

$$V = V_0 + 1.14 T_0 \exp (t/\tau),$$

where $T_0 = 70^\circ \text{ F}$, $V_0 = -100 \text{ V}$, and $\tau = 30.3 \text{ minutes}$. When the temperature decreased to 0°F, 66 minutes into the run, the case voltage dropped abruptly to +100 volts, then gradually the charge bled off during the soaking period.

The mechanism responsible for the abrupt decay of charge at 66 minutes has not been identified. After 66 minutes, the temperature of the TSSG case was 0°F. Either one or both of two explanations was considered credible. First, during the run, the ambient relative humidity of the WETL was 60 percent. When the temperature of the ceramic insert of the connector used to monitor case voltage decreased to the dew point, water condensed on the surface of the insert. The film of water could have shorted the pins to the connector shell, which makes electrical contact with the box. In this case, the charge would have been redistributed, but not neutralized, because both box and cart were isolated. Furthermore, a separate test was run in which the resistance between a pin adjacent to the shell and the shell was monitored as the temperature was reduced to -60° F. No change in resistance was noted; therefore, the first postulated mechanism was dismissed.

Alternatively, the charge generating mechanism could be self limiting. During each gas injection, pulses of solid CO₂ particulate can be observed through the semi-transparent walls of the lexan throttle assembly on the box CO₂ inlet. If it is assumed that collisions of this particulate with the metallic TSSG case is responsible for charge generation, the process would be inhibited by the buildup of CO₂ frost on the TSSG case. The frost forms an insulating dielectric coating on that portion of the TSSG case exposed to particulate impact. After the frost layer forms, input CO₂ particulate would impact on a coating of CO₂ frost adhering to the case instead of impacting on the metallic surface of the case. At this point, charge generation would stop and any charge accumulating on the case would drain away. The same argument can be made if the solid particulate consisted of frozen water. Although the CO₂ is recirculated, hermetic integrity is not enforced and the system is not completely closed. The circulating gas probably contains some water vapor which would condense and freeze to form ice particulate. In either case the maximum charge generated by particulate charging would be self limiting.

Figure 5. MC3072 Case Charge Buildup and Temperature vs. Time (case, box, cart, TSSG internal electronics floating)

Figure 6 shows the TSSG case voltage buildup and temperature versus time when the cold conditioning box and the internal TSSG electronics were both connected to facility ground. This was the test configuration used when the MC3072 failures noted above were observed. The grounding apparently smoothed out most of the fine structure variation during charge buildup and decay, otherwise the amplitude variation with respect to time is essentially the same as that observed in the previous case (Figure 5). However, the temperature of the TSSG case was between 20° and 30°F when the maximum charge was attained. It should be noted that in this configuration, the voltage differential between individual internal TSSG components and the case is maximized.

Referring again to Figure 1, the fire set, TSSG, and junction box in the B61 are tested as a system. The MC2948 TSSG case is made of a nonconducting foam. Figure 7 shows the charge buildup on the floating ground plane of the isolated portion of the fire set. The voltage increase of the ground plane with decreasing temperature is similar, qualitatively, to that observed on the MC3072 metallic case. However, the maximum voltage attained is 2750, almost 5 times greater than that shown in Figure 5. In addition to differences in the impact surface areas, the higher voltages attained in the B61 tests can be attributed to differences in the roughness and composition of the plating layers. Hart, et al., have shown that a wide range of charging currents, including polarity reversals, are associated with differences between the work functions of the plating materials.⁴ To illustrate the dependence of charge buildup on temperature, the

⁴ Hart, J., Y. M. Huang, and D. T. Schnitzler, 1975, "The frictional charging of metals by a carbon dioxide spray," *J. Phys., D: Appl. Phys.*, **8**, 1941-1947.

same data presented in Figure 7 is presented in Figure 8, in which TSSG case voltage is plotted as a function of case temperature. It is interesting to note that the peak voltage attained by the case occurs at about -30°F. The geometrical features of the charging function shown in Figure 7 are preserved in Figure 8 because of linear decrease of temperature with time shown in Figure 7. It should be noted that the charge decay after reaching the maximum shown in Figure 8 occurs while the temperature is still decreasing in an approximately linear manner. That is, the charge decay is not a function of the rate of CO₂ injection by the Thermotron because the cooling of the CO₂ is accomplished solely by the injection-expansion process.

Figure 6. MC3072 Case Charge Buildup and Temperature vs. Time (case floating, box, and TSSG internal electronics grounded)

Figure 7. Isolated Ground Plane Charge Buildup and Temperature vs. Time (case, box, cart, fire set, and TSSG electronics floating)

Figure 8. Isolated Ground Plane Charge Buildup vs. Temperature

3.0 Recommended Test Procedure Remediation

Remediation of the charge buildup on the B83 TSSG case is accomplished by ensuring that the TSSG case is bonded by a conducting braid to the test box and that the test box is connected to facility ground. Similarly, the ground plane of the B61 fire set should be connected to the facility ground. Without further measurements, it cannot be determined if the foam case of the MC2948 TSSG will acquire a charge on exposure to cold conditioning. The environmental temperature box, QU1659, should also be bonded to the facility ground. The effectiveness of this procedure was demonstrated conclusively by a test performed on an MC3072 simulator at Pantex on June 15, 1994. Although no tests were performed on the MC3268 or the MC3269, which are TSSGs used in the W80 systems, the test procedure modifications recommended here should be regarded as generic. (The test bed for the W80 should be grounded, thereby protecting the TSSG.) The metallic case of any component subjected to cold conditioning should be bonded to the facility ground. Also, auxiliary environmental temperature boxes should be bonded to the facility ground.

A significant effort was expended on a study of the basic charging mechanism. A preliminary report on this work, including a comprehensive bibliography on related studies, is appended. It is recommended that these studies be continued to advance our knowledge of the physics of ESD charging mechanisms. Also, it is not obvious why the temperature at which charge inhibition occurs should exhibit such a wide variation. In all the tests reported here, the ambient relative humidity of the WETL was above 60%. Also, charge inhibition occurred at temperatures substantially below the dew point. Because, at some future date, it may be necessary to subject unshielded components to cold conditioning, it would be desirable to have an explanation for this phenomena.

APPENDIX

The propensity of carbon dioxide fire extinguishers to acquire an electrical charge when discharged has often been reported by fire fighters.¹⁻³ Moreover, several severe explosions have been attributed to ignition of explosive gas-air mixtures resulting from ESD sparks generated by CO₂ systems designed to snuff out fires.⁴⁻⁷ Accordingly, a number of experimental studies of aerosol charge generation mechanisms have been conducted on an ad-hoc basis, usually to resolve some issue raised during the investigation of an ESD environmental hazard.⁸⁻¹³ Other studies or text references relevant to the current investigation are cited in the attached bibliography.¹⁴⁻¹⁸

It is generally recognized that electrostatic charging does not accompany the release of most gases. Carbon dioxide is unusual in that during the expansion process, there is a flash separation in which particles of solid CO₂, that is, dry ice particulate, is formed. These particles acquire a negative charge when they collide with a metallic surface, leaving that surface positively charged. This process can be very effective. As noted above, if liquid CO₂ at a pressure of 285 psig is exhausted to atmospheric pressure, the exhaust is composed of about 47% solid particulate and 53% gas by weight.¹⁶ Only the particulate is effective in the charging process. Charging cannot be induced by ionization of individual molecules of carbon dioxide gas because the kinetic energy of a carbon dioxide molecule with a velocity as high as 500 ms⁻¹ is only 0.06 eV, which is two orders of magnitude less than typical ionization energies.¹⁵

Before the Pantex investigation was conducted, some preliminary experiments were performed in the Electromagnetic Analysis and Test Department ESD laboratory. A duplicate of the throttle valve assembly used in the cold box, minus the variable flow control, was constructed of lexan and mounted on a galvanized plate as shown in Figure A-1. Compressed carbon dioxide gas was allowed to expand adiabatically through a small hole in the nozzle of a fire extinguisher diffuser horn to form a stream of mixed gaseous and solid carbon dioxide. The solid particulate was directed against a variety of metallic obstructions placed normal to the flow. Obstructions were insulated from the galvanized plate, or ground plane, which was connected to the laboratory facility ground. Voltage and capacitance measurements were made with reference to the ground plane.

Figure A-2 shows, schematically, the experimental arrangement used for preliminary laboratory studies of particulate charging. A conducting copper screen intercepted the flow of CO₂ particulate from the diffuser horn. The voltage (V) attained by the screen was determined by means of a MONROE model 245 fieldmeter. The capacitance (C) measured between the screen and the galvanized ground plane was 100 pF. The charge acquired by the screen is given by the product CV.

Two sources of CO₂ were used: one was a standard General Fire Extinguisher Corp. Model 15 RH extinguisher, capacity 15 lb CO₂; the other, a siphon type liquid CO₂ cylinder, capacity 116 lb. The flow of CO₂ from the fire extinguisher was controlled by an ON-OFF valve, while the flow from the siphon cylinder was controlled by means of a conventional CO₂ regulator. (See Figure A-1).

Injection of CO₂ from the extinguisher was so energetic that the fieldmeter was driven off-scale (10 kV). By means of the regulator, the flow from the siphon was held steady at a pressure of 180 lb/in. With the controlled flow, the voltage on the screen gradually increased to a sustained peak of 500 V after a 3-minute period. At this point, the screen, which was clearly visible, acquired a coating of dry ice which appears to be a charge limiting mechanism. That is, solid CO₂ particulate impacting on a layer of dry ice will not effectively charge a metallic substrate.

Figure A-1. Cold Box Laboratory Simulation (carbon dioxide from gas cylinder expands adiabatically through a diffuser horn to create a particulate stream that impinges on the plate of the throttle valve assembly.)

Figure A-3 shows a scheme proposed to mitigate charge buildup. A second screen was placed in the CO₂ flow upstream from the first screen. This screen was grounded to facility ground and the previous experiment was repeated. The maximum voltage attained by the downstream screen was 20 V.

Although the preliminary tests in the ESD laboratory showed that the charge induced by CO₂ particulate injection could be reduced substantially by interposition of grounded screens in the CO₂ stream, these same modifications, which were made on the throttle inputs of the WETL cold boxes, were not very effective. Figure A-4 shows a screen inhibitor and a baffle constructed of brass shim stock with louvers whose purpose was to allow the passage of cold CO₂ gas and, at the same time, impede the passage of solid CO₂ particulate. The brass baffle was connected to facility ground. Figure A-5 shows the charge buildup of the floating ground plane (B61) and temperature-versus-time when the cold box throttle assembly is baffled. (See Figure A-4.) The baffle is electrically connected to the cold box and the voltage measurement is made with respect to the box. The maximum voltage attained in this configuration is 450 V at a temperature of about 20% of the maximum voltage reached in the unbaffled configuration (see Figure 7). It is clear that the baffle by itself is not sufficient to effectively inhibit ESD charging.

A number of other configurations were monitored with results comparable to those described here, and elaboration on these is not warranted at the present time. It is sufficient to state that the physics of the charging phenomena, complicated by a very convoluted path for the charging particulate, are very complex and worthy of further study.

Figure A-2. Experimental Arrangement for Detection of Charged Particulate in CO₂ Flow

Figure A-3. Experimental Arrangement for Mitigation of the CO₂ Charging Mechanism

Figure A-3. Experimental Arrangement for Mitigation of the CO₂ Charging Mechanism

Figure A-4. Cold Box ESD Charge Suppressors (Left – Brass Baffle, Right – Copper Screen)

**Figure A-5. Baffle-Inhibited Charge Buildup on Isolated Ground Plane (B61)
(Fieldmeter Referenced to Cold Box and Baffle)**

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