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Technical Advisory Team (TAT) Report On the Rocket Sled Test Accident of October 9, 2008

Prepared by Sandia National Laboratories for the NNSA Accident Investigation Board

Anthony J. Medina, Jerome H. Stofleth, and Michael A. Dinallo

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-1451

Abstract

This report summarizes probable causes and contributing factors that led to a rocket motor initiating prematurely while employees were preparing instrumentation for an AIII rocket sled test at SNL/NM, resulting in a Type-B Accident. Originally prepared by the Technical Advisory Team that provided technical assistance to the NNSA's Accident Investigation Board, the report includes analyses of several proposed causes and concludes that the most probable source of power for premature initiation of the rocket motor was the independent battery contained in the HiCap recorder package. The report includes data, evidence, and proposed scenarios to substantiate the analyses.

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Acronyms

AIB	Accident Investigation Board
DOE	Department of Energy
DUT	device under test
EM	electromagnetic
ESRC	Explosive Storage Review Committee
HERO	hazards of electromagnetic radiation ordnance
LED	light emitting diode
NNSA	National Nuclear Safety Administration
SHBESD	severe human body electrostatic discharge
SNL	Sandia National Laboratories
TAT	Technical Advisory Team

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1. ACCIDENT SUMMARY

1.1 Introduction

On October 9, 2008, at approximately 4:40 p.m., an accident occurred while a contract employee and three Sandia National Laboratories (Sandia) employees were preparing instrumentation for an AIII rocket sled test at the 10,000-foot sled track located in Area III at Sandia. The purpose of the regularly scheduled test was to evaluate the performance of MC4152 thermal batteries during a simulated B61 penetration environment. The accident occurred when a rocket motor ignited prematurely. The contractor employee sustained a compound fracture of the femur and first- and second-degree burns on his hands and arms; he was airlifted to the hospital where he underwent emergency surgery. The other three employees initially reported ringing in the ears and possibly impaired hearing; two were taken to the hospital and released, and the other declined immediate treatment.

In response to the accident, the National Nuclear Safety Administration (NNSA) declared the event a Type-B Accident, thereby requiring an external investigation board to lead the accident investigation. The NNSA created such a team—called the Accident Investigation Board (AIB)—composed of personnel from the Sandia Site Office and from Kirtland Air Force Base (AFB). This team worked with Sandia representatives from the rocket sled test site to document and collect evidence. In response to a request from the AIB, Sandia established a Technical Advisory Team (TAT) to provide technical assistance, advice, and recommendations to the AIB as to the probable causes and contributing factors of the accident.

1.2 Accident Details

The accident involved the unexpected initiation of a Zuni Mk 71 Mod 1 rocket motor as engineers and technicians were preparing a test payload for use. The details of the hardware configuration, as described to the TAT at the time of the accident and immediately thereafter, were as follows:

- The rocket sled appeared to function as intended, eventually ending up in the position down the track as planned for this shot and as experienced in the preceding four tests.
- The unexpected initiation occurred as a technician was installing an indicator light emitting diode (LED) plug, as designed and planned, on the J2 connector on top of the payload box.
- A shorting plug (shunt) was in place across the rocket initiator.
- Two MC4152 thermal batteries had not been initiated either intentionally or unintentionally.

- The firing set box planned to set off the rocket initiators was not connected to the rocket structure in any way.

2. TECHNICAL ADVISORY TEAM MEMBERSHIP

The TAT members were selected from across Sandia to provide a broad technical capability from which to provide technical advice, study, investigation, and analysis for the Accident Investigation Board (AIB). To prevent any conflict of interest from affecting decisions or analyses, the personnel selected were not members of the organizations that experienced the accident. The following members were selected:

- Anthony Medina, TAT Leader, Director of Energetic Components Center
- Jaime Moya, Senior Manager of Explosive Technology Group and mechanical engineer experienced in field test and explosive operations
- Greg Scharrer, Department Manager and explosives expert
- Ron Franco, Department Manager and electronics engineer familiar with payloads of the type used in these tests
- Steve Heffelfinger, Department Manager and former sled track operations manager
- Jerry Stofleth, firing systems engineer experienced in explosive field test operations
- Mike Dinallo, electromagnetic analyst (for electrostatic discharge and radio frequency analysis)
- Kathy Alam, chemist
- Kevin Howard, electromagnetic measurement technician
- Clint Haslett, electronics technician

3. PROPOSED CAUSES OF THE ACCIDENT

As part of its role in assisting the AIB, the TAT performed background studies of all the separate components and subsystems involved in the sled track experiment in order to provide technical information, analysis, and opinions for the AIB. As part of these studies, the TAT held a brainstorming meeting to identify all the possible initiation methods that could have caused the premature initiation of the rocket. For each possible initiation method/source, the TAT followed through and performed rudimentary analyses to ascertain which scenarios were realistic, which scenarios could immediately be dismissed as not possible, and what follow-on activities could be pursued to evaluate those that appeared most promising. The scenarios identified by the TAT are listed separately in sections 3.1 through 3.6 below, along with the TAT's opinion on whether or not the scenario was a realistic potential cause of the premature ignition. For those that appeared to have a higher probability of likelihood, the TAT performed further studies and measurements and compiled evidence and documentation associated with each. (That evidence is summarized in each section below, and documentation is included in the appendices to this report.).

3.1 Proposed Cause A: Rocket Propellant Self-Initiated

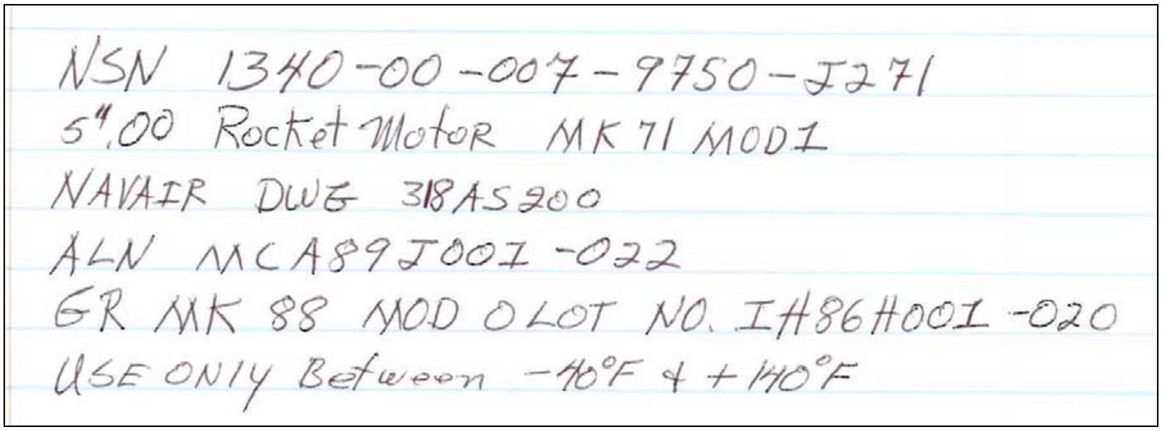
The TAT investigated the possibility that the propellant of the rocket self-initiated or was initiated by phenomena other than the designed-in initiators. The rocket propellant is a double-based fuel of approximately 49 percent nitrocellulose (12.6 percent N), 40.6 percent nitroglycerin, and six more constituents of small quantities. Because of its constituents, the propellant needs to have sufficient stabilizer to ensure it does not self-heat through a decomposition process and self-ignite. (These propellants are stabilized at the time of manufacture with ingredients that react with nitrogen oxide decomposition products. However, as the level of stabilizer diminishes over time to the point that it can no longer consume the decomposition products, the decomposition rate may accelerate and may, in certain cases, produce spontaneous ignition through self-heating. An increased decomposition rate may also cause energetic materials to become more sensitive to initiation stimuli, thus making them more hazardous to handle, store, or transport.) Sandia's Explosive Storage Review Committee (ESRC), established in early FY08 and chaired by Senior Scientist Dr. Anita Renlund, is charged with reviewing the stability of such devices and lot sampling the explosive material to ensure it is sufficiently safe. The committee has taken samples from rocket motors of the type used in the accident, but it has not filed its formal report on the test results. However, per an email from Jeff Cherry, manager of the sled track operation, the testing indicated that the stabilizer was at an acceptable level and was not a concern for self-ignition or significantly enhanced sensitivity to other means of ignition (see copy of e-mail in Appendix A).

Furthermore, were the rocket to have self-ignited as a result of the decomposition process described above, it would not have operated as intended because the ignition would have occurred in the center of the missile, where the thermal runaway process would have occurred. It would not have occurred near an edge because it would have lost heat to the outside, thereby eliminating the hazard.

3.2 Proposed Cause B: Electrostatic Discharge Initiated the Initiator

The TAT investigated the sensitivity of the initiator to electrostatic discharge (ESD) and the amount of energy and/or power that could have potentially been delivered to the initiators. (Information on the initiators is contained in Appendix B.)

The markings on the actual rocket motor under consideration indicate that it was an Mk-71, Mod 1 system. Figure 1 was taken from the actual motor by Ed Garavaglia (Sandia National Laboratories) for verification.



NSN 1340-00-007-9750-J271
5".00 Rocket Motor MK 71 MOD1
NAVAIR DWG 318AS200
ALN MCA89J001-022
GR MK 88 MOD 0 LOT NO. IH86H001-020
USE ONly Between -40°F & +140°F

Figure 1. Data Taken from Spent Rocket Motor

Two igniter types are used in the Mk 71 motor (Naval Air Systems Command). The Mod 2 version of this rocket contains an igniter that is certified to not be susceptible to ESD and hazards of electromagnetic radiation ordnance (HERO). The Mod 1 version of this rocket motor (this motor type) is considered ESD and HERO susceptible, meaning that ESD and electromagnetic (EM) energies should be considered as potential ignition sources.

Igniter

The igniter used in this rocket motor was an Mk 282 Mod 0 igniter (assuming original equipment). This igniter (see Figure 2) consists of a steel can containing two each Mk 1 Mod 0 electric squibs connected electrically in parallel and filled with approximately 35 grams of $BKNO_3$ propellant (see Appendix B).

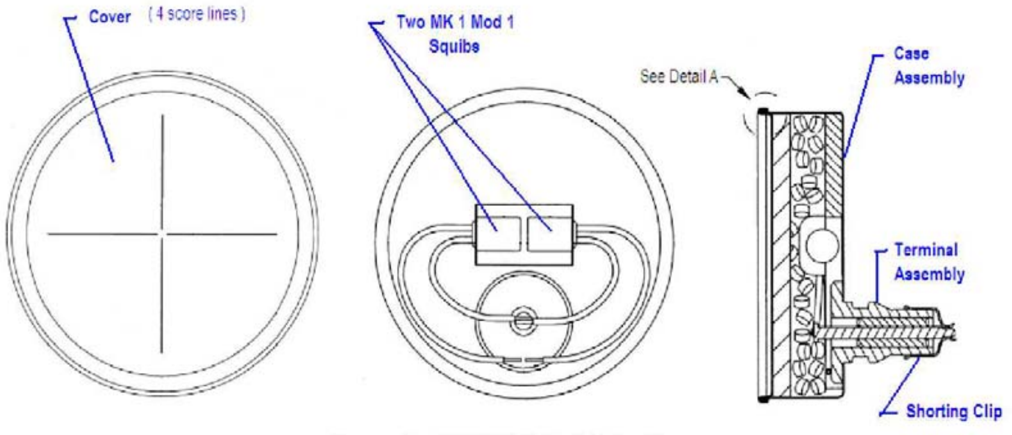


Figure 1: MK 282 Mod 0 Igniter
(Note: Shorting Clip is not on igniter while it's loaded in the motor.)

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Figure 2. Mk 282 Mod 0 Igniter

Each squib consists of a 1-ohm bridge-wire coated with a pyrotechnic material (DDNP/$KClO_4$) surrounded by 75 mg of black powder (see Figure 3).

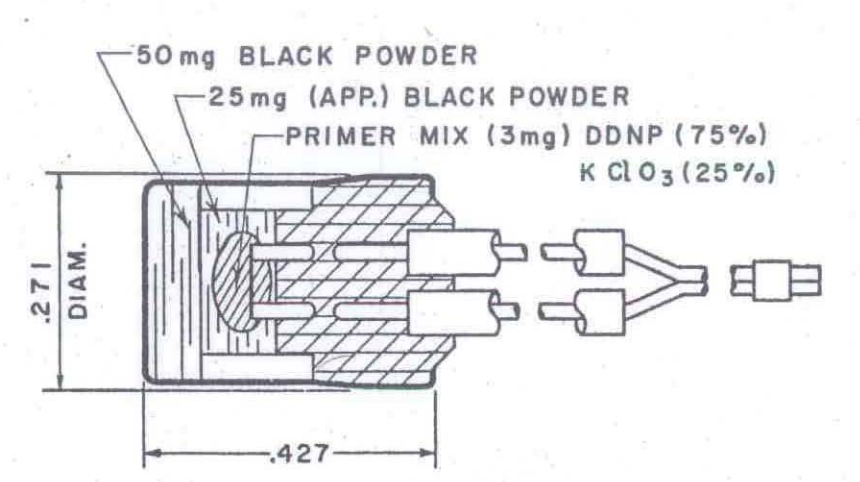

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Figure 3. Mk 1 Mod 0 Squib

Two squibs are connected electrically in parallel and mounted inside the igniter can. One lead from each squib is bonded to the inside of the metallic igniter can. The other lead from each squib is connected together and soldered to an electrically isolated binding post inside the igniter can. This single "high-side" lead is routed through the isolated terminal assembly to a contact band external to the igniter assembly, which is mounted inside the rocket. The "low-side" squib pin, squib case, igniter, and igniter assembly are all conductive, and when mounted in the rocket, they make electrical contact with the rocket motor case, making the rocket motor case the same electrical potential as the low-side pin of each squib. (See Appendix B, Figure B-4.)

Squib

This type of initiator (squib) functions via a required combination of electrical power and energy. The specific response to these power and energy parameters may be characterized through various methods of analysis. We were able to discover multiple sets of historic test data from which to derive some measure for these power and energy requirements.

To first order, a device such as the Mk-1 squib (see Appendix B, Figure B-3) functions on total heat accumulated in its bridge-wire while under electrical impetus. The heat is accumulated by electrical current passing through the bridge-wire (effectively a 1-ohm resistor), while at the same time, the heat is being dissipated (or conducted out of the bridge-wire) through conduction to its surroundings. The explosive initiates when the bridge-wire reaches a certain critical temperature. This dynamic requires a minimum energy to change the temperature of the bridge-wire, and it also requires a minimum power (rate of energy delivery) to ensure thermal dissipation is overcome.

This initiation requirement for this squib can, at first order, be described via a hyperbolic relationship between power and energy, along with some associated statistical uncertainty. If the energy AND power are at minimum levels, the initiator will fire—this relationship is regular, but not constant except for very high levels of power (where minimum energy should be constant) or very high levels of energy (where minimum power should be constant).

Typically, when testing for these parameters, a multitude of measurement obstacles must be overcome. A variety of strategies and standards have been developed over the years to attend to these obstacles, but coupled with manufacturing variations, these processes naturally lead to a statistical assessment of the power and energy parameters. As well, various techniques provide for specific results for a particular configuration. Therefore, absolute results from various techniques will not be exactly the same. For example, results from a capacitor discharge test technique will produce comparable values for a capacitor discharge firing circuit. However, a capacitor discharge is neither constant power nor constant energy and, therefore, it cannot be easily plotted on the curve in Figure 4 below. If, however, the curve is known entirely, then the likelihood of initiation can be derived mathematically.

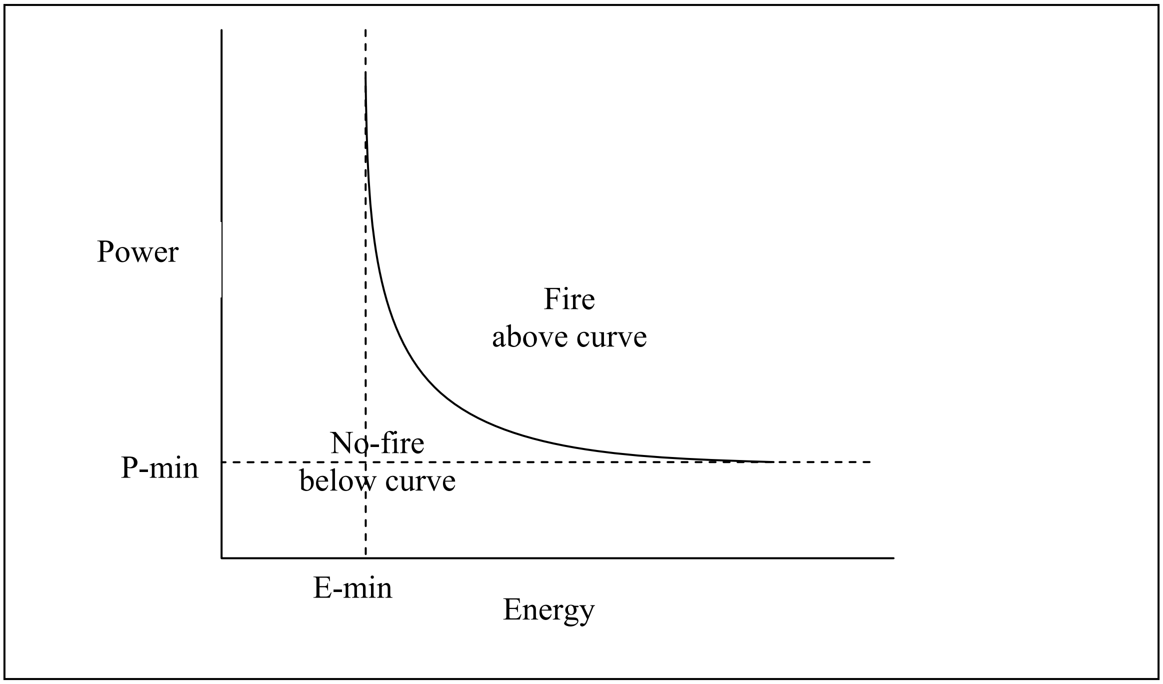


Figure 4. Power and Energy Relationship for Mk 1 Mod 0 Squib

Firing Data

Firing energies from the *Electric Initiator Handbook* are derived through the discharge of a 1-μf capacitor into a single Mk 1 Mod 0 squib. The results are shown in Table 1:

Table 1. Energy from Discharge of 1-μf Capacitor into Mk 1 Mod 0 Squib

Function Probability %	**Charged Capacitor (1 μf)**	**Energy in Capacitor (mJ)**
95	67 volts	2.24
50	57 volts	1.63
5	50 volts	1.25

Values for squib initiation data derived from Hampton and Gaylor were derived from constant current energy sources. The energy stimulus data shown in Table 2 were derived from the firing of 8,000 squibs.

Table 2. Energy from Firing of 8,000 Squibs

Function Probability %	Firing Energy (mJ)
99.60	1.79
97.14	1.33
70.22	1.10
4.17	0.96
2.13	0.91
0.35	0.88

The final resource (Morbach) describes the results from a power stimulus. The data shown in Table 3 were derived from a 100-squib Bruceton test. These data are for DC to RF frequencies and are therefore applicable to constant power sources through EM-generated/coupled sources:

Table 3. Power from 100-Squib Bruceton Test

Function Probability	Firing Power (watts)
99.9% @ 90% confidence ("all-fire")	0.143
50%	0.097
0.1% @ 90% confidence ("no-fire")	0.065

These data will be compared to the levels derived later for likely ESD initiation sources.

Electrostatic Discharge (ESD)

There are two basic methods by which these squibs may be initiated: (1) pin-to-pin flow through the bridge-wire and (2) and pin-to-case (or case-to-pin) arcing.

In examining the Mk 282 igniter, we can rule out the pin-to-case scenario, assuming the ESD path originates at the rocket motor/sled body. If the ESD path originated anywhere else in the proposed system, the path to ground would have been through the firing cable, and not through the squibs. The pin-to-case scenario then becomes a case-to-pin path, where an ESD impetus is applied to the rocket motor case, travels through the igniter assembly, through the igniter, to the case of the squib(s), and then arcs to the low-side pin. However, this cannot occur because this pin is connected directly to the igniter body, making the pin and case electrically common. A secondary scenario may have the arc jump to the high-side pin, but this cannot occur either—the path of least resistance to this pin is through the low-side pin, and through the bridge-wire, and then on to ground. (See Figure 5.)

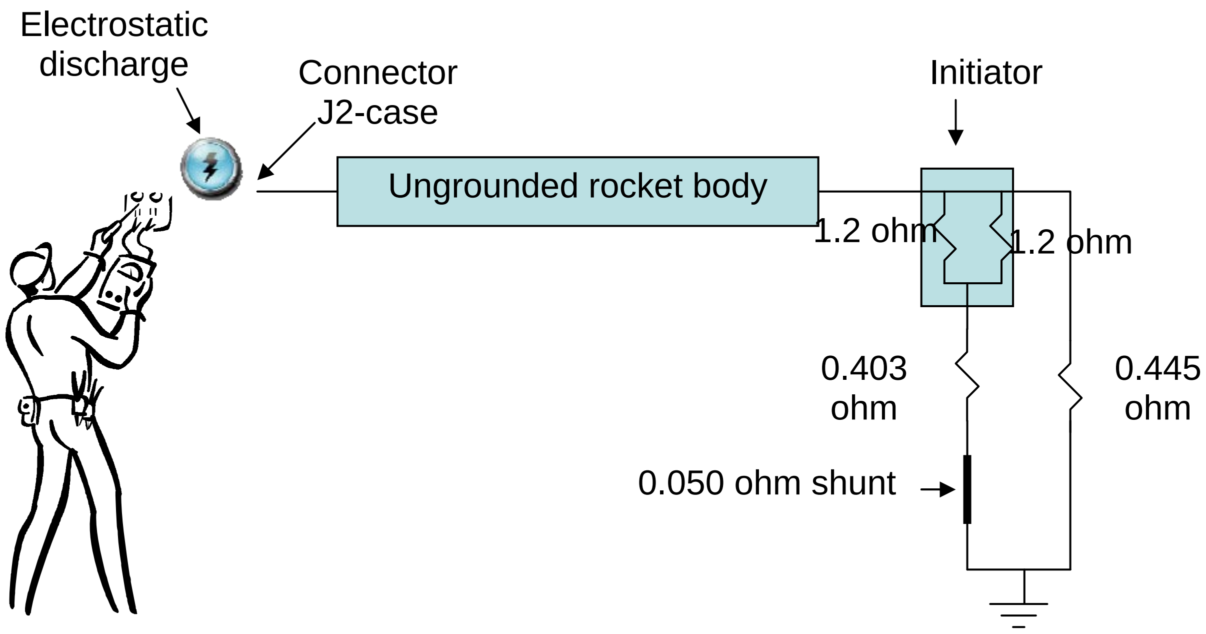


Figure 5. Proposed Scenario in Which ESD Could Have Reached Initiators

Pin-to-Pin

We evaluated several scenarios associated with a pin-to-pin ESD initiation with a commercial off-the-shelf electrical engineering and analysis software and modeling package. The circuit model used for ESD source is the Fisher Human ESD model (Barnum), which is widely accepted and utilized by the Department of Energy (DOE). Several other models provide various levels of threat for this configuration, but we chose this model as our standard. We connected this severe human body ESD (SHBESD) model to a 0.6-ohm load, which represents two squibs in parallel and the associated resistances in the igniter configuration. (See Figure 6.) This resistance value is a close estimate based on the actual reading recorded just before the rocket motor event.

Again, we assumed the ESD path initiated at the rocket motor case (or sled body) and propagated through the squibs to earth ground through multiple paths.

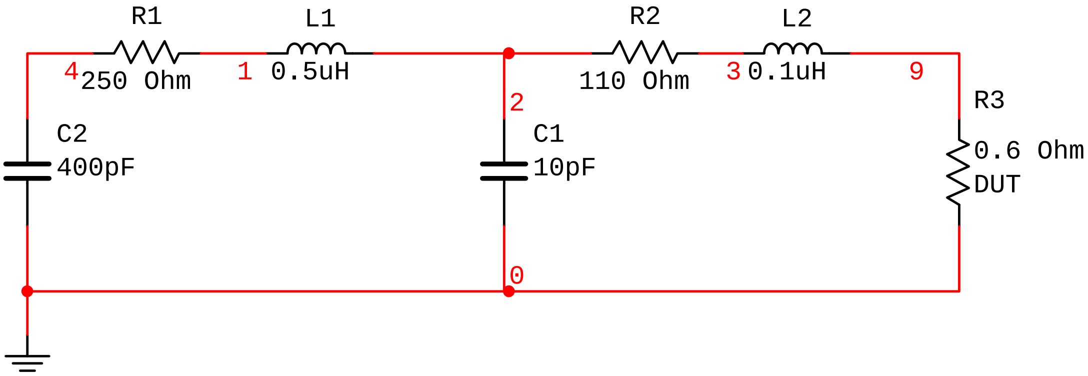


Figure 6. SHBESD into 0.6-Ohm Load

Analysis 1

Our first analysis modeled the HESD standard discharged directly into a 0.6-ohm resistor. The dynamic response can be seen in the plots in Figure 7 below. The current and voltage waveforms are multiplied together and then integrated to provide a total energy value, and this value is then divided by two to provide the energy level modeled for a single squib—assuming the two resistors are exactly balanced (which is likely). Below are the current and voltage traces:

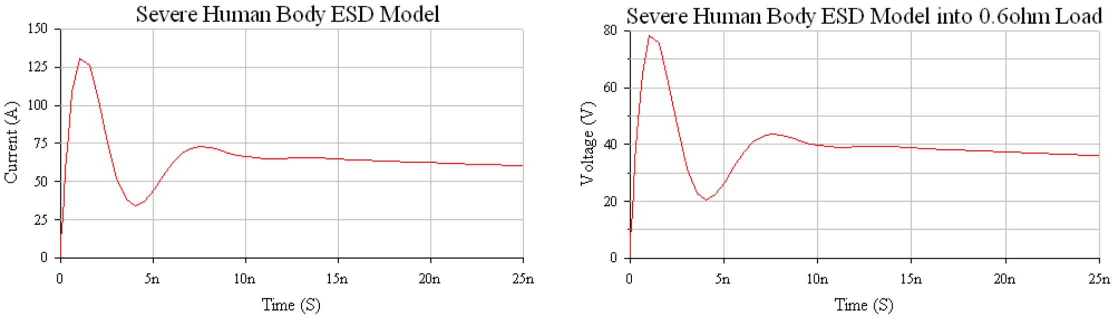


Figure 7. Current and Voltage

Allowing these waveforms to extend out in time and settle to zero, and then integrating, we get a value of 0.123 mJ per squib. (See Figure 8.)

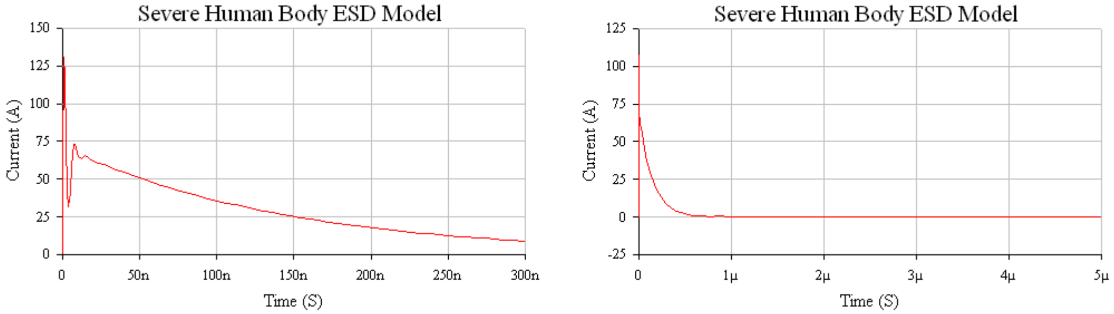


Figure 8. Waveforms Extended in Time

Analysis 2

The second model included the effect of the 100-foot Reynolds Type-C firing cable of nominal impedance that was attached to the initiator. These analyses actually considered several variations of this configuration driven by uncertainties in the cable connections: squibs connected to the 100-foot firing cable with the firing cable (1) shorted and grounded, (2) grounded but not shorted, (3) shorted but not grounded, and (4) not shorted and not grounded. After discussion amongst the TAT, we concluded that only one of these variations was plausible (the first one), as physical evidence suggested that the firing cable was indeed shorted and grounded prior to the event. As well, we ran models with ESD imposed at the sled body and at the far end of the firing cable. Again, we discount the ESD impetus at the far end of the firing cable based on physical and logical evidence. For the only viable variation to this squib-cable configuration, we used the representation shown in Figure 9.

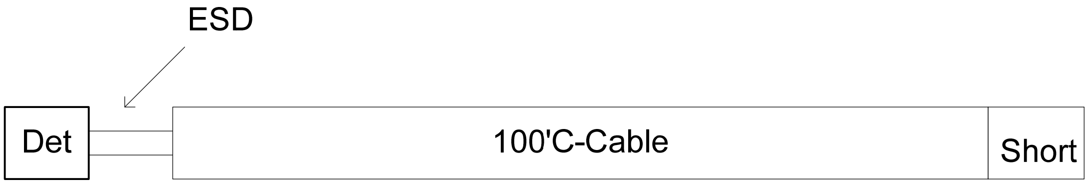


Figure 9. Variation to Squib-Cable Configuration

The circuit representation is shown in Figure 10:

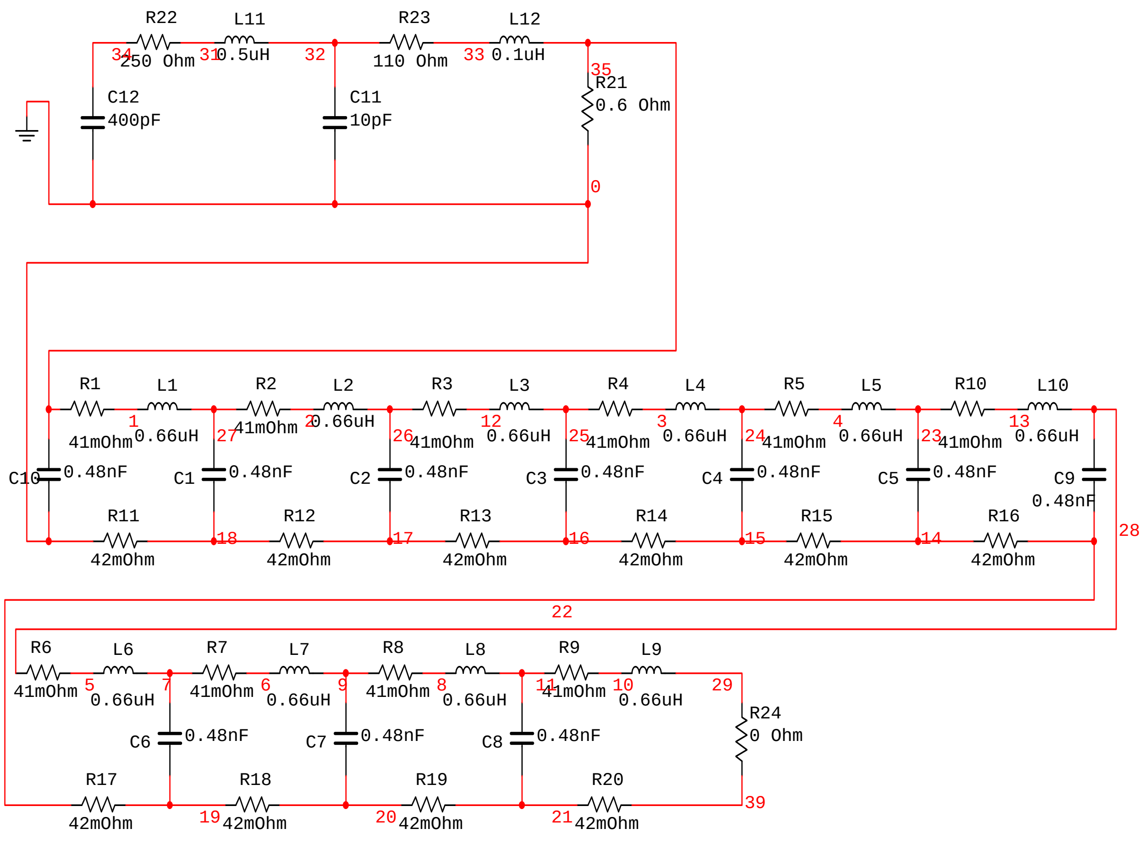


Figure 10. Circuit Representation

The energy accumulated in one squib from this configuration is negligible.

As an aside, if the cable was not grounded (shorted or not), an ESD pulse from the Fisher Model results in about 0.123 mJ of energy through each squib. This analysis is not shown for the reasons given above.

Analysis 3

In the final analysis, we increased the ESD impetus by using the Institute of Electrical and Electronics Engineers (IEEE) model for human and furniture combined. Those parameters are shown in Table 4 below.

Table 4. IEEE Model for Human and Furniture Combined

40 kV

Component or parameter	IEEE 62.47 PESD	IEEE 62.47 FESD
Body capacitance (Cb)	60 to 300 pF (300 pF)	60 to 300 pF (300 pF)
Body inductance (Lb)	0.5 to 2 μH (0.5 μH)	0.02 to 0.1 μH (0.02 μH)
Body resistance (Rb)	150 to 1500 Ω (150 Ω)	2 to 90 Ω (2 Ω)
Hand capacitance (Ch)	3 to 10 pF (10 pF)	3 to 20 pF (20 pF)
Hand inductance (Lh)	0.05 to 0.2 μH (0.05 μH)	<0.01 μH (0.01 μH)
Hand resistance (Rh)	20 to 200 Ω (20 Ω)	<20 Ω (20 Ω).

The results are the same as for the last analysis—the energy coupled to the squibs is negligible, provided the cable is grounded. The short on the cable has no effect on the analysis—the key factor is the cable being grounded. Without a ground connection at the far end of the cable, the energy through each squib could reach up to 42mJ with this aggressive representation of an ESD pulse.

Indeed, this is why this igniter is considered ESD and HERO susceptible. If the squibs are not properly grounded, they can easily be set off by a reasonable ESD pulse, especially one generated by the loading of this rocket into a helicopter tube.

Conclusion

In comparing the minimum firing energy from a capacitive discharge testing to the energy that could be imposed by the Fisher model for SHBESD, we find a discrepancy of about an order of magnitude. The energy required for 5 percent reliability is reported as 1.250 mJ. The energy generated into the squibs via the SHBESD model is 0.123 mJ when there is no cable attached. This is approximately 1/10th of the required energy for a very low probability of firing.

This result is considered the only viable scenario for ESD directly into the squibs. We have shown that there is no method for pin-to-case or case-to-pin initiation via ESD. We are assuming through physical evidence that the firing cable was grounded at the far end to earth ground. The shorting plug at the end of the cable is of no consequence if the cable is not grounded. With the cable grounded, the energy that can accumulate in the squibs is negligible. With the cable not grounded, and more severe ESD input, enough energy can indeed accumulate in the squibs to initiate a reaction—again, however, we have discounted this case. We have verified the cable impedance to be within manufacturer specifications. (See Appendix B for additional data.)

3.3 Proposed Cause C: Radio-Frequency Energy Fired the Initiator

Purpose

Radio frequency (RF) analysis established an estimate of the power received by the rocket propellant detonator leads due to the radio frequency environment.

Background (Cable Loops, Dipoles, and Transmission Line Models)

The range of RFs that can be present at the rocket sled track location spans the low kilo-hertz through several hundred mega-hertz frequency range. Due to the different RF coupling approaches, which are RF-wavelength-dependent relative to the length of the initiator cable, this broad-band of frequencies typically is divided into three bands and corresponding coupling models.

The longer wavelengths or lower frequency range (~ 1 kHz to 100 kHz; actual frequencies will depend on length of cable) typically models the cable as a loop antenna. This loop predominantly couples or picks up the RF ambient environment magnetic field component and determines an open circuit voltage that drives an impedance load producing RF loop current. At the shorter wavelengths or higher frequencies (~ 10 MHz to 1 GHz; again specific frequency range is cable length dependent) typically models the cable as a dipole antenna. This dipole predominantly couples with the electric field component that produces a voltage across and current through each side of the dipole wire lengths. The intermediate frequency band (100 kHz to10 MHz) models the cable as a transmission line producing voltage and current proportional to line impedance parameters. Each of these modeling approaches can be evaluated using closed form analytic techniques and finite difference or finite element numerical methods, in either the time or frequency domains. These approaches and methods are readily available in the electromagnetic literature (textbooks, journals, agency reports).

Model Approach (Dipole Model)

Known power and frequency band of RF emitters are used to decide what frequency band-based model (loop, dipole, or transmission line) is appropriate to estimate ambient RF-field-induced voltage and current on exposed electrical conducting cables. Knowing that hand-held Motorola-made ASTRO XTS 500 (5 watt) radios are present during sled track test activities and that the communication band is in the several 100- to 1000-MHz range, an electric dipole model can be used to estimate safe track-side operational RF environments' electric field strength. Other RF emitters can similarly be modeled once emitter power and frequency range is established at the sled track site.

Since a dipole model is appropriate to estimate power received by detonator leads, the V-curve method for establishing acceptable distances from RF transmitters can be used. However, an estimate of power received by the detonator leads using implicit formulation of V-curve transmitting and receiving dipole antenna characteristics will be used.

Model Calculations

The power received (P_{rec}) by a dipole antenna representing the track sled test fixture and rocket body is power density incident (P_{inc}) at the receive dipole, times the receive dipole power effective (capture) area (A_{rec}), written as:

$$P_{rec} = P_{inc} * A_{rec}.$$

The expression for A_{rec} is,

$$A_{rec} = (\lambda^2 /4\pi)*G_r ,$$

G_r is the gain of the receive antenna and $\lambda$is the corresponding wavelength associated with RF power density frequency f (i.e., λ=c/f, where c is speed of light). The power transmitted at the RF source is P_t and relates to the power density at the dipole as,

$$P_{inc} = P_t *G_t/(4\pi R^2),$$

Where G_t is the transmitting antenna gain and R is the distance between the transmitter (Motorola radio) and receive antenna (sled track test fixture).

Using transmit and receiving gains of 1.5 (for $< \lambda/2$ short dipole antennas) at a separation distance R of 3-meter (from the track to meet far field criteria) and a 5-watt transmitter power at the low frequency end 100MHz (λ = 3 meters), the power received is

$$P_{rec} = P_t *G_t * G_r * (\lambda/4\pi R)^2 = 0.071 \text{ watts}.$$

Similarly, at the upper RF frequency 1GHz (λ = 0.3 meters) and gains of 1.5, the power received is 0.0007 watts (0.7mW). These power levels can be compared to the all-fire level of 1.35 watts and the no-fire level of 0.05 watts.

Conclusion

In comparing the minimum firing energy from a capacitive discharge testing to the energy that could be imposed by these RF coupling phenomena, we found a discrepancy of about more than an order of magnitude for the higher frequency (1 GHz) scenario. We therefore discounted this frequency band from further analysis. At the low frequency band (100 MHz) the potential power coupled into the system is comparable to the no-fire level of the initiator; however, because this firing level still maintains an approximate 5 percent probability of firing the initiator, we conducted further analysis.

We analyzed the circuit into which this energy would be coupled. The diagram for this circuit is shown in Appendix C. Were 0.070 watts to be coupled into the initiator circuit, this energy would be available as a current within the circuit containing the initiators and the shorting plug (shunt). The power would therefore be shared based on the impedance ratios of the components. Analysis of the way the RF power would be distributed within the initiator circuit shows the amount of power available to each initiator would be significantly below the no-fire power for it. We therefore concluded this was not a likely source of premature initiation of the rocket motors.

3.4 Proposed Cause D: Thermal Batteries Fired the Initiator

Tests were being conducted to evaluate the performance of the MC4152 thermal batteries in a simulated environment that was to be provided by the rocket sled test. Thermal batteries (called devices under test, or DUT, in the experiment documentation package) are inert devices that require activation before becoming an active battery. When inert, they provide absolutely no power at their output connections. They are activated by firing an initiator similar to that of the Zuni rocket initiator.

Two thermal batteries were in the experimental package. The thermal batteries were to be activated immediately before rocket initiation, and their output voltage was to be monitored by the HiCap recorder during the entire duration of the rocket movement on the track. The TAT hypothesized that these thermal batteries, if activated, could have been a potential source of energy to cause the premature initiation of the rocket. In addition, if their activation signal could have been mistakenly routed to the rocket initiators, this could have had a potential effect.

In conjunction with the AIB, the TAT inspected the thermal batteries present during the accident. Each of the two devices was evaluated and characterized as NOT having been fired during the activities of October 9. Their bridge-wires were completely intact and provided impedance values expected of unfired units. This conclusively eliminated the thermal batteries as a potential source of energy causing the premature initiation of the rocket.

During the evaluation of the signal wires that would have been used to activate the thermal batteries, the TAT determined that the firing lines were not connected in a way that would have provided a potential path to the rocket initiator. The C-cable was not connected to the fireset, and there was no potential path to the rocket initiator. The ground wire from this signal pair could not have provided a separate path to earth.

3.5 Proposed Cause E: HiCap Recorder Battery Fired the Initiator

The TAT investigated the possibility that the batteries that powered the HiCap recorder instrument were the source of the rocket sled initiation. The batteries used for this application are Panasonic Lithium Ion Prismatic Series CGA batteries. The batteries have a nominal open-cell voltage of 3.7 volts each; three of these batteries were used in series for this application, resulting in a battery potential voltage of 11.1 volts, maximum. The actual battery stack voltage was measured at 10.8 volts, which is within the expected operating voltage range. (In the following discussion, the three cells will be referenced as a single battery.) The battery is charged before use of the recorder package to ensure it has sufficient charge to power to the HiCap recorder instrumentation package. The battery is live (producing voltage and current) during all phases of the integration of the HiCap recorder box into the rocket sled test configuration.

An analysis of the current-sourcing capability of the battery was performed to ascertain whether or not the battery was capable of producing the currents necessary to initiate the rocket motor initiators. The specifications on the battery indicate the battery has an internal impedance of 0.20 ohms. An impedance of this low value indicates the battery would be able to produce upwards of 40 amperes for a short period of time (when heat would degrade battery performance or the battery would catch on fire). This level of current is over an order of magnitude higher than necessary to fire the rocket motor initiator.

During the investigation into the current sourcing capability of the HiCap recorder battery, the TAT discovered that the HiCap recorder also uses a “super capacitor” in parallel with the battery. This circuit configuration is used to ensure that the battery/supercapacitor can source surge currents without disrupting the battery voltage—in essence, it is a filter to ensure the HiCap recorder circuitry does not encounter power-source glitches during times of high current usage. The addition of this supercapacitor component makes the HiCap recorder power system even more capable of providing the necessary power for rocket motor initiation. It makes the power system perform as a voltage source, capable of supplying almost unlimited current for very short time periods (microseconds to milliseconds).

Given the capacity of this power source, the TAT investigated the possibility that this energy was somehow available outside the HiCap recorder package. The TAT investigated connections, both intended and unintended, for both the power and ground connections for the HiCap battery. The TAT measured the resistance and capacitance between all pins of the J2 connector, which is the expected connection path into the HiCap recorder package. All connector resistances and capacitance values were well within expected values and did not indicate a surreptitious current path to the detonators. However, during the performance of these measurements, the AIB representative informed the TAT of a suspicious black mark that looked like a charring path on the J2 connector: this might have been indicative of a short circuit arc. The mark was centered on Connector J2, Pin 4, which is the pin on which the HiCap recorder battery power is brought outside the package for the LED indicator module. Investigating this J2-Pin 4 circuit, the TAT identified that the battery power was brought to this pin WITHOUT any current limiting resistance. *In essence, the full power of the battery was available on this pin should a ground path back to the battery be identified.*

The TAT then investigated potential grounding paths for the connection to the HiCap recorder battery negative terminal. It identified a path on the HiCap enable cable used to trigger the HiCap recorder to start recording just prior to rocket motor initiation. This ground connection was found to *exist without any current limiting resistance*. The ground was due to a short in the facility wiring (see Appendix E, Figure E-9). Note that the facility wiring should have been isolated from ground, but due to a fault in the facility wiring, it was, in fact, grounded. The TAT thus concluded that this was a very likely source for the surreptitious path to rocket motor initiators and a high probability cause of the accident. The TAT therefore stood down until permission was obtained from the AIB to investigate this further. A discussion of the follow-on investigation is contained in section 5, Analysis Leading to Proposed Cause of Premature Rocket Motor Initiation.

3.6 Proposed Cause F: Firing Set Initiated the Initiators

The TAT considered the possibility that the field test firing set may have malfunctioned, thereby prematurely igniting the rocket motor. However, information obtained from the AIB and personnel performing the test established that the firing set was not connected to the rocket in any manner at all. This absolutely eliminated this as a potential cause of the incident. Appendix F contains a photo of the test firing set.

4. TESTING AND MEASUREMENTS COMPLETED TO SUBSTANTIATE TECHNICAL ANALYSIS

Table 5. Battery Test MDM 51

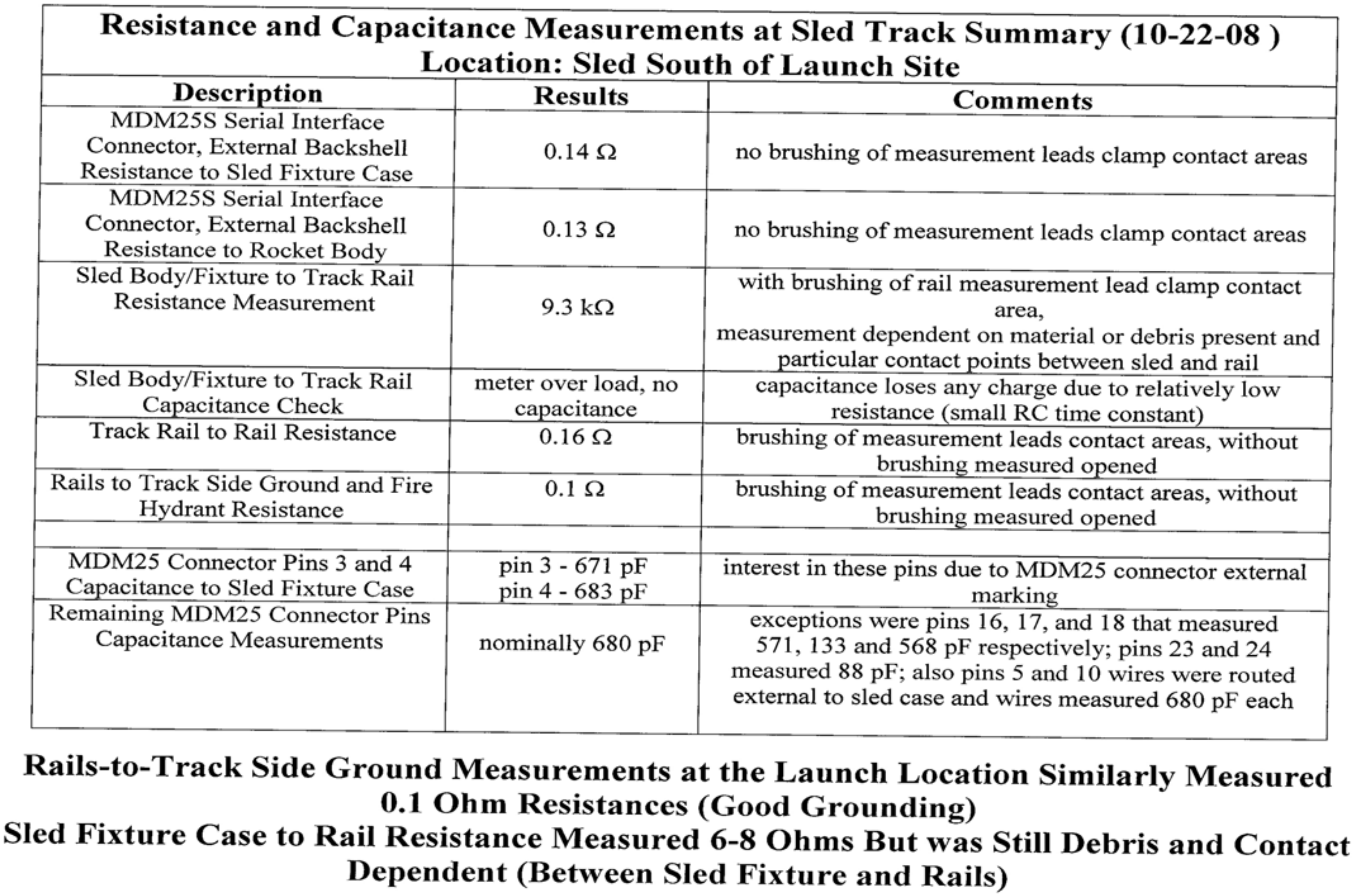
MDM 51 P

PIN #	DESCRIPTION
1	Ch 1 +
2	Ch 1 –
3	Ch 2 +
4	Ch 2 –
5	Ch 3 +
6	Ch 3 –
7	Ch 4 +
8	Ch 4 –
9	Ch 5 +
10	Ch5 –
11	Ch 6 +
12	Ch 6 –
13	Ch 7 +
14	Ch 7 –
15	Ch 8 +
16	Ch 8 –
26	Ch 9 + (model 7270 accel)
27	Ch 9 – (model 7270 accel)
42	Ch 9 (+ power for accel)
46	Ch 9 (gnd for accel)
28	Ch 10 + (trigger accel)
29	Ch 10 – (trigger accel)
43	Ch 10 (+ power for trigger accel)
47	Ch 10 (gnd for trigger accel)

Table 6. Continuity Checks at Test Site by Explosives Safety Personnel

Continuity Checks with Fluke Meter (Calibrated) and Simpson Meter Not Calibrated)			
From Item	**To Item**	**Status**	**Remarks**
Fire set Location			
Ground Strap connected to body of the Fire set	Ground Strap Body Cable Clamp	Good	Grounding Strap has three clamps
Ground Strap Body Cable Clamp	Ground Strap Backside Cable Clamp	Good	Grounding Strap has three clamps
Ground Strap connected to body of the Fire set	Ground Strap Backside Cable Clamp	Good	Grounding Strap has three clamps
Backside Ground Source Unpainted	Ground Strap Body Cable Clamp	Good	Grounding Strap has three clamps
Backside Ground Source Painted	Ground Strap Body Cable Clamp	Bad	Grounding Strap has three clamps
East Rail Location			
Wrist Strap	Wrist Strap at Band	Good	None
Wrist Strap	East Rail	Bad	None
Wrist Strap Clamp	East Rail	Bad	None
Wrist Strap	East Rail	Bad	None
Wrist Strap	Wrist Strap Clamp	Good	None
Wrist Strap	Wrist Strap	Good	None
East and West Rail			
East Rail	West Rail	Bad	None
East Rail	East Rail	Bad	Half way between 44 an 45, Did finally get good check at a rust spot
East Rail	East Rail	Bad	Half way between 46 an 47, Did finally get good check after rubbing away at the rail
Wrist Strap on ground South of Fire set Location			
Ground Strap Body Cable Clamp (#1)	Ground Strap Mid-Body Cable Clamp	Good	Grounding Strap has three clamps
Ground Strap Mid-Body Cable Clamp	Ground Strap Body Cable Clamp (#3)	Good	Grounding Strap has three clamps
Sled and Rocket Motor Location			
West Rail	Sled Shoe	Bad	Right Front Shoe
Sled Shoe	Sled Shoe	Good	Right Front Shoe
West Rail	West Rail	Bad	None
West Rail	West Rail	Bad	Simpson Meter, only very slight deflection
Sled	Rocket Motor Nozzle	Good	None
Shoe	Sled & Rocket Motor	Good	None

Table 7. Resistance and Capacitance Measurements Taken by TAT Personnel



Resistance and Capacitance Measurements at Sled Track Summary (10-22-08)
Location: Sled South of Launch Site

Description	Results	Comments
MDM25S Serial Interface Connector, External Backshell Resistance to Sled Fixture Case	0.14 Ω	no brushing of measurement leads clamp contact areas
MDM25S Serial Interface Connector, External Backshell Resistance to Rocket Body	0.13 Ω	no brushing of measurement leads clamp contact areas
Sled Body/Fixture to Track Rail Resistance Measurement	9.3 kΩ	with brushing of rail measurement lead clamp contact area, measurement dependent on material or debris present and particular contact points between sled and rail
Sled Body/Fixture to Track Rail Capacitance Check	meter over load, no capacitance	capacitance loses any charge due to relatively low resistance (small RC time constant)
Track Rail to Rail Resistance	0.16 Ω	brushing of measurement leads contact areas, without brushing measured opened
Rails to Track Side Ground and Fire Hydrant Resistance	0.1 Ω	brushing of measurement leads contact areas, without brushing measured opened
MDM25 Connector Pins 3 and 4 Capacitance to Sled Fixture Case	pin 3 - 671 pF pin 4 - 683 pF	interest in these pins due to MDM25 connector external marking
Remaining MDM25 Connector Pins Capacitance Measurements	nominally 680 pF	exceptions were pins 16, 17, and 18 that measured 571, 133 and 568 pF respectively; pins 23 and 24 measured 88 pF; also pins 5 and 10 wires were routed external to sled case and wires measured 680 pF each

Rails-to-Track Side Ground Measurements at the Launch Location Similarly Measured 0.1 Ohm Resistances (Good Grounding)

Sled Fixture Case to Rail Resistance Measured 6-8 Ohms But was Still Debris and Contact Dependent (Between Sled Fixture and Rails)

5. ANALYSIS LEADING TO PROPOSED CAUSE OF PREMATURE ROCKET MOTOR INITIATION

After completing the set of analyses identified in section 3 of this report, the TAT concluded that the most probable source of power for the premature initiation of the Zuni rocket motor was the independent battery contained in the HiCap recorder package (the scenario described in section 3.5). The TAT consulted with the chair of the AIB and received permission to pursue the investigation to determine if an actual scenario could be developed, based on evidence and measurements taken by the TAT and AIB, showing how this battery energy could have reached the rocket motor initiators.

After comprehensively compiling the electronics schematics of the HiCap recorder, the connector wiring of the rocket sled test setup, a review of the activities being performed at the time of the accident, and an evaluation of the shorting plug wiring, the TAT identified a probable circuit path that could have caused the premature ignition of the rocket motor. This theory was developed based entirely on data the AIB provided to the TAT and measurements performed by the TAT in the presence of AIB personnel. The TAT believes this is the most probable cause of the accident. If requested by the AIB or other authorities, the TAT believes a re-enactment of this proposed scenario could demonstrate the fundamental premises of how the energy from the battery in the HiCap recorder package reached the rocket motor initiators.

In developing this causal theory, the TAT believes the following issues are paramount to understanding how this energy reached the rocket motor initiators.

Significant Issues

- The HiCap recorder had an internal 10.8-volt battery. The battery connection was brought outside the package to Pin 4 on the outside J2-connector. This battery connection was NOT current limited with a series resistor. The internal impedance of the battery was calculated to be 0.2 ohms from data contained in the battery specification data (see Appendix E, Figures E-13 and E-14).

- The HiCap recorder has an exposed miniature MDM 25-pin connector with metallic exposed pins labeled as Connector J2. The case of the J2 connector is electrically connected to the housing and, therefore, to the rocket body. There was potential evidence of arcing present on the connector body next to J2 - Pin 4 (see Figure 11, Figure 12, Figure 13, and Figure 14 below), although extensive chemical analysis of this evidence is still in process to definitely identify the marks as char or not. Although evidence of charring would greatly substantiate this proposed scenario, the TAT believes the proposal is still valid without evidence of charring. Not all short circuits will produce combustion products.

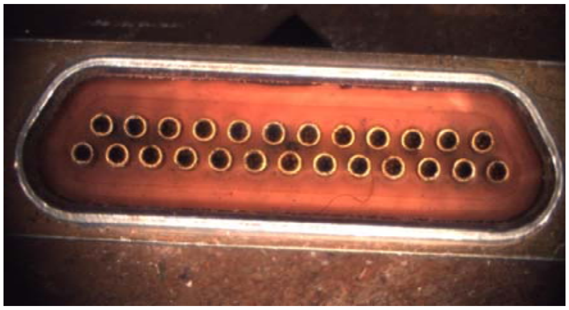


Figure 11. Clean, New Connector

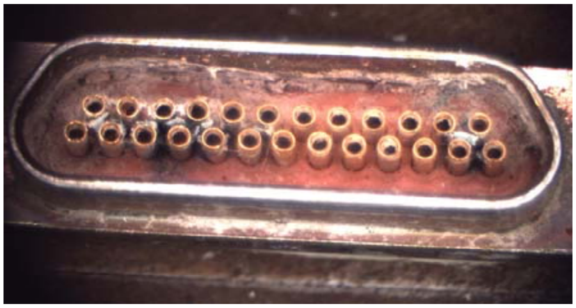


Figure 12. Connector from Accident

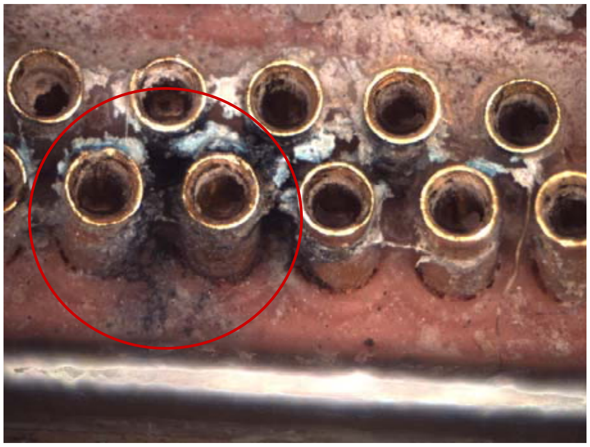


Figure 13. Close-Up of Pins 3-4

Figure 14. Close-Up of Connector Pin

- Ground connections to the sled track rail are suspect unless the rails are severely scraped to remove rust. Information provided to the TAT indicated that this level of scraping and/or grinding on the rails was not conducted prior to the accident (See Figure 15). Measurements performed by personnel from Safety Engineering 4122 and repeated by TAT personnel showed lack of electrical connectivity between the rails, wrist straps to rail, and wrist strap clamp to rail. These measurements are listed in section 4 of this report. The result is a likely case of an ungrounded (floating) missile case.

Figure 15. Ground Clamp on Sled Track Rail

- Detonators are parallel redundant with resistance of 1.2 ohms each (see Appendix B for details on the initiators). The safety shorting plug (shunt) was located at the end of 106 feet of C-cable. The resistance of the cable was measured at 0.414 ohms for the center conductor and 0.478 ohms for the shield. The detonator shorting plug was also grounded to earth ground at the junction/panel box as shown in Figure 16 below.

-

Figure 16. Shunting Plug Ground Connection

- The battery ground was brought outside the package with a dedicated wire that was one of a pair of wires used to trigger the HiCap recorder to start recording. The battery ground was NOT current limited. This connection was found to be grounded to earth ground at the junction/panel box due to a short in the facility wiring. Note that the facility wiring should have been isolated from ground, but due to a fault in the facility wiring, it was, in fact, grounded. The wire was connected to the panel box as shown below in Figure 17.

Figure 17. Panel Box Connections of Signal Wires

Figure 18. HiCap Recorder Showing Loose Signal Wires

Results

The resulting situation was a case where a potential closed circuit path from the positive terminal of the HiCap recorder battery positive to the HiCap recorder battery negative was identified. The only gap in this hypothesized circuit is the connection from the HiCap recorder Connector J2-Pin 4 to the case of either the connector or to the rocket body itself. The TAT hypothesizes that this final connection (from J2-Pin 4 to J2-Case) occurred when the explosives technician was inserting the LED indicator module into the J2-connector and accidentally shorted J2-Pin 4 to the case of Connector J2. Note that the case of this LED module is metal and would have easily provided the conduction path necessary to close this circuit. (Refer Appendix E, Figures E-2 through E-4.)This would have created a short circuit between the two points and would have completed the circuit between the HiCap recorder battery and the rocket motor initiators. (Grounding conditions at the time of the accident cannot be verified, but post-test measurements have shown that the resistance between the sled and the sled track rail varied between 6 ohms and infinite ohms, depending on how the sled was rocked.)

From information provided by the AIB to the TAT, personnel present during the accident distinctly heard a noise that sounded like an arc or static discharge just before the rocket motor ignited. The TAT believes the scenario proposed above could have produced such a noise. Please note that the TAT did not speak with personnel involved in the accident.

Per the discussion above, the site configuration that would have resulted is depicted in Figure 19 below, which shows each of the salient components that played a role in the proposed accident scenario.

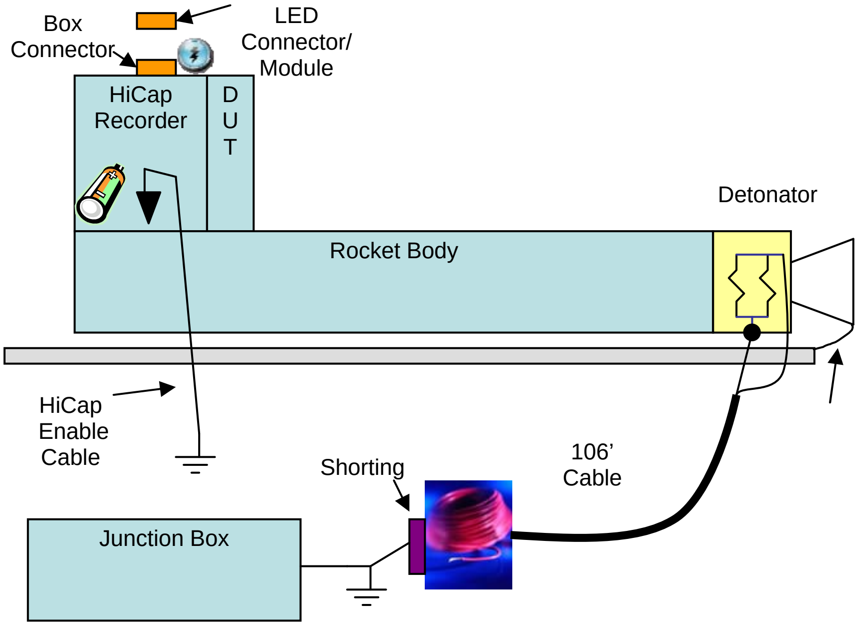
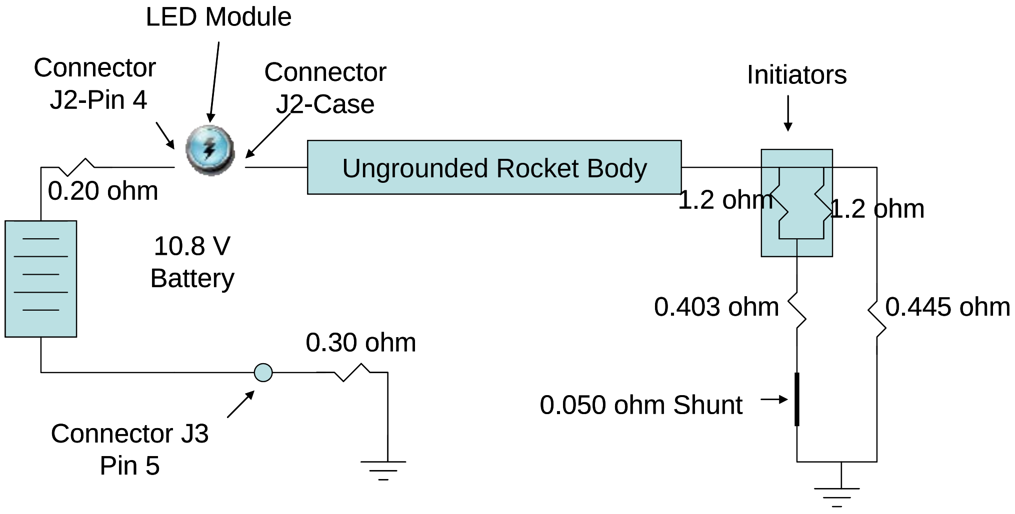


Figure 19. Key Components of Scenario

From this scenario, the TAT performed key measurements and analyses to characterize the situation to enable a closed-form calculation of the current that could be provided to the rocket motor initiators. The resulting lumped-sum equivalent electrical circuit of the scene at the time of the accident is shown below in Figure 20. In it, one can see that the resulting current provided to each of the individual rocket motor initiators was estimated to be 1.97 amperes, which is substantially above the Zuni rocket motor initiator all-fire current level of 1.5 amperes. A current of this value is essentially guaranteed to fire the initiators and commence rocket motor ignition.



$$\text{Detonator Current} = \frac{10.8\text{ volts }(.297)}{2\,(0.813)\text{ ohms}} = 1.97\text{ amps} > 1.5\text{ amp all-fire}$$

Figure 20. Resulting Electrical Circuit

After identifying this as the cause of the accident, the TAT brainstormed to identify why it had not happened in any of the recent tests involving the exact hardware used in the accident. The following key reasons were identified:

- The proposed scenario requires an ungrounded rocket motor body. During the time impedance measurements were being taken between the rocket motor chassis and ground, the TAT observed that the grounding was erratic. By leaning the rocket motor body in different directions, one could change the impedance measures dramatically. It should be noted that leaning the rocket motor body from between the tracks in the direction outside the tracks (as a technician would do if he were working on the payload while stationed between the tracks) seemed to be the worst direction for providing a grounded rocket chassis. Note that this was a post-fact observation and may not completely or accurately describe the situation before the accident.

- The completion of the electric circuit requires the shorting of Connector J2-Pin 4 to the case of Connector J2 when the LED module was being inserted. Were this not to happen, the electrical path described in this section would not have been completed and no current would have flowed as hypothesized.

The TAT proposes that Sandia fund a follow-on activity to identify the root causes of the situations leading up to this accident and that appropriate corrective actions to be taken to prevent similar situations from occurring in the future.

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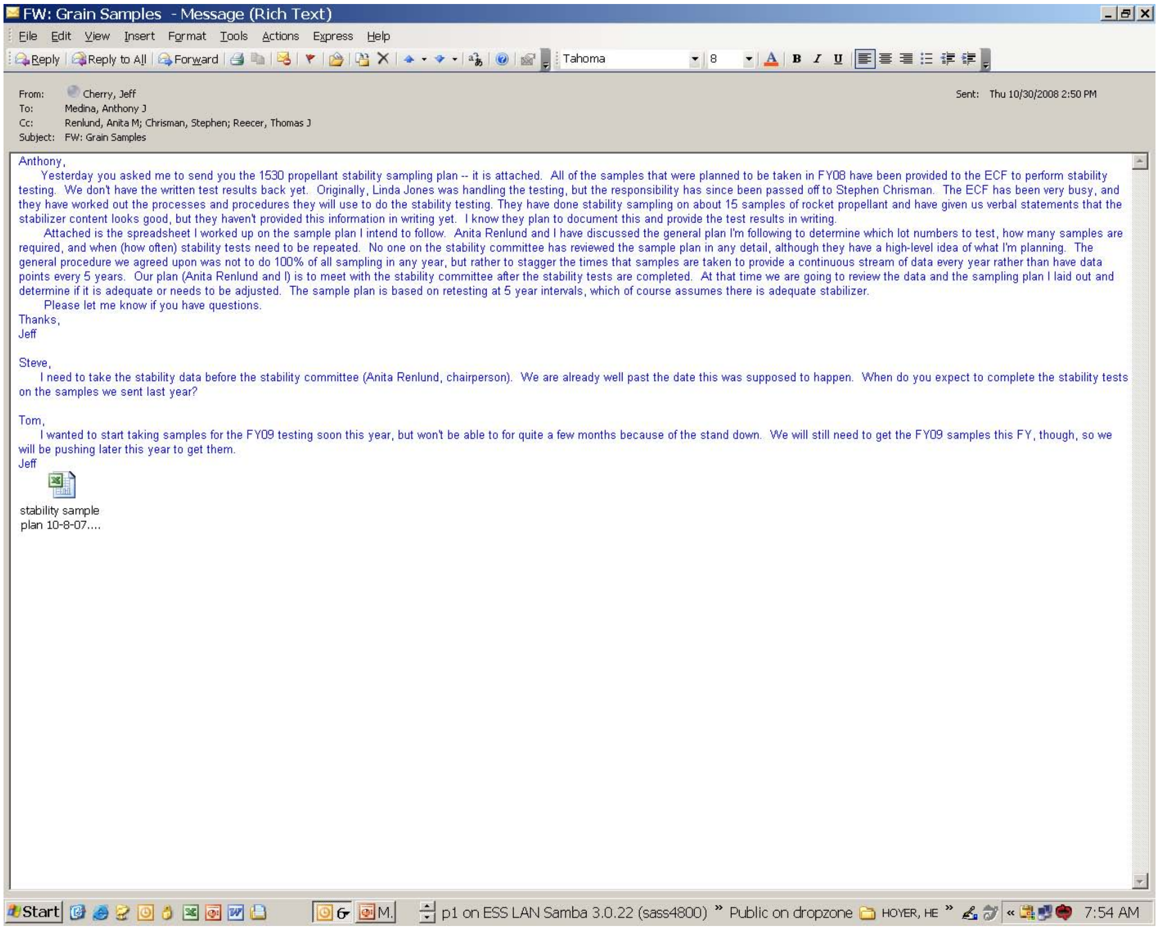
APPENDIX A: ROCKET PROPELLANT SELF-INITIATED – EVIDENCE CONSIDERED



From: Cherry, Jeff
To: Medina, Anthony J
Cc: Renlund, Anita M; Chrisman, Stephen; Reecer, Thomas J
Subject: FW: Grain Samples
Sent: Thu 10/30/2008 2:50 PM

Anthony,

Yesterday you asked me to send you the 1530 propellant stability sampling plan -- it is attached. All of the samples that were planned to be taken in FY08 have been provided to the ECF to perform stability testing. We don't have the written test results back yet. Originally, Linda Jones was handling the testing, but the responsibility has since been passed off to Stephen Chrisman. The ECF has been very busy, and they have worked out the processes and procedures they will use to do the stability testing. They have done stability sampling on about 15 samples of rocket propellant and have given us verbal statements that the stabilizer content looks good, but they haven't provided this information in writing yet. I know they plan to document this and provide the test results in writing.

Attached is the spreadsheet I worked up on the sample plan I intend to follow. Anita Renlund and I have discussed the general plan I'm following to determine which lot numbers to test, how many samples are required, and when (how often) stability tests need to be repeated. No one on the stability committee has reviewed the sample plan in any detail, although they have a high-level idea of what I'm planning. The general procedure we agreed upon was not to do 100% of all sampling in any year, but rather to stagger the times that samples are taken to provide a continuous stream of data every year rather than have data points every 5 years. Our plan (Anita Renlund and I) is to meet with the stability committee after the stability tests are completed. At that time we are going to review the data and the sampling plan I laid out and determine if it is adequate or needs to be adjusted. The sample plan is based on retesting at 5 year intervals, which of course assumes there is adequate stabilizer.

Please let me know if you have questions.

Thanks,
Jeff

Steve,

I need to take the stability data before the stability committee (Anita Renlund, chairperson). We are already well past the date this was supposed to happen. When do you expect to complete the stability tests on the samples we sent last year?

Tom,

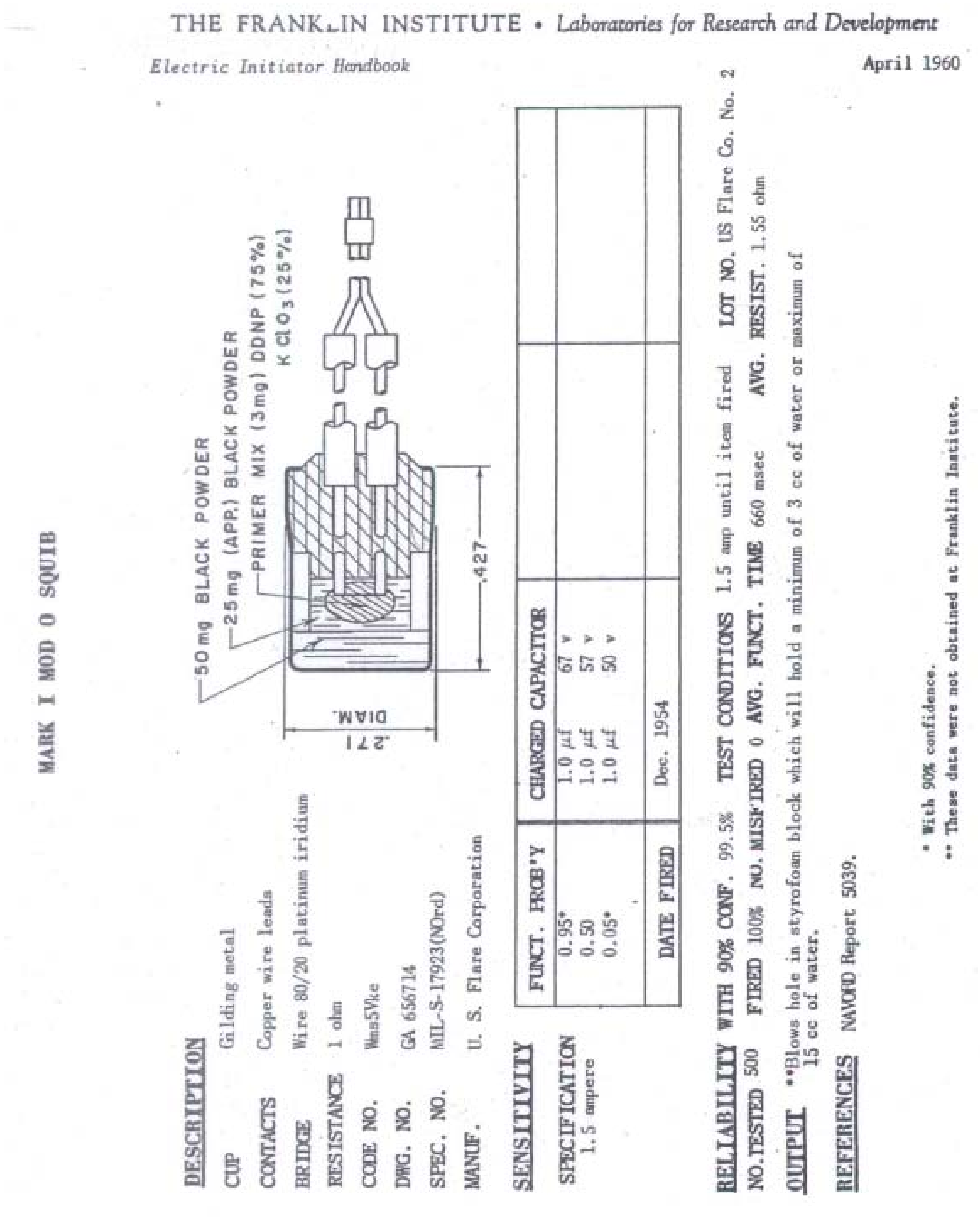
I wanted to start taking samples for the FY09 testing soon this year, but won't be able to for quite a few months because of the stand down. We will still need to get the FY09 samples this FY, though, so we will be pushing later this year to get them.

Jeff

stability sample plan 10-8-07....

Figure A-1. Stability Sampling Plan E-Mail

APPENDIX B: ELECTROSTATIC DISCHARGE INITIATED THE INITIATOR – EVIDENCE CONSIDERED



THE FRANKLIN INSTITUTE • *Laboratories for Research and Development*

Electric Initiator Handbook

April 1960

MARK I MOD 0 SQUIB

DESCRIPTION

CUP	Gilding metal
CONTACTS	Copper wire leads
BRIDGE	Wire 80/20 platinum iridium
RESISTANCE	1 ohm
CODE NO.	Wms5Vke
DWG. NO.	GA 656714
SPEC. NO.	MIL-S-17923(NOrd)
MANUF.	U. S. Flare Corporation

SENSITIVITY

SPECIFICATION
1.5 ampere

FUNCT. PROB'Y	CHARGED CAPACITOR		
0.95* 0.50 0.05*	1.0 µf 67 v 1.0 µf 57 v 1.0 µf 50 v		
DATE FIRED	Dec. 1954		

RELIABILITY WITH 90% CONF. 99.5% TEST CONDITIONS 1.5 amp until item fired LOT NO. US Flare Co. No. 2
NO. TESTED 500 FIRED 100% NO. MISFIRED 0 AVG. FUNCT. TIME 660 msec AVG. RESIST. 1.55 ohm

OUTPUT **Blows hole in styrofoam block which will hold a minimum of 3 cc of water or maximum of 15 cc of water.

REFERENCES NAVORD Report 5039.

* With 90% confidence.
** These data were not obtained at Franklin Institute.

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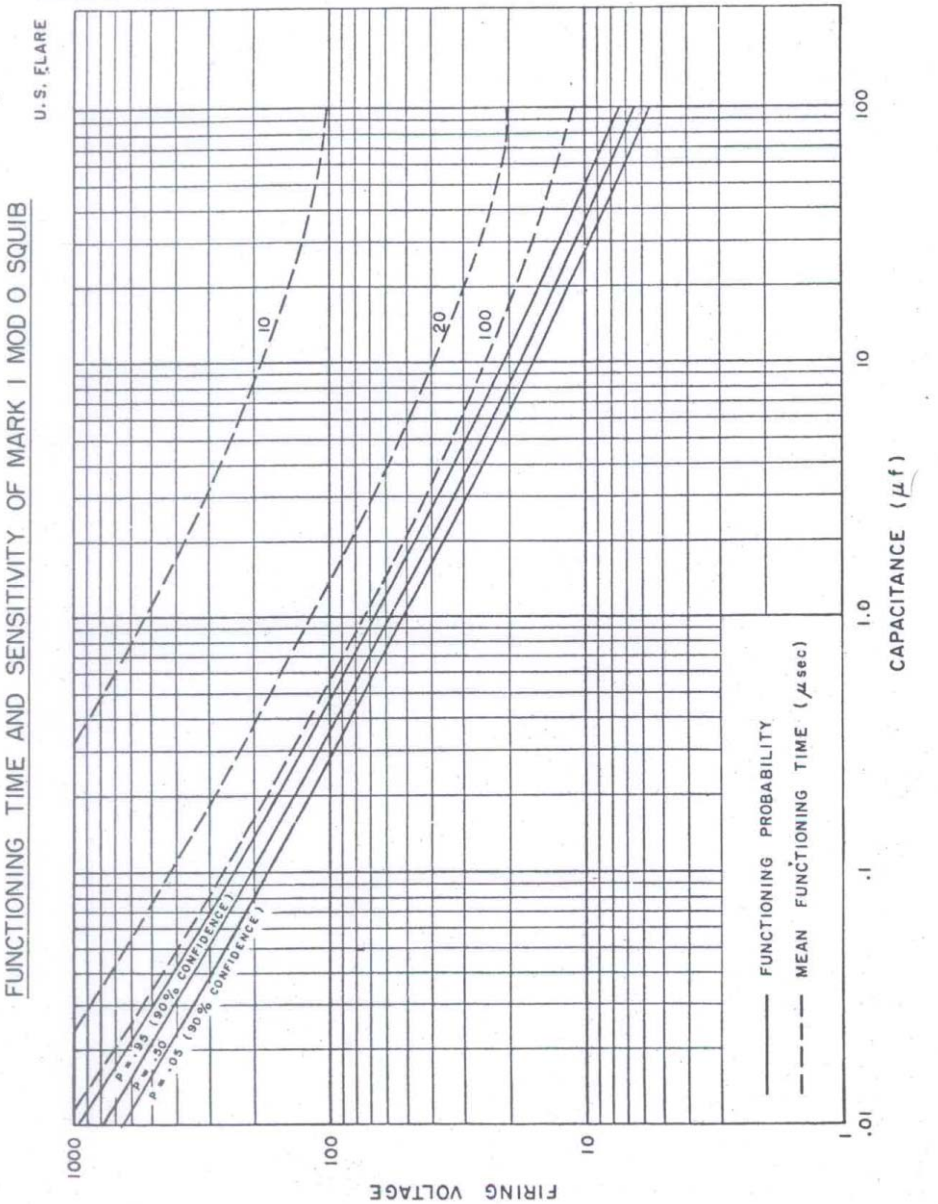
Figure B-1. Mk1 Mod0 Squib Data

THE FRANKLIN INSTITUTE • *Laboratories for Research and Development*

Electric Initiator Handbook April 1960



IV-4. 1.8B

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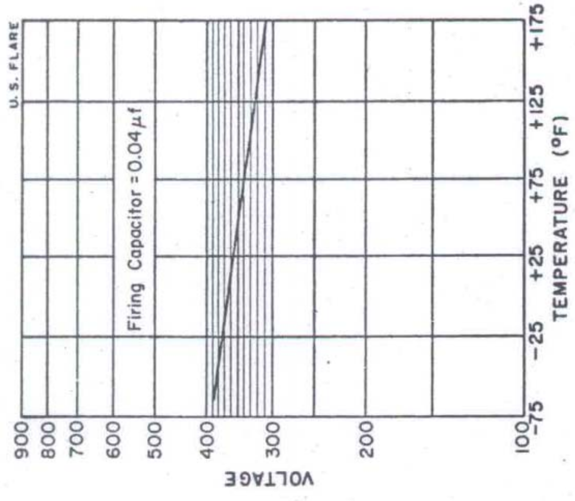
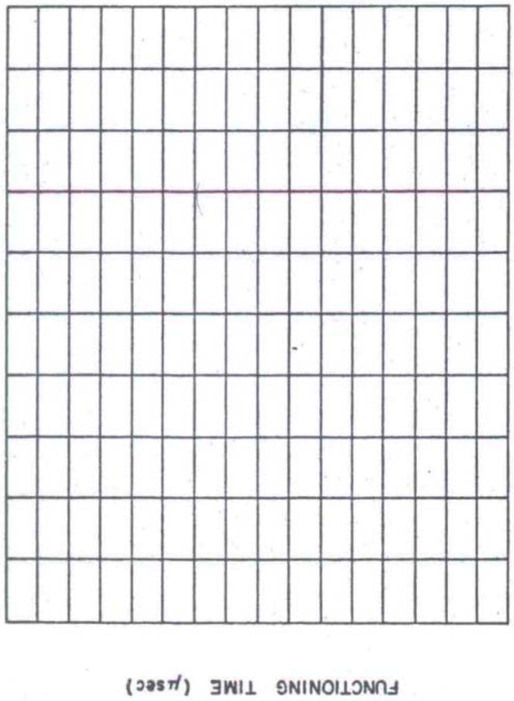
Figure B-1. Mk1 Mod0 Squib Data, continued

MARK I MOD 0 SQUIB

EFFECT OF TEMPERATURE ON AVERAGE FIRING SENSITIVITY



FUNCTIONING TIME



IV-4.1.8C

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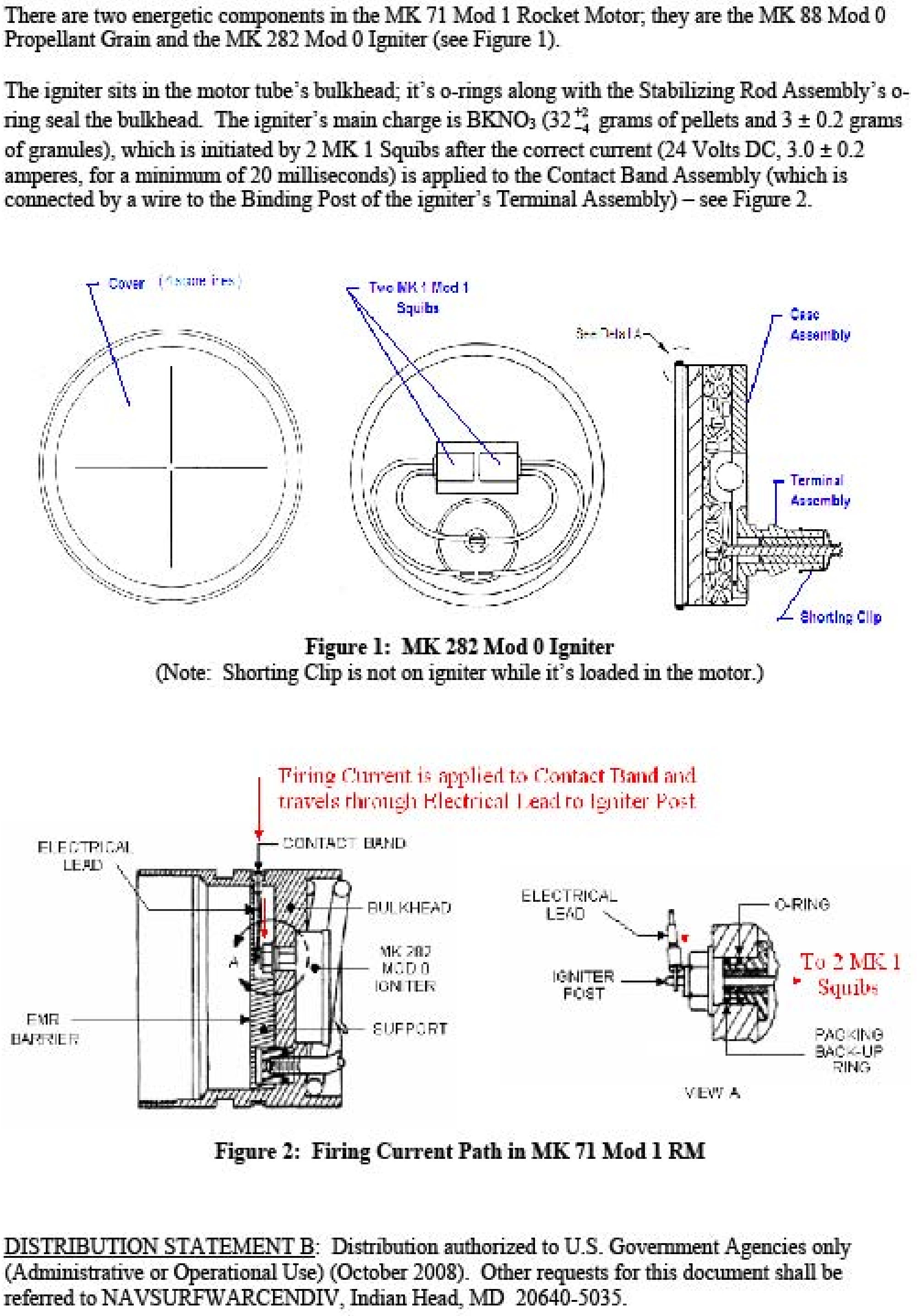
Figure B-1. Mk1 Mod0 Squib Data, continued



There are two energetic components in the MK 71 Mod 1 Rocket Motor; they are the MK 88 Mod 0 Propellant Grain and the MK 282 Mod 0 Igniter (see Figure 1).

The igniter sits in the motor tube's bulkhead; it's o-rings along with the Stabilizing Rod Assembly's o-ring seal the bulkhead. The igniter's main charge is $BKNO_3$ (32^{+2}_{-4} grams of pellets and 3 ± 0.2 grams of granules), which is initiated by 2 MK 1 Squibs after the correct current (24 Volts DC, 3.0 ± 0.2 amperes, for a minimum of 20 milliseconds) is applied to the Contact Band Assembly (which is connected by a wire to the Binding Post of the igniter's Terminal Assembly) – see Figure 2.

Figure 1: MK 282 Mod 0 Igniter
(Note: Shorting Clip is not on igniter while it's loaded in the motor.)

Firing Current is applied to Contact Band and travels through Electrical Lead to Igniter Post

Figure 2: Firing Current Path in MK 71 Mod 1 RM

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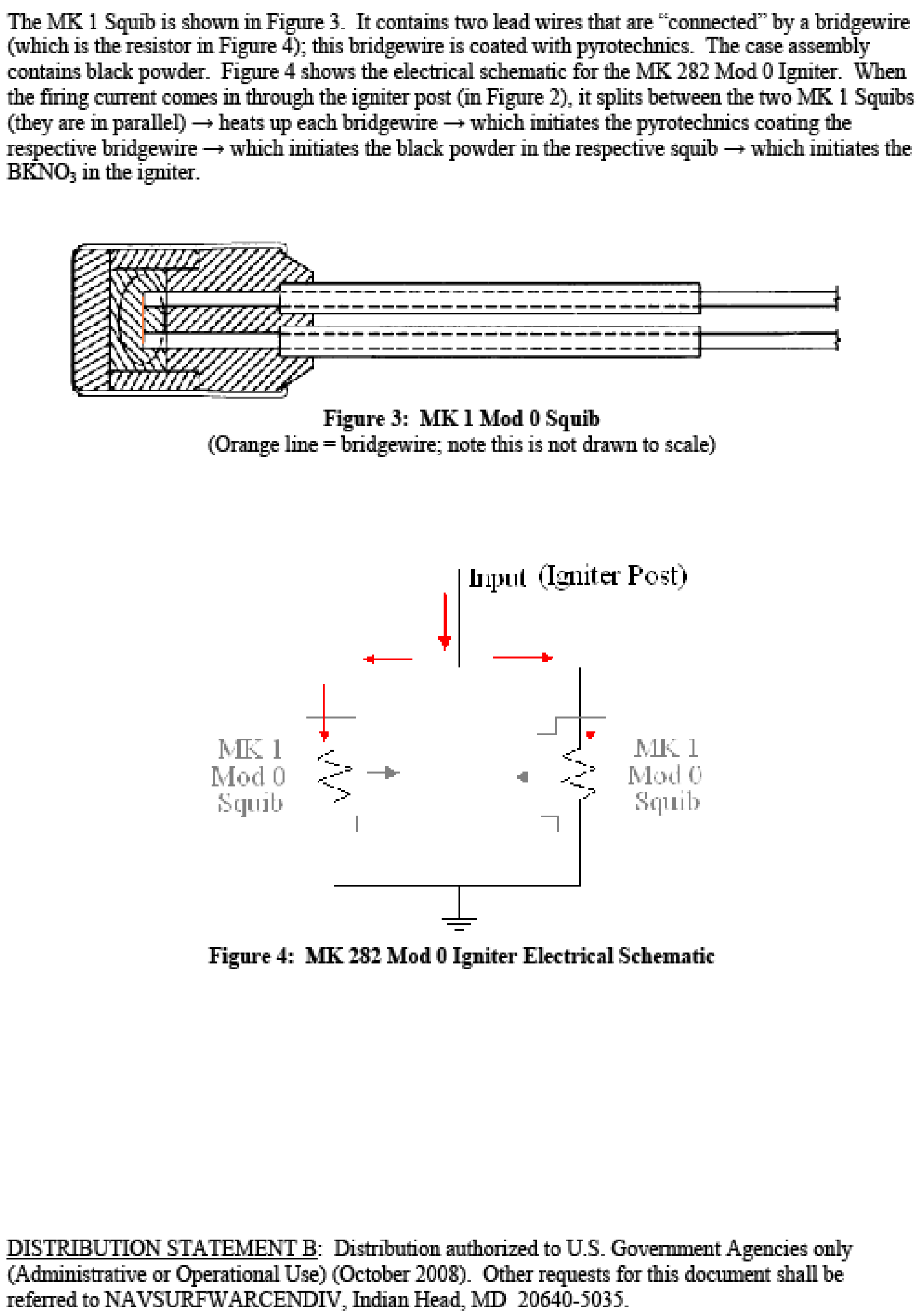
Figure B-2: MK 282 Mod 0 Igniter Information



The MK 1 Squib is shown in Figure 3. It contains two lead wires that are "connected" by a bridgewire (which is the resistor in Figure 4); this bridgewire is coated with pyrotechnics. The case assembly contains black powder. Figure 4 shows the electrical schematic for the MK 282 Mod 0 Igniter. When the firing current comes in through the igniter post (in Figure 2), it splits between the two MK 1 Squibs (they are in parallel) → heats up each bridgewire → which initiates the pyrotechnics coating the respective bridgewire → which initiates the black powder in the respective squib → which initiates the $BKNO_3$ in the igniter.

Figure 3: MK 1 Mod 0 Squib
(Orange line = bridgewire; note this is not drawn to scale)

Figure 4: MK 282 Mod 0 Igniter Electrical Schematic

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Figure B-3: MK1 Squib

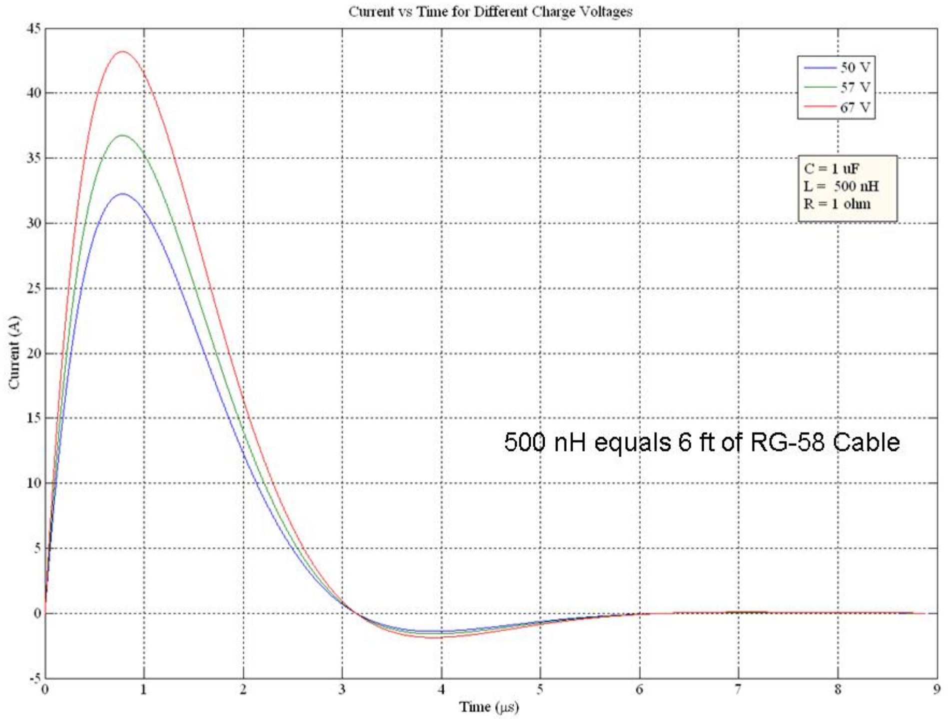
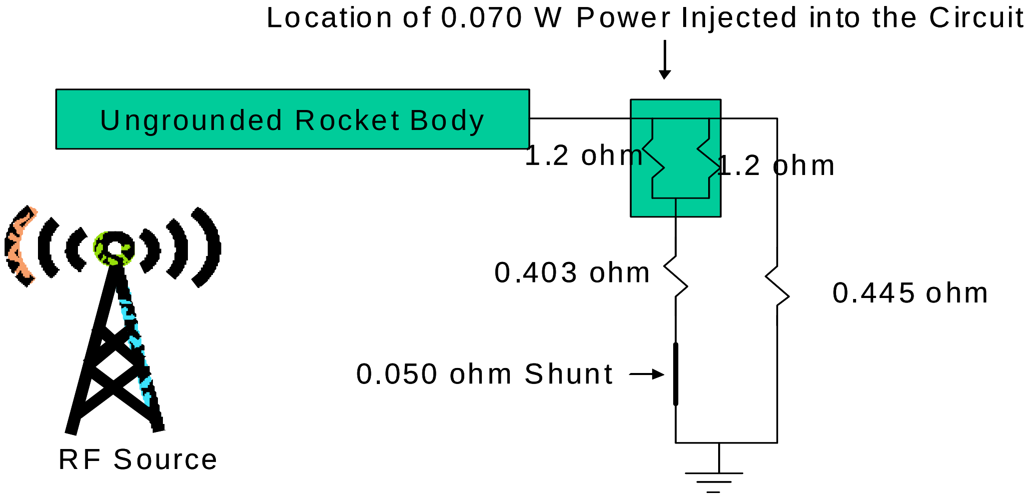


Figure B-4. Firing Current

Figure B-5. Wrist Strap

APPENDIX C: RADIO-FREQUENCY ENERGY FIRED THE INITIATOR – EVIDENCE CONSIDERED

Figure C-1. Hand-Held Radio Used for Sled Track Activities



$$\text{Initiator Power} = \left[\frac{.070\text{ W }(.30)}{2\ (0.28)}\right]^2 * 1.2\text{ ohms} = 0.0016\text{ W} \ll 0.065$$

Figure C-2. Radio Frequency Power Calculation

APPENDIX D: THERMAL BATTERIES FIRED THE INITIATOR – EVIDENCE CONSIDERED

Intentionally left blank

APPENDIX E: HICAP RECORDER BATTERY FIRED THE INITIATOR – EVIDENCE CONSIDERED

Figure E-1. Ground Clamp

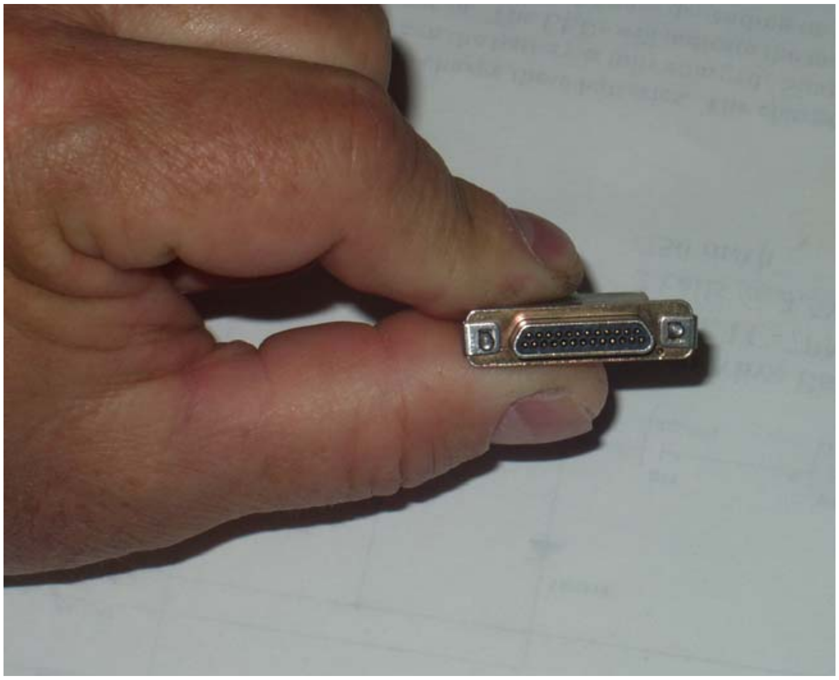


Figure E-2. Connector View of LED Module

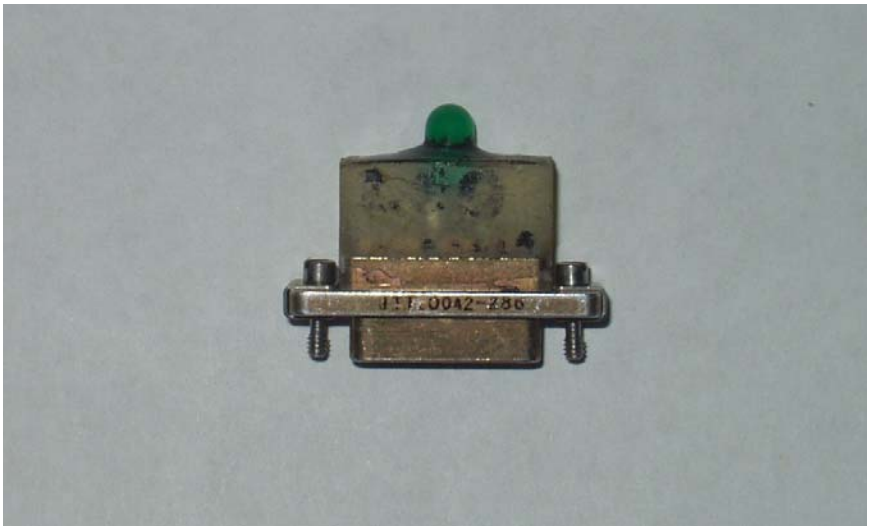


Figure E-3. Side View of LED Module

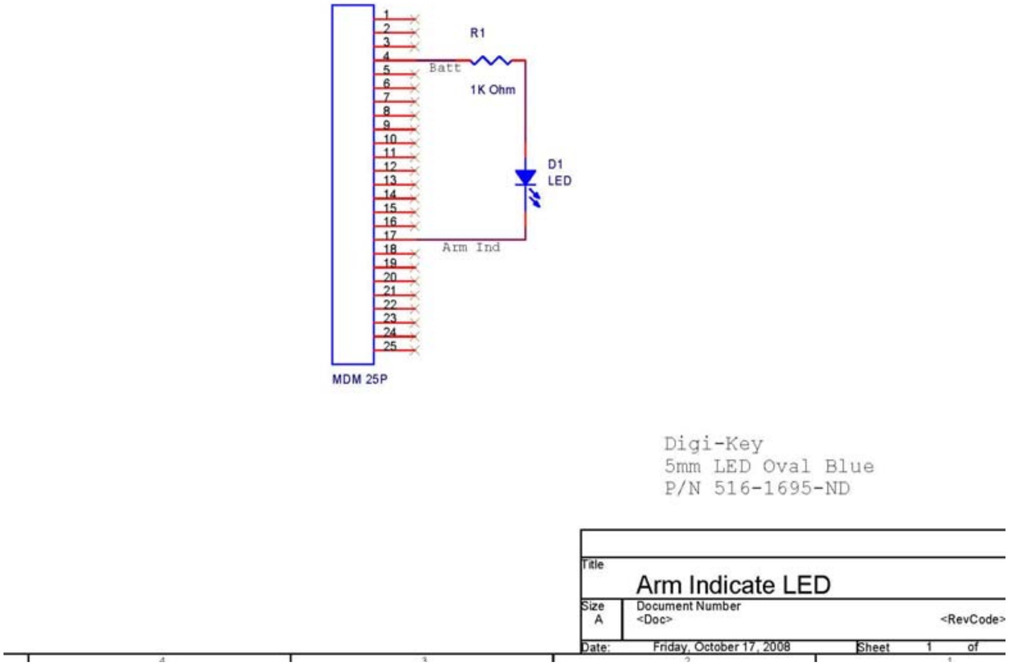


Figure E-4. LED Schematic

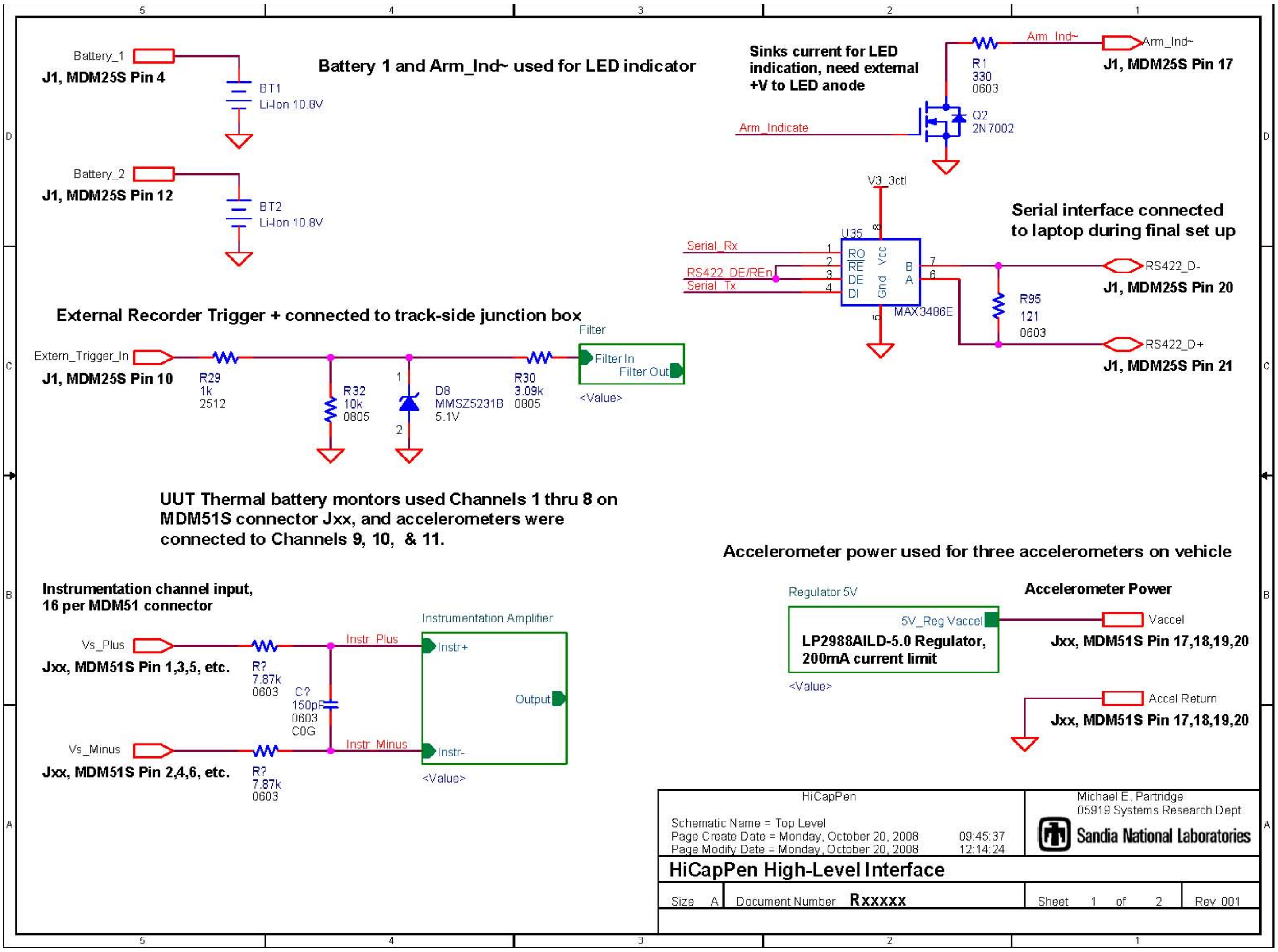


Figure E-5. HiCap Electrical Interfaces

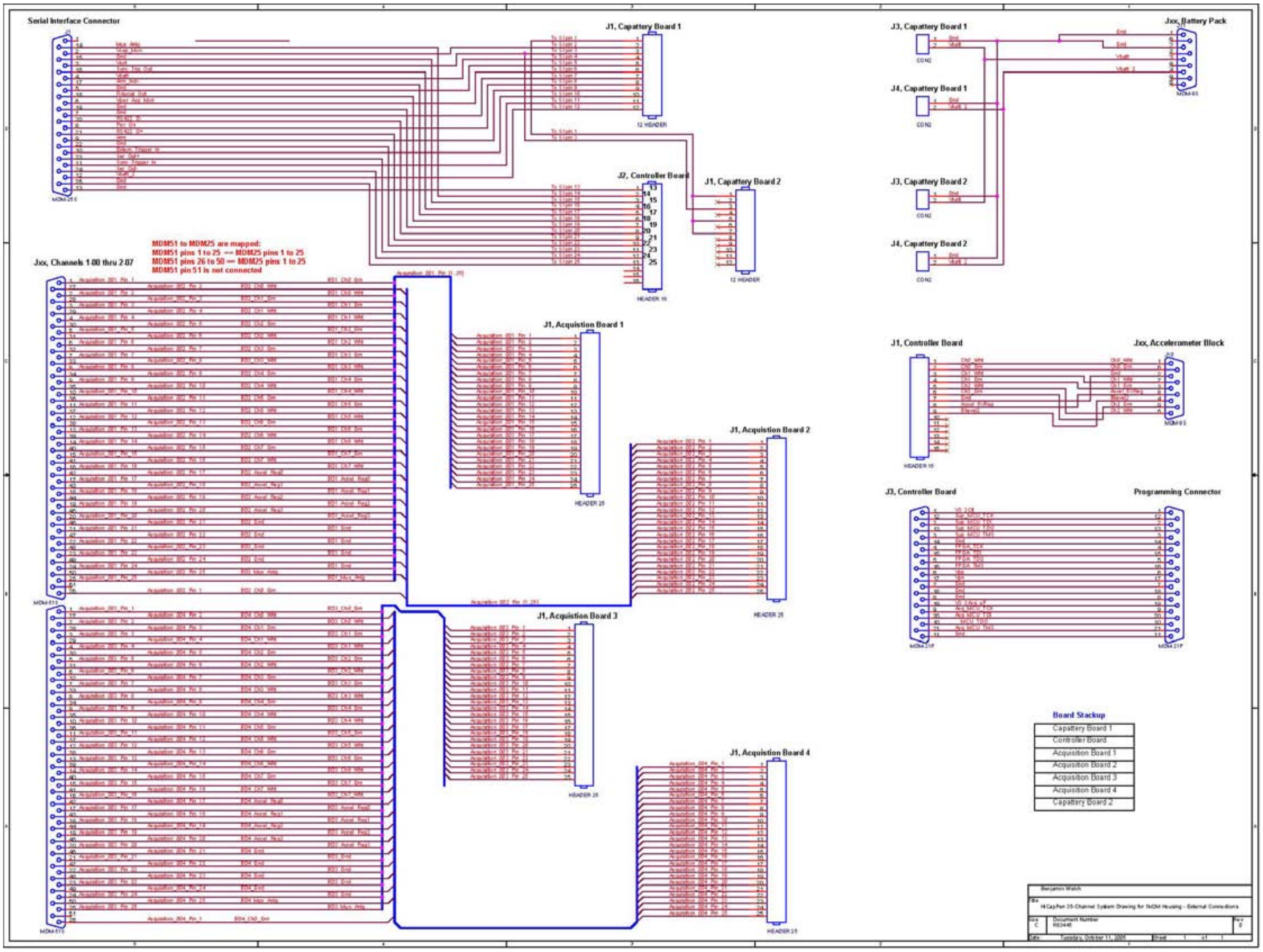
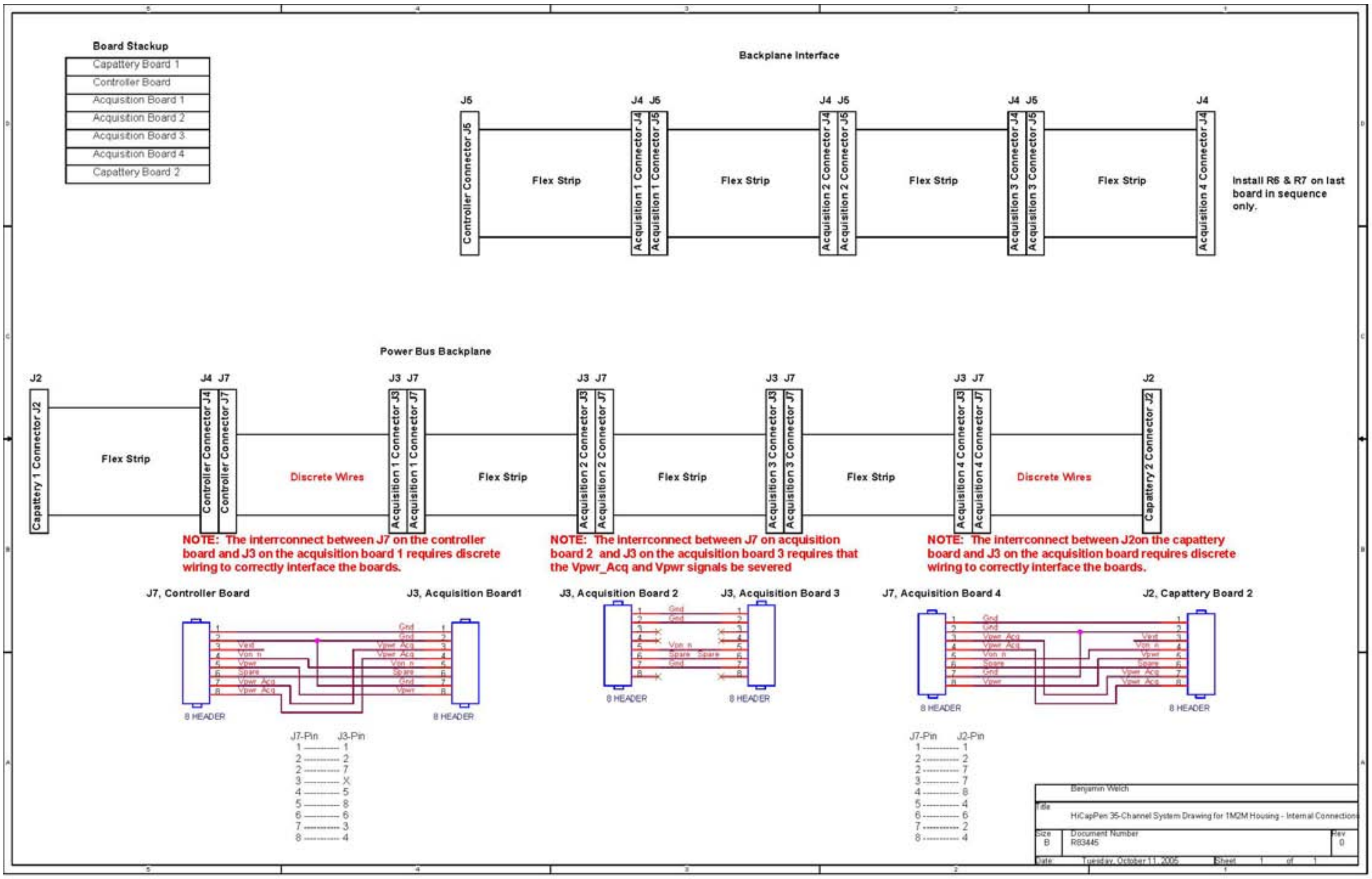


Figure E-6. HiCap Pen External Connection



Install R6 & R7 on last board in sequence only.

NOTE: The interrconnect between J7 on the controller board and J3 on the acquisition board 1 requires discrete wiring to correctly interface the boards.

NOTE: The interrconnect between J7 on acquisition board 2 and J3 on the acquisition board 3 requires that the Vpwr_Acq and Vpwr signals be severed

NOTE: The interrconnect between J2on the capattery board and J3 on the acquisition board requires discrete wiring to correctly interface the boards.

J7-Pin J3-Pin
1 ---------- 1
2 ---------- 2
2 ---------- 7
3 ---------- X
4 ---------- 5
5 ---------- 8
6 ---------- 6
7 ---------- 3
8 ---------- 4

J7-Pin J2-Pin
1 ---------- 1
2 ---------- 2
2 ---------- 7
3 ---------- 7
4 ---------- 8
5 ---------- 4
6 ---------- 6
7 ---------- 2
8 ---------- 4

Benjamin Welch
Title HiCapPen 35-Channel System Drawing for 1M2M Housing - Internal Connections
Size B Document Number R83445 Rev 0
Date Tuesday, October 11, 2005 Sheet 1 of 1

Figure E-7. HiCap Pen Internal Connection

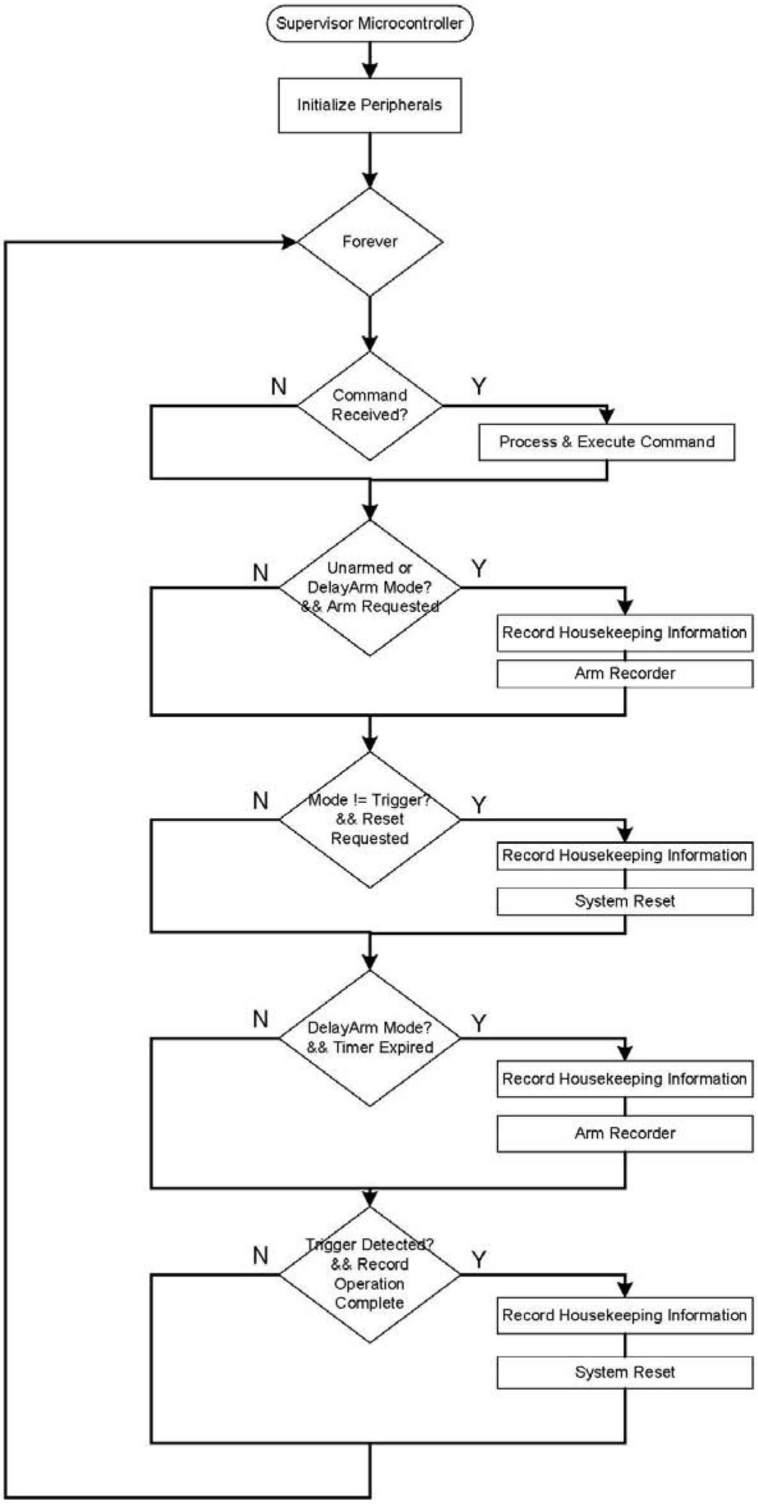


Figure E-8. HiCap Flowchart

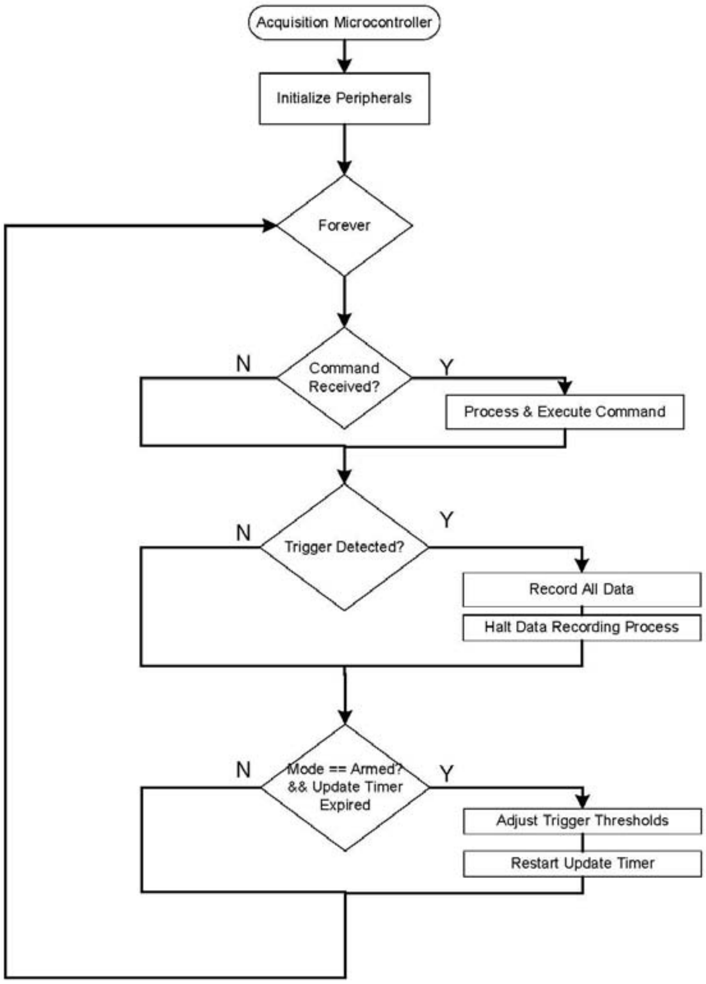
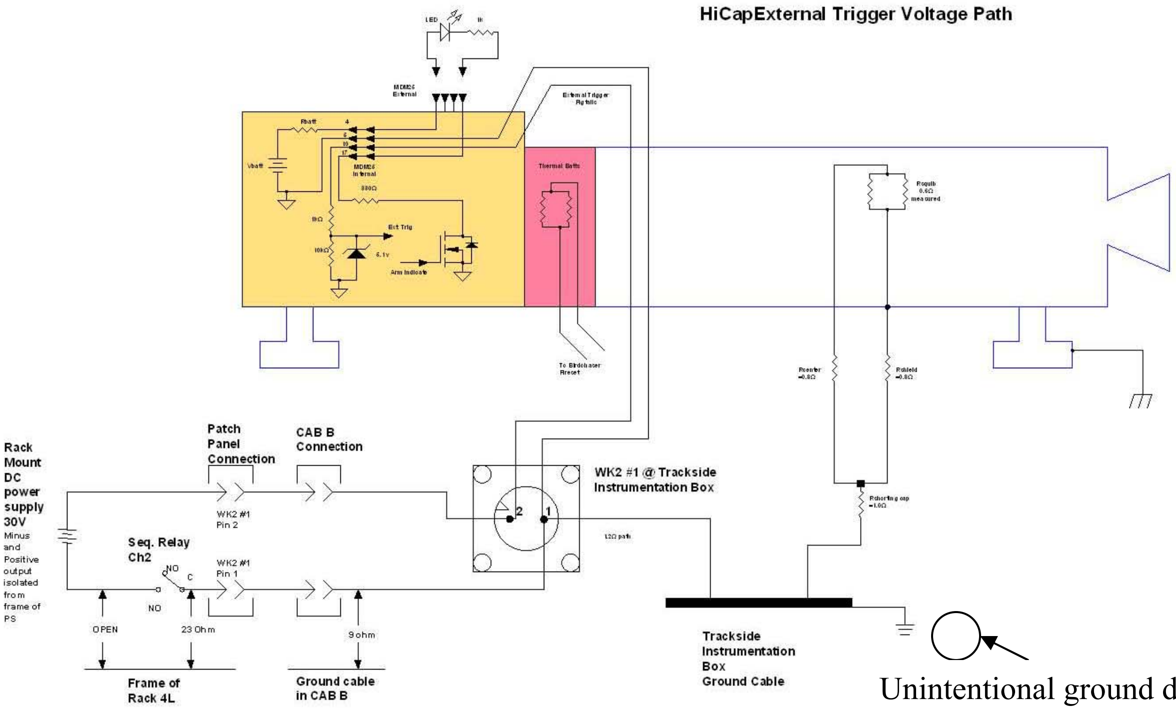


Figure E-8. HiCap Flowchart, continued



Unintentional ground due to faulty facility wiring

Figure E-9. HiCap External Trigger Voltage Path

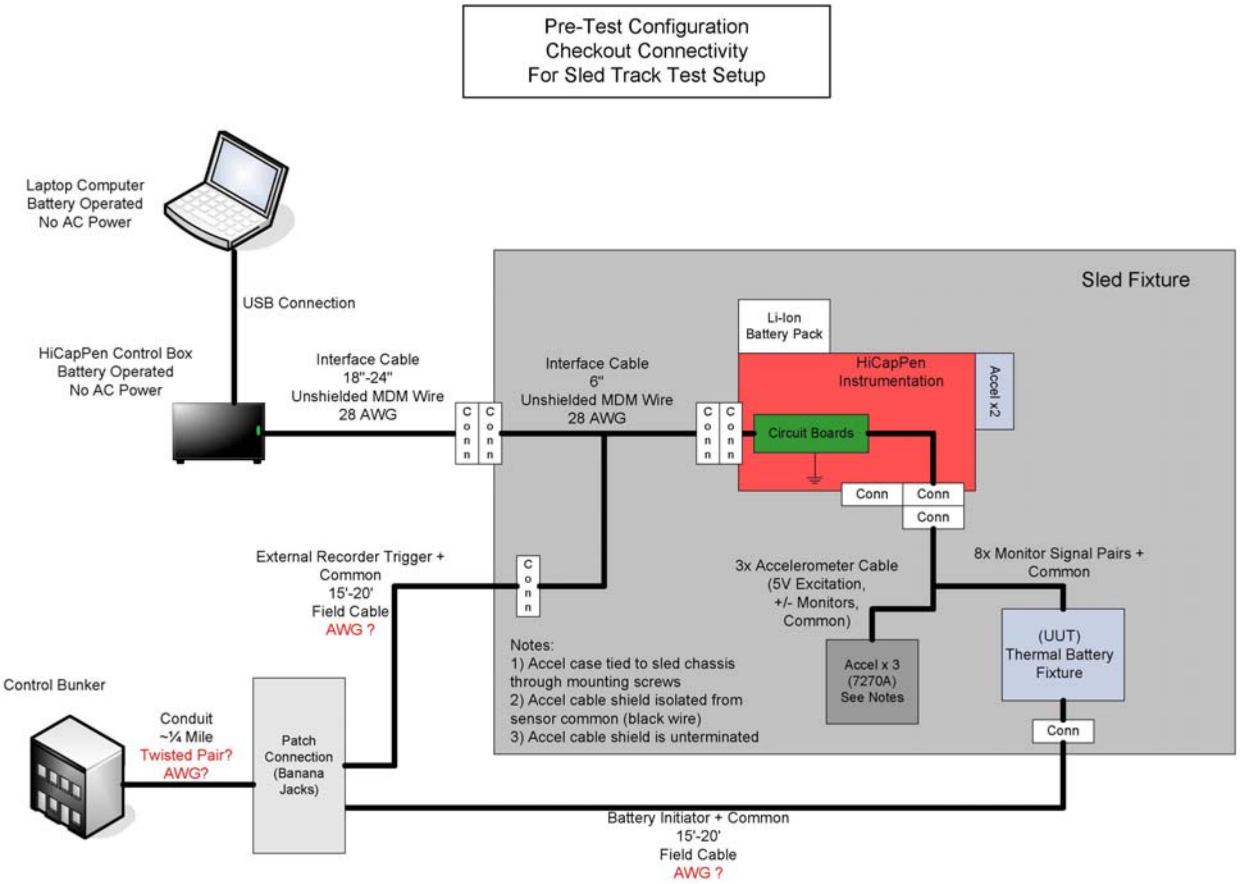
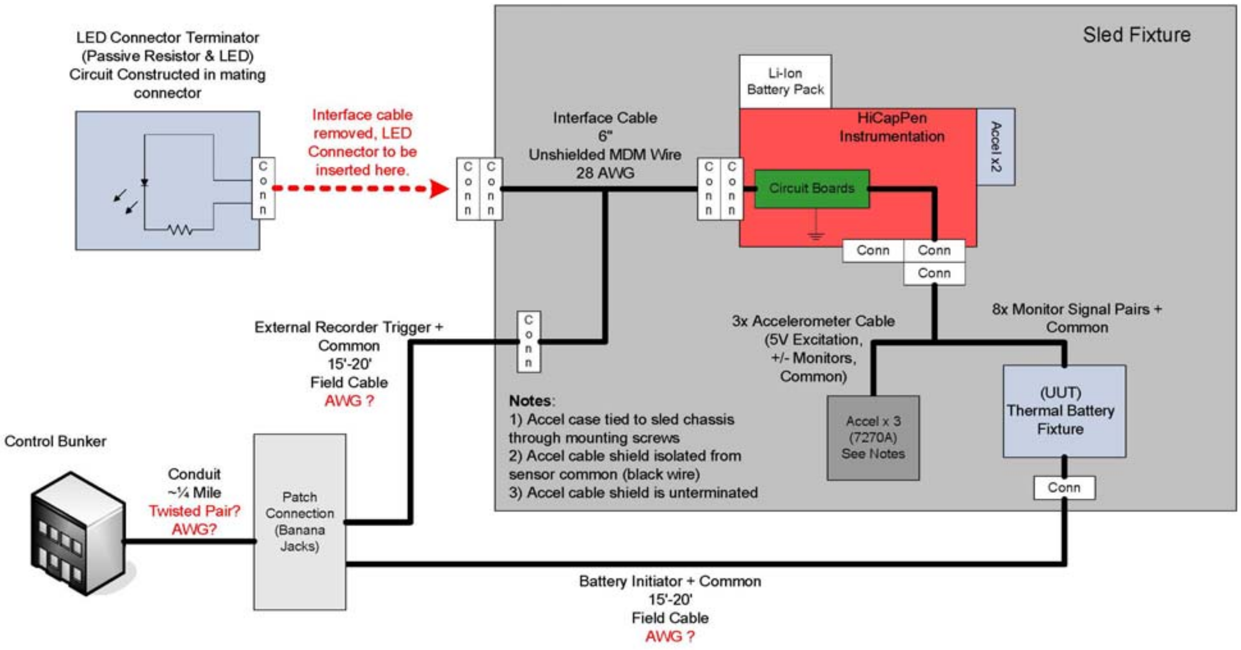


Figure E-10. Sled Test Setup with HiCap Computer Connected

Pre-Test Wrap-Up Connectivity
For Sled Track Test Setup



Notes:
1) Accel case tied to sled chassis through mounting screws
2) Accel cable shield isolated from sensor common (black wire)
3) Accel cable shield is unterminated

Figure E-11. Sled Test Setup with HiCap (Ready for Rocket Motor Initiation)

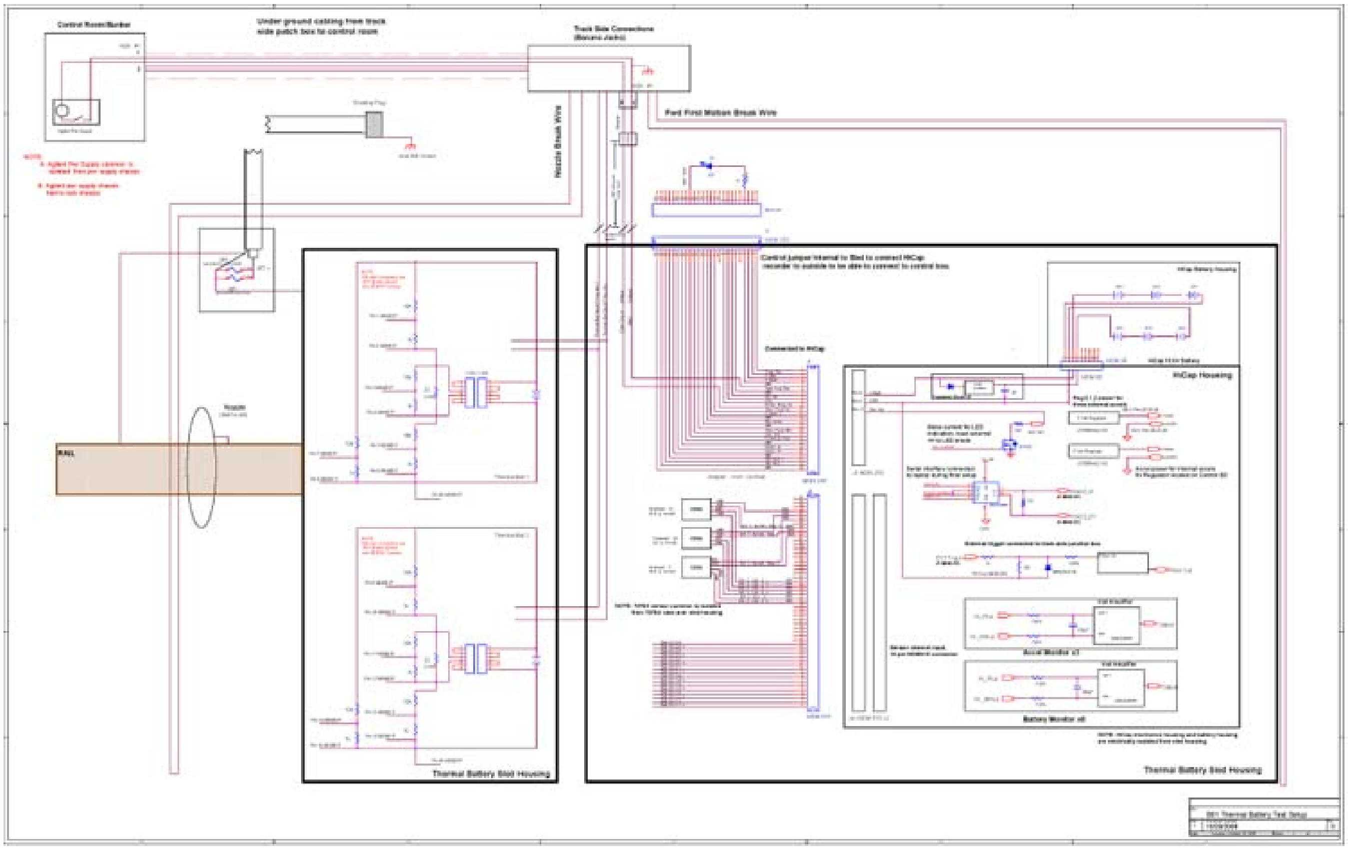
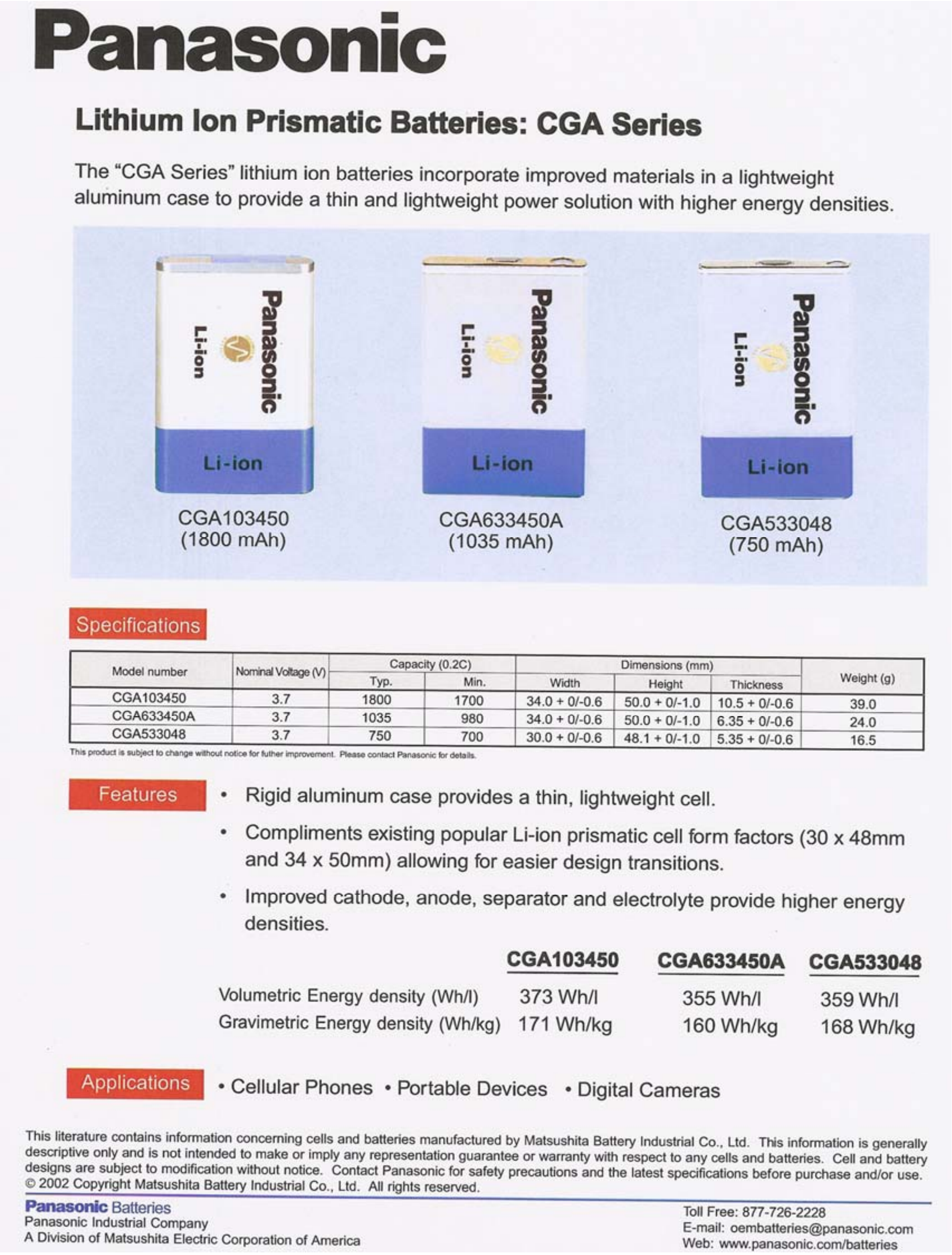


Figure E-12. Entire Accident Electrical Schematic



Panasonic

Lithium Ion Prismatic Batteries: CGA Series

The "CGA Series" lithium ion batteries incorporate improved materials in a lightweight aluminum case to provide a thin and lightweight power solution with higher energy densities.

CGA103450
(1800 mAh)

CGA633450A
(1035 mAh)

CGA533048
(750 mAh)

Specifications

Model number	Nominal Voltage (V)	Capacity (0.2C)		Dimensions (mm)			Weight (g)
		Typ.	Min.	Width	Height	Thickness	
CGA103450	3.7	1800	1700	34.0 + 0/-0.6	50.0 + 0/-1.0	10.5 + 0/-0.6	39.0
CGA633450A	3.7	1035	980	34.0 + 0/-0.6	50.0 + 0/-1.0	6.35 + 0/-0.6	24.0
CGA533048	3.7	750	700	30.0 + 0/-0.6	48.1 + 0/-1.0	5.35 + 0/-0.6	16.5

This product is subject to change without notice for futher improvement. Please contact Panasonic for details.

Features

- Rigid aluminum case provides a thin, lightweight cell.
- Compliments existing popular Li-ion prismatic cell form factors (30 x 48mm and 34 x 50mm) allowing for easier design transitions.
- Improved cathode, anode, separator and electrolyte provide higher energy densities.

	CGA103450	**CGA633450A**	**CGA533048**
Volumetric Energy density (Wh/l)	373 Wh/l	355 Wh/l	359 Wh/l
Gravimetric Energy density (Wh/kg)	171 Wh/kg	160 Wh/kg	168 Wh/kg

Applications • Cellular Phones • Portable Devices • Digital Cameras

This literature contains information concerning cells and batteries manufactured by Matsushita Battery Industrial Co., Ltd. This information is generally descriptive only and is not intended to make or imply any representation guarantee or warranty with respect to any cells and batteries. Cell and battery designs are subject to modification without notice. Contact Panasonic for safety precautions and the latest specifications before purchase and/or use.

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Panasonic Industrial Company
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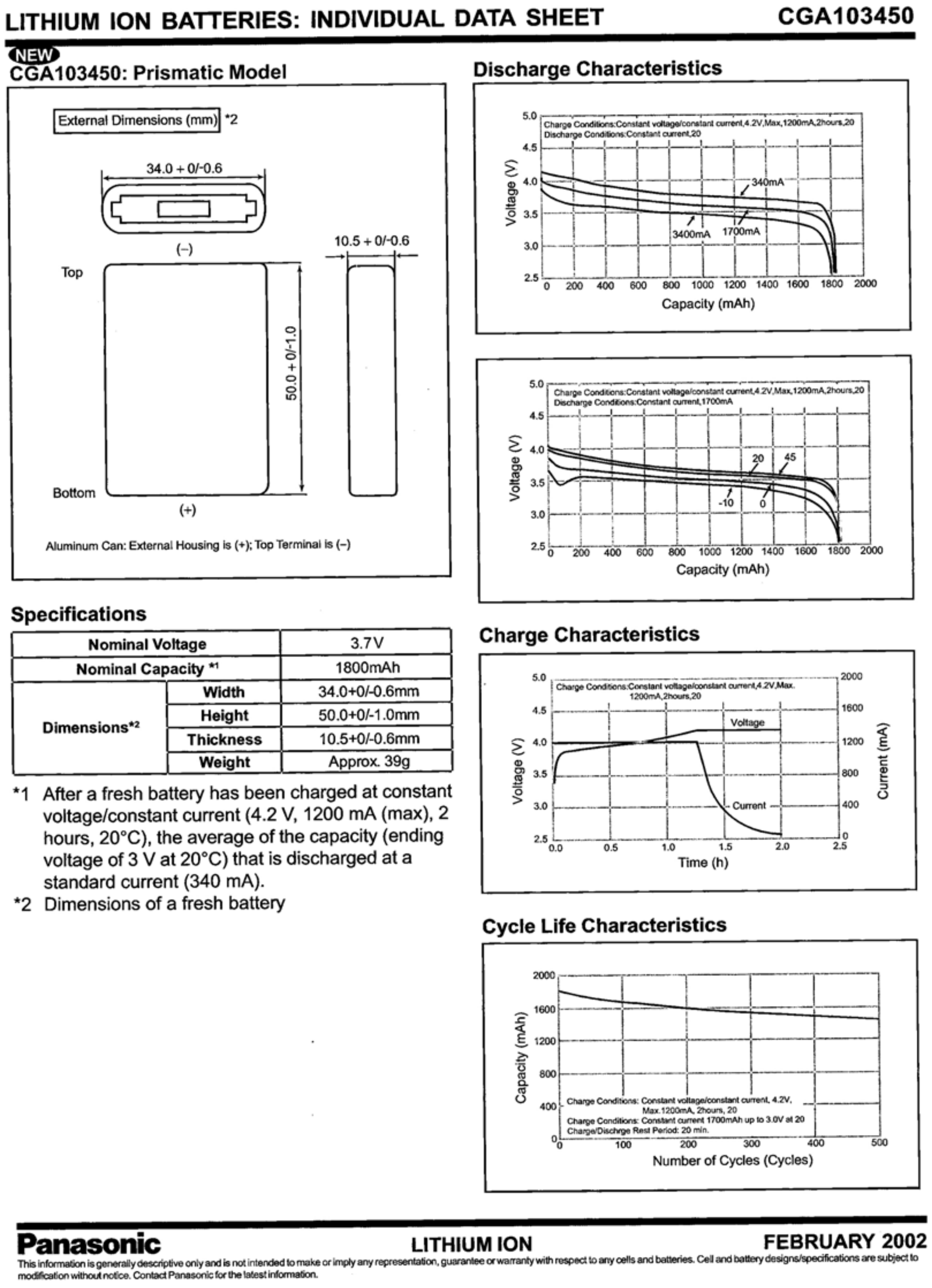
Figure E-13. Lithium Ion Prismatic Batteries: CGA Series Specifications



LITHIUM ION BATTERIES: INDIVIDUAL DATA SHEET **CGA103450**

NEW

CGA103450: Prismatic Model

Specifications

Nominal Voltage		3.7V
Nominal Capacity *1		1800mAh
Dimensions*2	**Width**	34.0+0/-0.6mm
	Height	50.0+0/-1.0mm
	Thickness	10.5+0/-0.6mm
	Weight	Approx. 39g

*1 After a fresh battery has been charged at constant voltage/constant current (4.2 V, 1200 mA (max), 2 hours, 20°C), the average of the capacity (ending voltage of 3 V at 20°C) that is discharged at a standard current (340 mA).

*2 Dimensions of a fresh battery

Discharge Characteristics

Charge Characteristics

Cycle Life Characteristics

Panasonic **LITHIUM ION** **FEBRUARY 2002**

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Figure E-14. Lithium Ion Batteries: Individual Data Sheet

APPENDIX F: FIRING SET INITIATED THE INITIATORS – EVIDENCE CONSIDERED

Figure F-1. Fire Set Planned for Use to Initiate Rocket Motor Initiators

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