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SAFETY REVIEW OF THE THERMAL TRANSIENT TEST

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14. ABSTRACT

Thermal transient testing (TTT) is a proven method for nondestructively evaluating electro-explosive devices with energetic materials in contact with a bridgewire. A commercial off-the-shelf (COTS) TTT system consisting of a control unit, multimeter, desktop computer, and a pair of test chambers was procured for use in the characterization and evaluation of novel and legacy devices used by the U.S. Army. A thorough risk evaluation was performed on the system and several high-risk deficiencies were identified. The survivability of the test chamber was evaluated through modeling and simulation in arbitrary Lagrangian-Eulerian three-dimensional (ALE3D) and Abaqus software. These simulations indicated that the chamber was unlikely to survive an M6 blasting cap, which is representative of a large explosive item that would be likely to undergo TTT. The results were confirmed through testing. Several safety improvements were made to the system, including improved electrical isolation through a custom designed in-line safety controller.

15. SUBJECT TERMS

Thermal transient test Electro-explosive Bridgewire Detonator Hotwire Initiator Safety controller Nondestructive testing Picatinny Arsenal Explosive Development Facility

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INTRODUCTION

Thermal transient testing (TTT) is an established methodology for evaluating the quality of spotted bridgewire systems commonly found in electrically initiated devices, such as detonators and igniters (refs. 1 to 4). The thermal transient methodology is a nondestructive testing (NDT) technique that can be used on fully assembled devices that are difficult to inspect through traditional NDT techniques. These kinds of low-voltage devices are typically evaluated through function testing of a sample, which consumes the tested items. A wide variety of defects can be discerned by TTT, such as poor contact between the bridgewire and spot charge, abnormal electrical resistance that is symptomatic of defects in the bridgewire or its connection points, and changes in system behavior that are indicative of altered properties of the components used. This inspection technique, although widely used in the manufacture of airbag igniters used in automobiles, is not typically used to inspect electric initiators used in U.S. Army devices. The U.S. Army Combat Capabilities Command (DEVCOM) Armaments Center (AC) Explosive Development Facility (EDF) at Picatinny Arsenal, NJ has procured a commercial off-the-shelf (COTS) TTT system from Santa Barbara Automation, Santa Barbara, CA. This system will primarily be used to evaluate and characterize new designs and support investigations of existing U.S. Army devices.

A TTT system evaluates a bridgewire by dynamically measuring the voltage drop across the device while applying a short duration electrical pulse of fixed current, by which the resistance of the device can be calculated. The application of an electric stimulus causes the bridgewire to undergo Joule heating, which causes an increase in electrical resistance that is measured by the test system. The magnitude and rate of change of the bridgewire's resistance is used to calculate its temperature and rate of heat transfer into the surrounding medium. This data can be used to discern the coverage and quality of the spot charge on the bridgewire. For example, a completely-covered bridge would transfer heat quickly via conduction, whereas a partially-covered bridge would experience a combination of conduction into the spot charge and air. The partially-spotted wire would undergo slower heat transfer, which would result in a greater temperature in the bridgewire and a correspondingly greater resistance. A thorough discussion of the mathematical model used for this methodology can be found in references 2 and 5.

This report will describe the COTS TTT system and the findings of the risk analysis that was performed. The risks inherent to TTT and several safety-related design shortcomings in the COTS TTT system will be described. A thorough description of the system modifications used to improve the overall risk rating, including an analysis of the test chamber's survivability and a custom designed in-line safety controller, will be presented.

SAFETY EVALUATION OF THE SYSTEM

The TTT system is a bench-top unit designed for low-volume testing in a laboratory setting. This system consists of a control unit, shown in figure 1, a Keithley 2010 multimeter, a desktop computer to run the thermal transient software, and a pair of test chambers. The multimeter measures the resistance of the bridgewire using the 4-wire (Kelvin) method.

Figure 1
TTT system control unit

In accordance with U.S. Army DEVCOM AC policies that guide operations involving energetics, a standard operating procedure (SOP) and deliberate risk assessment (DRA) of the process were generated (ref. 6). The hazard analysis evaluates each of the tasks described in the SOP to determine the circumstances that could result in injury to personnel or damage to the equipment. Each of the identified hazards is evaluated to determine its likelihood of occurrence and severity. The process of evaluating and quantifying risk is guided by Department of the Army Pamphlet 385-30, “Risk Management” (ref. 7).

The risks that are unique to TTT, and not common to all operations involving the handling and testing of low voltage initiators, are primarily associated with the possibility of initiating the test article as a result of running the test, either during the application of current or shortly thereafter. Although intended to be nondestructive, TTT can readily cause the energetic material to thermally degrade through the application of a test current that is large in magnitude or duration to thermally degrade the energetic spot charge. Damaging a device in this manner will be common while characterizing a bridgewire system; development of upper limits for testing is vital, especially when attempting to generate inspection parameters for use in an industrial setting. Due to the high likelihood of initiating test articles during the characterization process, the procedures in the SOP were developed with the assumption that setting off an initiator is an infrequent but expected occurrence and not a failure or incident. The risk to personnel and equipment while interrogating a device must be minimized; therefore, the test chamber must be capable of containing fragments and overpressure from all possible devices without loss of integrity.

A couple of significant hazards were identified with the TTT system. The test chambers that came with the system, shown in figure 2, are rectangular boxes made from stainless steel with polycarbonate plates affixed to the interior walls. Each of the chambers has a full-sized door on the front, a circular vent centered on the rear face, and a pedestal for holding the test sample in the center. The SOP was written to encompass testing of a variety of devices and types of energetics. However, this system will primarily be used to evaluate detonators with explosive output charges. Explosive testing in a confined space requires the enclosure to be explosively rated, which is typically calculated as a trinitrotoluene (TNT) mass equivalence for a given number of cycles or total exposure time. Santa Barbara Automation was asked if their chambers are explosively rated. They responded that no such testing had been performed, but that they were aware of several instances where devices loaded with zirconium potassium perchlorate (ZPP), a pyrotechnic compound used in airbag igniters, had ignited without damaging the chamber. The survivability of the test chamber and its ability to protect the test personnel is critical to reducing risk to an acceptable level. An analysis of the smaller test chamber is described in the next section.

Figure 2
Test chamber front (left) and rear (right)

The other inherent hazard that was identified is an issue with the electrical isolation of the test article after being installed into the pedestal inside the chamber. The system is designed to prevent the application of the test current until a sensor on the chamber door reads as closed and the user has prompted the system to arm using a button on the graphic user interface (GUI). However, a small voltage can be measured across the fixture leads when the chamber door is closed but the system has not yet been armed by the user. Furthermore, the magnetic door closure sensor reads as closed when the door is still partly open, as shown in figure 3.

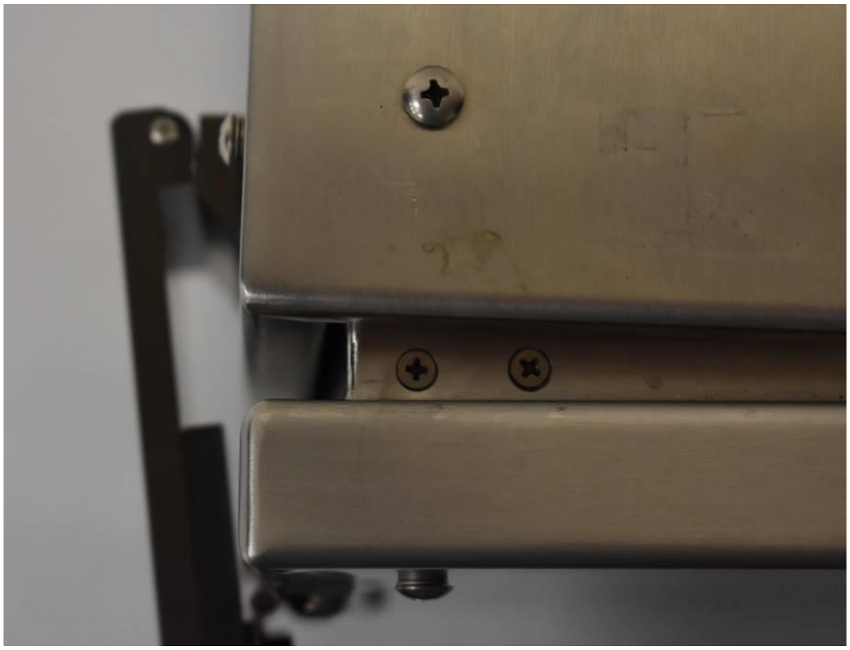

Figure 3
Chamber door position where sensor reads closed position

The loss of electrical isolation to the test article prior to the door being fully closed and latched is a source of significant risk for the operator due to potential exposure to overpressure and fragmentation in the event of the test article initiating. The likelihood of exposing the test article to a voltage large enough to initiate it is difficult to quantify; electrically fired initiators have a wide range of sensitivities and this test will often be used to interrogate devices of novel or suspect pedigree. Additionally, the test will be used for new initiators under development whose sensitivity have not yet been quantified. According to the U.S. Army pamphlet on risk management, the severity and likelihood of a device initiating due to stray voltage, including electrostatic discharge (ESD), were judged to be both critical and likely, which rates as high risk (tables 3-2 and 3-3 in ref. 7). Typical safety precautions when working with sensitive energetics and electrically fired initiators, such as proper grounding and bonding and personal protective equipment (PPE), will significantly decrease the likelihood of such an event. However, fixing the system’s innate ability to allow the test article to be exposed to any stray voltage prior to door closure is necessary to reduce the likelihood and severity of this risk to an acceptable level. Furthermore, the GUI does not allow a retest to be performed without cycling the door closure switch, which requires the user to open the chamber door. This would expose personnel if the test article were to cook off while the door is open. The established best practice when the test personnel are unsure of the safety in handling a device is to allow a minimum of 30 min to elapse. Allowing a method for retesting enables the test personnel to evaluate if the previous test had a deleterious effect on the test article, which will be instructive in guiding the application of a 30-min cool-off period.

ANALYSIS OF THE TEST CHAMBER

To assess the risk of using the test chambers provided by Santa Barbara Automation, a simulation was run where an M6 blasting cap is functioned inside. The M6 was selected due to its relatively large net explosive weight (NEW), 2 g of 1,3,5-trinitro-1,3,5-triazinane (RDX), and the likelihood of its being testing at the EDF. The chamber was modeled using Abaqus/Explicit 6.14 structural analysis with a time-pressure field generated using arbitrary Lagrangian-Eulerian three-dimensional (ALE3D) software tool (ref. 8). The pressure field was generated assuming that the M6 was detonated in a horizontal position in the center of the chamber with the output end facing to the right. The ALE3D analysis was run with 24 tracer particles per wall at 10,000 time points for a duration of 1 ms. Figure 4 is a series of images depicting the evolution of the pressure field within the chamber. The interior dimensions of the chamber are approximately 200 mm wide, 225 mm tall, and 300 mm deep.

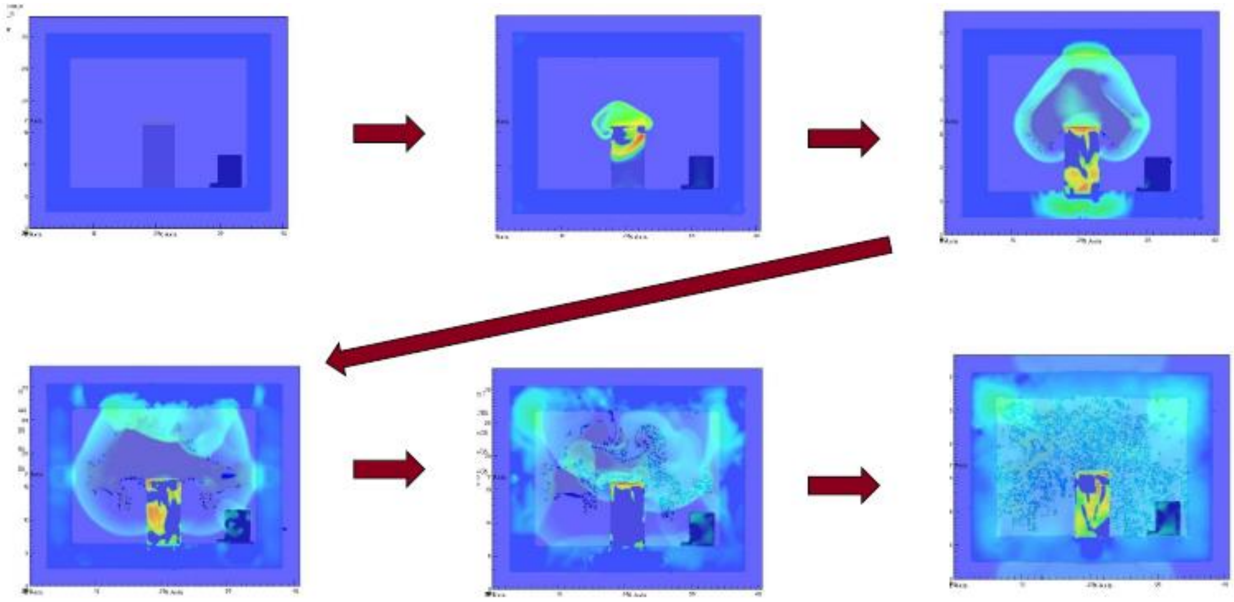

Figure 4
Evolution of the pressure field inside the test chamber from an M6

The Abaqus model was generated primarily using 8-node brick elements with a minority of 10-node tetrahedral elements with reduced integration and hourglass control. The materials used in the analysis were aluminum 6061-T6 for the latching mechanism and hinge, polycarbonate for the internal panels, and stainless steel 17-4 for the outer shell. The material property models use Johnson-Cook plasticity for the aluminum and polycarbonate, an interpolated stress-strain curve for the stainless, and Johnson-Cook damage and fracture models for each of the materials. The polycarbonate panels were tied to the stainless shell, as were the bolted surfaces of the hinges to their mating surfaces. The dynamic analysis was run using nonlinear materials and geometry out to 4 ms. The one-way coupling between ALE3D and Abaqus/Explicit assumes small deformations due to the assumption that the chamber is expected to stay intact throughout the explosive event.

The simulation shows that the outer walls of the chamber are expected to bulge but survive, as shown in figure 5, although the door hinge and latch hinge each fail. At 1 ms, the door hinge knuckles begin to unwrap from around the center post with complete separation by 2 ms, as shown in figure 6. In figure 7, the hinge that allows the latching mechanism to pivot starts to shear by the 1-ms timestep. By 4 ms, the door has been shown to separate completely from the chamber.

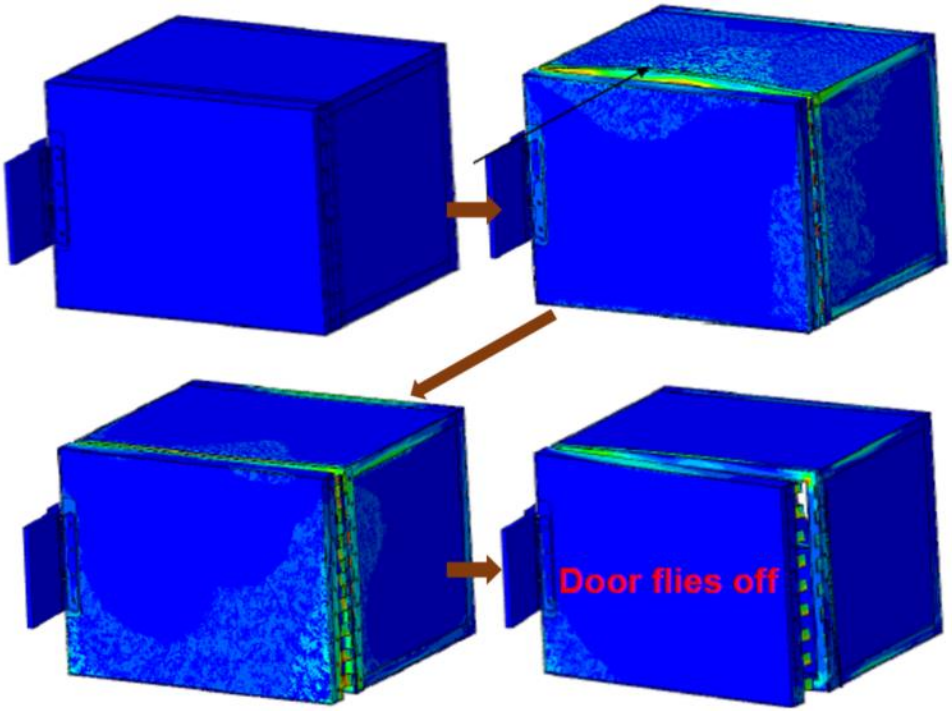

Figure 5
Abaqus simulation of the pressure field at 0, 1, 2, and 4 ms

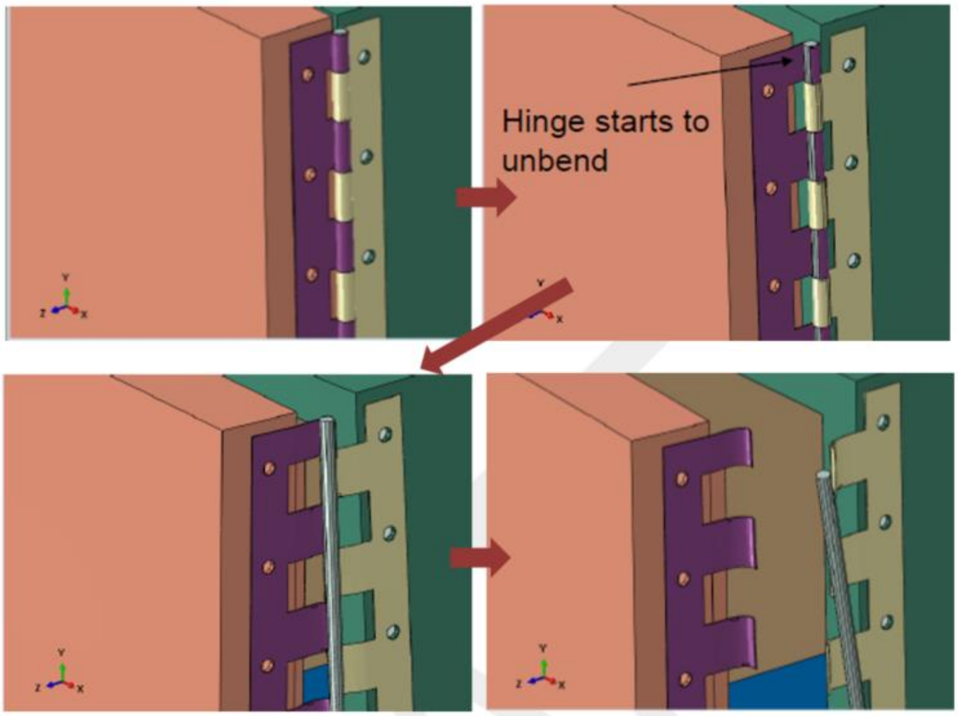

Figure 6
Abaqus simulation of the door hinge at 0, 1, 2, and 4 ms

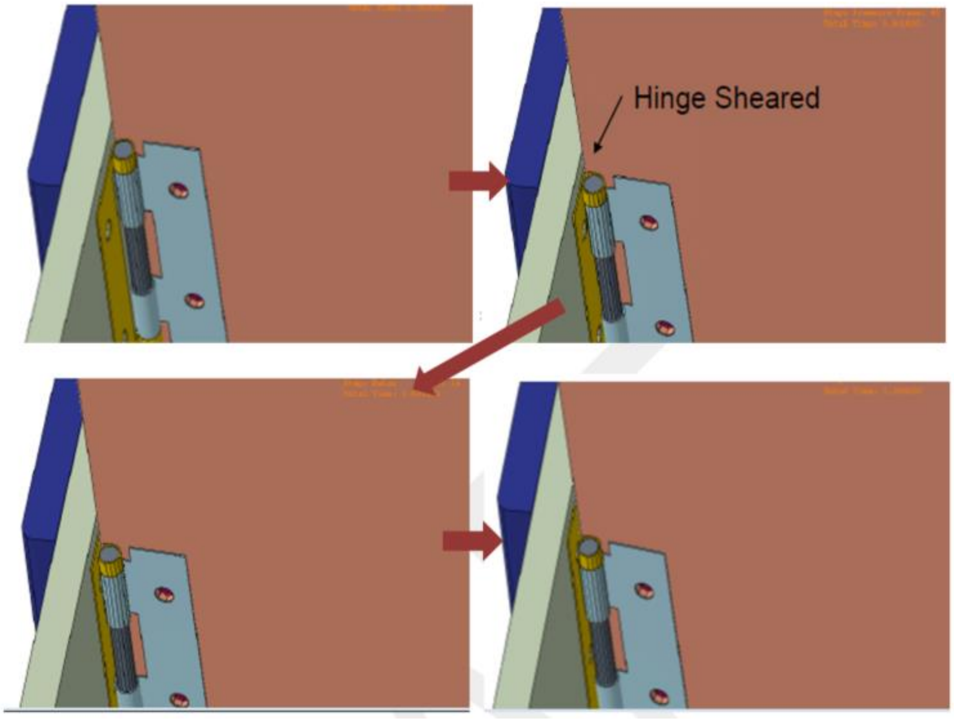

Figure 7
Abaqus simulation of the latch hinge at 0, 1, 2, and 4 ms

The results of the simulation imply that the chamber would not survive an M6 initiating, nor would it be expected to adequately protect the test personnel. After the simulation was completed, testing was performed by detonating an M6 blasting cap inside the test chamber. The M6 was positioned in the center of the chamber with the same orientation as ALE3D simulation. The event was captured with regular and high-speed imagery taken of the hinged side of the chamber. Strain gauges were placed on the top and side of the chamber's outer shell.

The test resulted in extensive damage to the chamber. Standard speed video, a screen shot from which is presented in figure 8, shows the front door opening while a jet of gaseous products shoots out of the rear exhaust port. The high-speed imagery shows the chamber walls bulging and the hinge knuckles stretching significantly while the door oscillates.

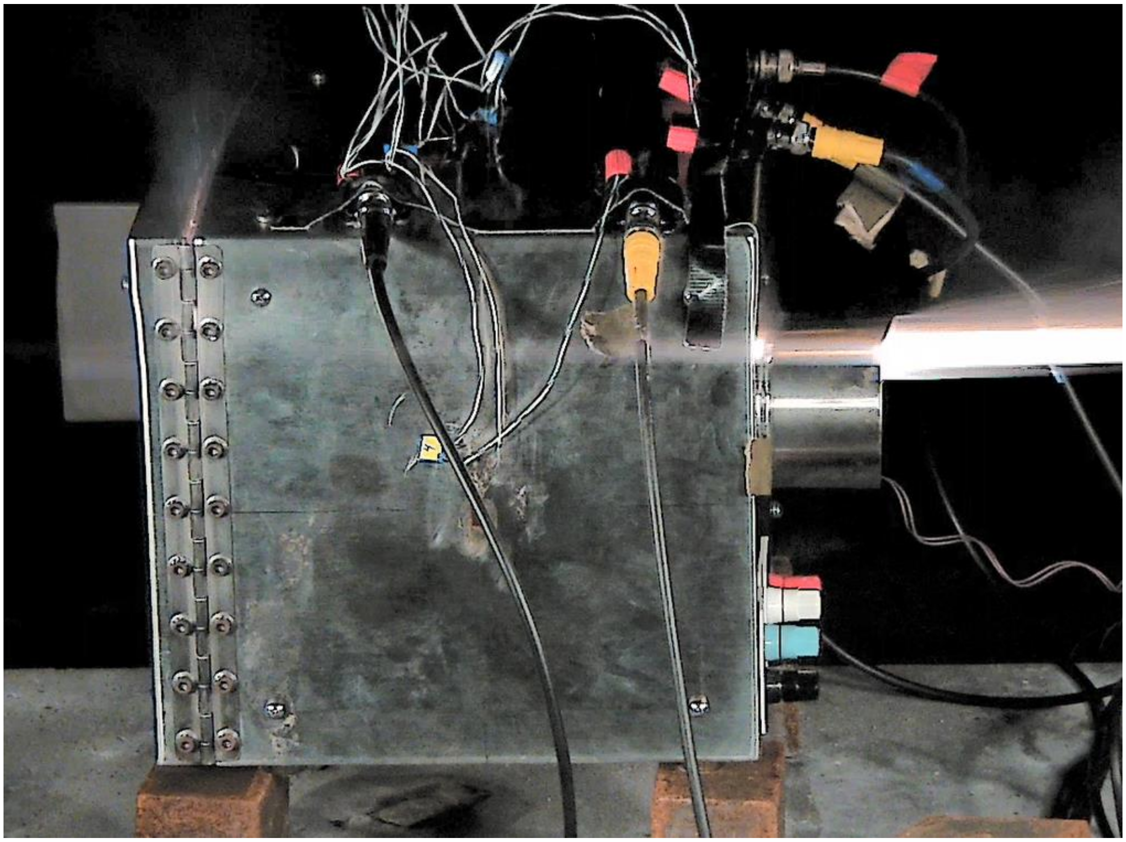

Figure 8
Side view of chamber immediately after M6 initiation

An inspection of the chamber after the test shows significant bowing of the chamber's walls, as shown in figure 9. Furthermore, the hinge deformed significantly, preventing the door from closing and the latch from engaging. The chamber likely managed to prevent any fragments from exiting, as evidenced by scarring on the polycarbonate plates. However, the large volume of gasses observed leaking past the door would have been a significant safety hazard and the chamber was effectively destroyed. The damage to the hinge and latch was not as extensive as the Abaqus simulation predicted. This is likely due to deviations in the material properties used in the model versus those of the actual chamber's materials, which were estimated. Furthermore, the simulation may have overpredicted the confinement of the gaseous products, which were able to escape past the door. However, the simulation accurately predicted the wall deformations and hinge failure, which combined to render the chamber unusable. Unfortunately, usable strain gauge data was not collected, preventing further refinement of the model.

Figure 9
Chamber after testing with bulged top surface (left) and stretched hinge (right)

SYSTEM MODIFICATIONS

The modifications to the TTT system focused on replacing the test chamber with a more survivable alternative and ensuring that the test article is electrically isolated prior to the test chamber door being closed and secured. Despite the larger volume of the second chamber, which would significantly reduce the magnitude of the peak pressure, the decision was made to seek an alternate design. This decision was due to the high likelihood of failure without making significant modifications and the cost associated with their implementation. The Teledyne RISI 167-9818 firing tank was selected to replace the test chamber. This model firing tank, which has a 10-g NEW rating, is used regularly at the EDF for a variety of small-scale explosive tests and is known to safely contain gasses and fragments from all electrically fired initiators that might undergo TTT. A mechanical position switch was selected to replace the magnetic door closure; this switch can be adjusted to read as being closed only after the door's retaining bolts have been secured and properly torqued.

A secondary safe and arm device, designated the safety controller unit, was designed for implementation in-line between the TTT control unit and the test chamber. The safety controller unit, shown in figure 10, was designed to keep the test pedestal leads shorted together, which will prevent stray voltage from reaching the test article after installation but prior to the firing tank's door being closed and secured. It also isolates the electrical connection from the control unit. The short across the firing tank leads is removed after the user turns on the unit and presses the ARM button. Pressing the DISARM or RESET buttons, as well as tripping the door closure sensor, will reset the safety controller to the safe state, which reestablishes the short across the firing tank leads. Pressing the RESET button, followed by the ARM button, allows the user to conduct a retest from the GUI without having to open the firing tank's door.

Connectors in chamber are energized when red 'ARMED' light is illuminated. Connectors are shorted if the green 'Disarmed' light is illuminated. If both or no lights are illuminated, a failure has occurred and the box requires maintenance.

Figure 10
Safety controller unit

The TTT system utilizes six signal lines between the test system and the test chamber. Four lines are used in a four-wire resistance test circuit (the Kelvin resistance measurement technique), where two are used as a current supply and two for voltage measurement. The remaining two signal lines are used for the door latching detection circuit. This circuit supplies current to one signal line and detects current returning on the other. The presence of a short circuit, from a closed switch, indicates a closed door. Through testing, it was determined that the shorting resistance must be less than 400 ohms to properly indicate a closed-door condition. While this detail is not important for the selection of a mechanical door switch, it is a significant detail used in the design of the safety controller.

The four-wire resistance line portion of the safety controller unit was designed using two banks of double-pole, double-throw relays. The first bank is responsible for disconnecting the four signal lines between the TTT control unit and the firing tank. The second bank is responsible for shorting the signal lines from the firing tank together. This is accomplished using one set of poles on each relay bank. The second pole of the first bank is connected to a red indicator light with a text overlay reading ARMED when the relays are toggled in the position allowing the pass-through of the signal lines. If the signal lines are allowed to pass through to the firing tank, regardless of the shorting, this light becomes illuminated to indicate to the user that the system is not safe for the opening of the chamber door or the attachment of a device into the system. The second pole of the shorting relays is connected to a green light with a text overlay reading SAFE. The presence of this light indicates the signal lines to the firing tank are shorted, and any current present on the lines has been eliminated or minimized to a safe level. The use of two independent indicator lights acts as a system fault detection, where it would be immediately apparent to the test personnel if either the isolating or the shorting sections of the circuit were inoperable. The door switch portion of the safety controller is handled using a third bank of relays. One relay is used to detect current flow through the door switch, which enables the first bank of relays toggling the safety controller into the armed position. This not only prevents the user from arming the safety controller with the door open, but it disarms the system should the door be opened with the safety controller in the armed state. The RESET button, which is used to reset the TTT software and allows the retest of a device without opening the door, is in series with the door switch. Pressing the RESET button has the same effect, from an electrical perspective, as opening the door; it resets the software and restores the safety controller unit into the disarmed state. The safety controller also contains circuitry to toggle the disarmed state should the power switch be toggled off when the safety controller is armed. A circuit diagram is included in the appendix.

CONCLUSIONS

A commercial off-the-shelf (COTS) thermal transient testing (TTT) system, procured from Santa Barbara Automation, Santa Barbara, CA, has been successfully implemented at the U.S Army Combat Capabilities Development Command (DEVCOM) Armaments Center (AC) Explosive Device Facility at Picatinny Arsenal, NJ. This test method is capable of nondestructively evaluating bridgewire initiated devices, such as detonators. A thorough risk analysis was performed, and several modifications were made to the COTS system to improve safety, which dropped the overall risk assessment from high to low. The test chambers included with the system were found, through modeling and simulation with empirical verification, to insufficiently protect personnel from overpressure and fragments in the event of a larger detonator functioning during a test. The electrical safety of the TTT system was also greatly improved through the inclusion of a custom designed in-line safety controller unit. The safety controller ensures that the test article remains shorted until the firing tank enclosing the test article is closed and the test operator manually arms the system. Furthermore, this upgrade allows the test operator to retest a device without opening the firing tank door and risking exposure to a test article cooking off. These upgrades, along with a variety of best practices documented in the standard operating procedure (SOP), have greatly reduced the overall risk when conducting TTT on energetic materials.

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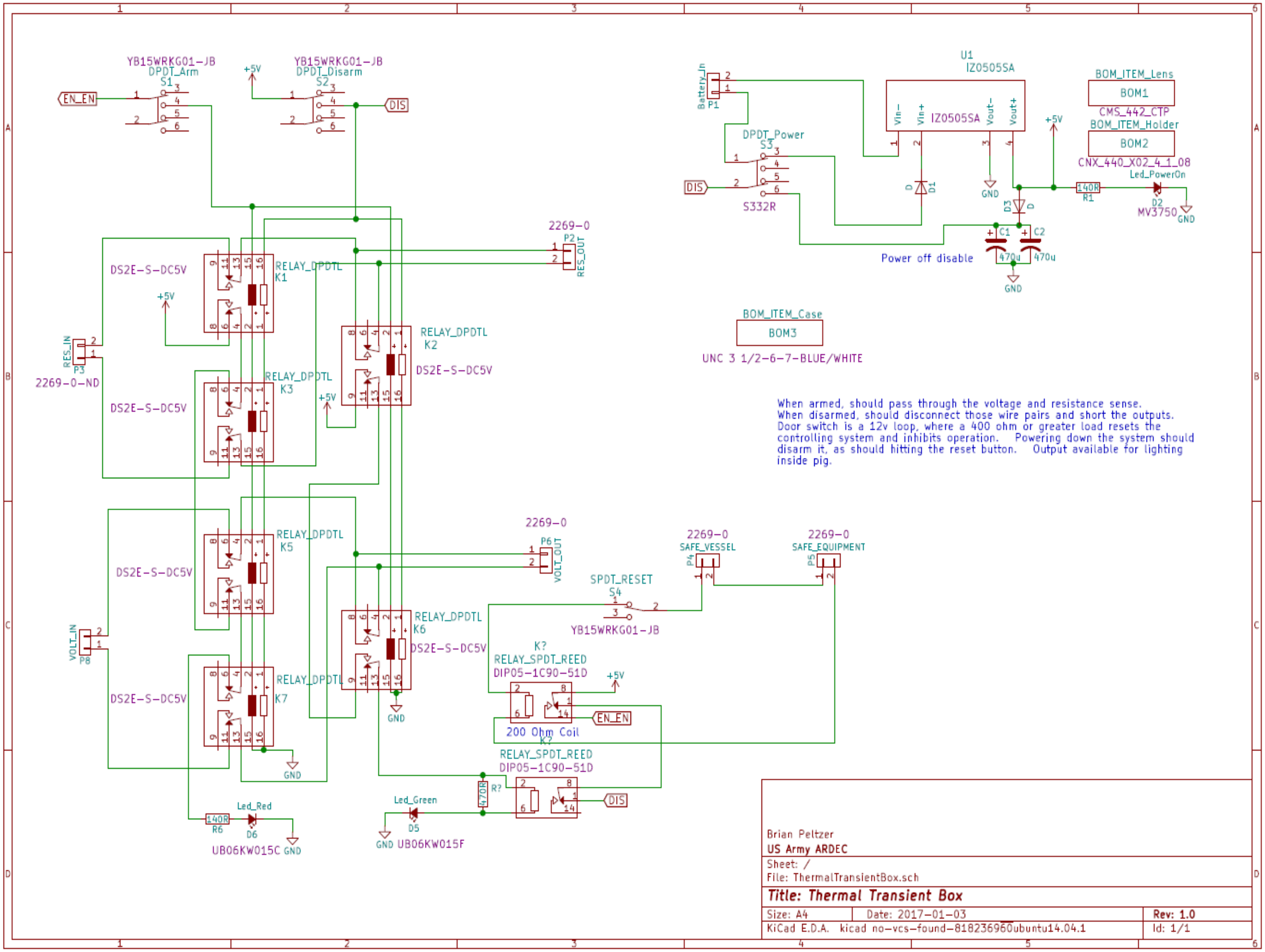
APPENDIX
CIRCUIT DIAGRAM OF SAFETY CONTROLLER UNIT



When armed, should pass through the voltage and resistance sense. When disarmed, should disconnect those wire pairs and short the outputs. Door switch is a 12v loop, where a 400 ohm or greater load resets the controlling system and inhibits operation. Powering down the system should disarm it, as should hitting the reset button. Output available for lighting inside pig.

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