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Technical Investigation of 11 January 1985
PERSHING II Motor Fire

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ABSTRACT

This paper describes the result of an accident investigation performed by a technical team at the US Army Missile Command, Redstone Arsenal, Alabama in support of the US Army Safety Command, Ft. Rucker, Alabama. The accident occurred near Heilbronn, Federal Republic of Germany, on January 11, 1985. A PERSHING II first stage motor burned as a result of efforts to remove it from its shipping container and place it on an erector launcher (EL).

Several possible causes of the motor ignition were considered during the course of the investigation. These were: crew error, incorrect procedures, sabotage, failure of mechanical parts, electrical short circuits, propellant defects, failure of other components mounted in the motor, and electromagnetic effects (radio frequency radiation, lightning, and electrostatic discharge (ESD)). After an intense three month investigation involving many government and private laboratories and researchers. All of these possible causes except ESD were eliminated from further investigation efforts because they were an unlikely, highly unlikely or impossible cause of the accident. Elimination of a cause was based on the results of witness statements (60), reasonable experimental data, debris examinations, computer analyses, and analytical calculations.

ESD was determined to be the only plausible explanation for the accidental motor burning. Tests deviced and conducted by the Electro-Magnetic Effects (EME) Team to discover the source of electrostatic charges, the migration of the charges to a critical location, and the effects of the charges on the propellant system have confirmed the postulated scenario. A series of tests designed to demonstrate and verify this conclusion has been conducted, resulting in a more detailed understanding of the exact sequence which resulted in the propellant ignition.

When the motor was lifted from the silicone foam rubber cradle pads, it was charged to a high, positive potential (with respect to the steel cradle) in the region between 130^{o} to 160^{o} from top dead center. The cradle pad was charge negatively in that region. Lifting the motor away from the cradle enhanced the energy and resulted in a redistribution of the electric field also into the propellant. Because the boom extension put lateral force on the motor, once it was free from the front thrust groove, the motor moved up and aft suddenly contacting the end cross beam at the end of the container with the skirt and nozzle and also at the top of the cradle edge with the side of the motor. This caused an arc discharge of the dielectric motor surface, thereby generating very high transient electric fields within the propellant chamber. This resulted in electric field stress breakdown of the hydroxyterminated polybutadiene (HTPB) binder within the propellant, activation of the oxidizer, and ignition of the propellant as the oxidizer reacted with the fuel of the propellant. The stiffness of the propellant grain and the case restricted gas expansion and created a high temperature region which supported further burning and pressure increase. After a

relatively short period (approximately one second) the mechanical stress on the grain from the high pressure pocket caused a sudden collapse of the grain. But, the rapid decrease in pressure due to the sudden increase in volume was insufficient to extinguish the fire. Collapse of the grain was such that it blocked gas flow through the nozzle, resulting in increased pressure buildup and ignition of an increasing surface of propellant. Soon the pressure was above the limits of the strength of the case and the aft end of the propulsion section was blown off. This violent rupture dismembered the lifting fixture and threw lethal debris about the accident site. A large mass of propellant was then expelled through the aft hole in the opened cylinder and the reactive forces drove the remaining forward section, propellant, and container into the Maschinenfabrik Ausburg-Nuremburg (M.A.N.) crane/tractor vehicle. Flying debris and flame were responsible for fatalities and injuries suffered by personnel assembled around the missile assembly site.

General Description of the PII First Stage Rocket Motor

A PII missile is assembled from five major sections. The first stage rocket motor is the largest and heaviest of the five sections. The first stage rocket motor is 144.74 inches (3.63 meters) long, 40 inches in diameter (1.02m) and weighs 9,145 pounds (4,148 kg). Most of the weight is the solid fuel rocket propellant. The rocket motor case is made of Kevlar filament and epoxy resin. Two cylindrical aluminum sections attached to the forward and aft ends of the rocket motor case provide four hard points used in lifting the section.

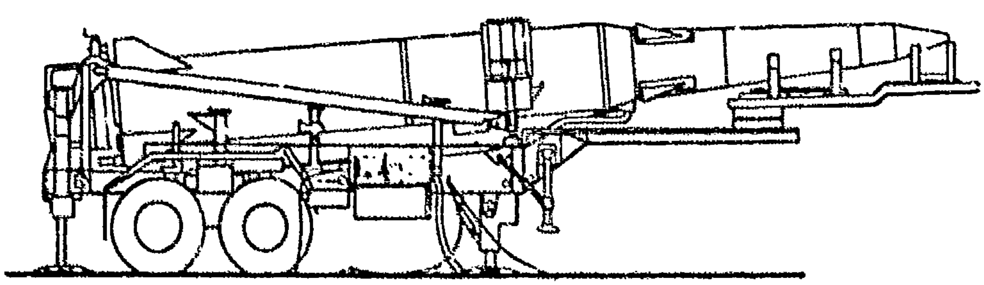

Figure 1. PERSHING II System fully assembled on the erector launcher.

Sequence of Events for the Accident Motor

The motor was manufactured during the summer of 1984 at Hercules, Inc. Magna, UT, accepted by the US Government on October 29, 1984, and shipped to Pueblo Army Depot Activity, Pueblo, CO, the same day. The aft skirt and other items required to complete assembly were installed at Pueblo, and the complete rocket motor, serial number P/S 12037, was placed in a steel shipping and storage container. It was then shipped to Germany in early December 1984, arriving at the "Ft. Redleg" complex on December 19. It was stored outside in its shipping container in a holding area until January 9, 1985, during a period of severe cold weather, with recorded night time temperatures below 0° (-17.8°C).

On January 9, 1985, rocket motor P/S 12037 was moved in its container from the holding area to a training assembly area on the Ft. Redleg complex.

In a typical assembly operation, rocket motors in their containers are placed side-by-side on the ground in close proximity to the erector launcher (EL). Next, the upper halves of the containers are removed, hoisting beams are attached to the sections and the sections are lifted out of their containers in sequence and lowered in place on the EL for mating to complete the assembly. Lifting is accomplished with a 10-ton hydraulic crane mounted on the M.A.N. tractor, which also serves as the prime mover for the EL. The M.A.N. tractor is positioned between the rocket motors and the EL during the operation.

Shortly before 2 p.m. on January 11, 1985, soldiers from a firing platoon of "C" Battery, 3rd Battalion, 84th Field Artillery, prepared to lift the rocket motor from its container to begin a missile assembly as part of their rountine training. There were 10 soldiers in proximity to the rocket motor, including a Captain who supervised the operation. Other soldiers were standing on the EL ready to receive the rocket motor for assembly. Assigned work was going on elsewhere in the immediate area by soliders not involved in the assembly operation.

The container holding rocket motor P/S 12037 had been placed perpendicular to the center line of the M.A.N. tractor with the aft end (nozzle end) of the motor pointing away from the tractor. As a normal procedure, another open container holding a second stage motor was beside the container holding rocket motor P/S 12037. Hoisting beams had been attached to both motors. All mechanical and electrical support equipment needed for the operation were turned on and were operating properly. The engine of the M.A.N. tractor was running to provide power to the crane. A 30 kW generator mounted on the tractor (used to provide power to the EL) was operating. Its circuit breaker was properly set in the "Off" position and the generator was functioning correctly.

The soldiers followed established procedures. Grounding connections were in place. No nuclear materials were in the area since they are never carried or present during training and field exercises.

Although it was not snowing, the ground was covered with snow and the sky was overcast. The air temperature was about 20°F (-7°C), but the motor temperature was about 10°F (-12.2°C).

At about 1:53 p.m., an attempt was made to lift rocket motor P/S 12037 from its container. A groove in the forward attachment ring of the rocket motor fits over a metal flange within the shipping container to prevent fore and aft movement of the rocket while being transported in the container.

Unless the rocket motor is level as it is being lifted, binding can occur between the container flange and the groove in the forward attachment ring. This happened in the first lift attempt. Although the aft end (nozzle end) of the rocket motor lifted about 5 inches (0.13 m), the forward end hung up, preventing the rocket motor from being lifted clear of the container. The lift was halted and the aft end of the rocket motor was lowered back into the container.

The crane boom position was repositioned (extended) and a second lift began. The rocket motor hung up momentarily, then released, causing the forward end to rise about 7 inches (0.178 m). The motor moved toward the starboard rear a few inches and the aft end bumped a steel cross member in the container as the side bumped the cradle. It was at this time, based on witness statements, that the motor caught fire and burned.

Due to the abnormal burning, pressure in the motor case increased beyond the strength of the case. The case ruptured in less than one second.

The aft dome of the motor (a hemispherical section of Kevlar), the nozzle attached to it with bolts, and the entire aft skirt to which it is attached, were expelled rearward together with numerous burning pieces of propellant. The aft dome, nozzle and aft skirt were later recovered about 410 feet (125 m) from the site of the fire.

When the motor case ruptured, it caused the hoist beam to fail, dropping the remaining forward portion of the motor into the container, where it continued to burn. At the same time, the container was driven forward approximately three feet (1 m) until it contacted the rear wheels of the M.A.N. tractor.

A consequence of debris analyses, this sequence of events first suggested the conclusion of the investigation that ignition was abnormal and occurred near the outside surface of the propellant grain (the portion nearest to the inside wall of the motor case) at a point about 94 inches (2.4 m) aft of the forward end of the rocket motor, at a location in proximity to the rear support cradle in the container. In a normal ignition sequence, the igniter in the forward end of the rocket motor flashes fire down a lengthwise cylindrical cavity through the center of the motor. The propellant then burns from the center outward toward the case wall. The proof that this was not a normal ignition is that the igniter was recovered in an unfired condition. The igniter had not been actuated.

Three soldiers, all in proximity to the motor when it caught fire, were killed. Nine others also in proximity were hospitalized. The heavy winter clothing (gloves, boots, parkas with hoods, etc.) worn by the soldiers, because of the cold weather, reduced the number and severity of burn injuries.

The second stage motor placed beside the first stage motor P/S 17037 was exposed to the fire and sustained scorching and heat damage but did not burn. The M.A.N. tractor was damaged. The EL was slightly damaged by impact from the M.A.N. tractor which tilted into its sides.

Methodology of the Accident Investigation

Elimination of Possible Cause

To determine the cause of this accident, all possible causes were investigated, by using available records, witness statements, analysis of recovered debris, and additional tests and calculations. The investigative technique used to accomplish this was by a fault tree analysis. The purpose of a fault tree analysis is to determine the logical interrelation of possible causes (faults) that might have resulted in the undesired event. The goal of this analysis was to determine the parameters governing an undesired ignition of the propellant and to list the possible causes in the order of the probability of their occurrence. This approach quickly narrowed the scope of the investigation. The scope and depth of this effort was reflected in the cost-approximately six million dollars.

Propulsion experts with considerable experience in this field assembled a list of all possible causes for the propulsion section malfunction. Using this list, they systematically constructed a fault tree for use during the accident investigation. Supporting the fault tree resulted in documents covering hundreds of tests and analyses. Through these tests, analyses, and calculations certain possible causes were eliminated as unreasonable. Chemical incompatability, abnormal motor manufacture and sabotage were scrutinized but rejected as possible causes. Other areas found as not having a sufficient rate of energy density in this accident sequence were (1) heat, (2) friction, (3) impact, and (4) electrical or electromagnetic sources -- other than ESD. Therefore, only mechanical and electrostatic effects remained to be investigated. Simulated mechanical and thermal loads, as may occur in the course of transport, storage, and handling, were further analyzed, including some additional tests. Further testing and analyses confirmed that the mechanical loads by themselves did not affect either the safety or the functioning of the first stage rocket motor. Under the given circumstances, purely mechanical causes were considered to be improbable and eliminated from further discussion. Hence, ESD was intensively investigated.

The Root Cause of the Accident

The outcome of this investigative process resulted in pragmatically eliminating all known possible causes -- except ESD, i.e., a discharge of electrostatic electricity, possibly in connection with mechanical effects in the propellant grain. Proof of this outcome was obtained from subscale and fullscale experiments, mathematical modeling, and analysis of the debris. The following sequence of events emerged from this process.

Technical Sequence of Events in the Motor

The sequence of events was determined from debris analysis and laboratory experiments, then further refined by observations made during demonstration tests. This sequence is depicted by the series of drawings shown in figure 2.

As the rocket motor was being lifted from the container, the separation of the Kevlar rocket motor case from the silicone rubber pads resulted in the creation of a static electric charge by a triboelectric process (see figure 1a). The charge was localized on the motor surface in the area above the pads and on the pads. In tests on tactical, full scale motors being separated from a shipping container cradle it has been found that the high charge density areas (hot spots) tended to be localized to the region between 130° and 160° from the top of the motor. Further, due to the fit of a specific motor into a specific container, these hot spots tended to be repeatedly created in certain areas. The density of the electrostatic charge has been shown to increase as the temperature and humidity decreased. The charge created by triboelectrification of the polyurethane painted Kevlar case does not dissipate rapidly. This is especially true in conditions of low temperature and low humidity. This charge gave rise to considerable electrial fields between the motor surface and also in the propellant grain. The motor moved up and back, bumping the steel cradle, and resulted in an external ESD. As a result, a subsurface electric arc occurred in the aft lower portion of the propellant resulting in propellant ignition as indicated by figures 2b and 2c. Such an internal arc can take place without puncturing the motor case. Furthermore, it was demonstrated by independent tests that the electrical field strength and the total electrostatic energy accumulated in the whole system are sufficient for electrical breakdown and/or ignition of the propellant.

The epicenter of the event was located between 130° and 150° of rotation, and approximately 94 inches aft of the forward surface of the propellant grain. The flame stabilized in a gas pocket between the bond-line and the grain, and the aft section of the grain started to implode. See figure 2c. The flame spread forward and aft at a higher rate than the circumferential rate. The stiffness of the propellant grain and the case restricted gas expansion and created a high temperature region which supported further burning and pressure increase. The mechanical stress on the grain from the high pressure packet caused a sudden, partial collapse of the center bore of the grain in the region of the gas pocket. But, the rapid decrease in pressure due to the sudden increase in volume was insufficient to extinguish the fire. Collapse of the grain center bore progressed fore and aft, reaching the aft end first, such that it blocked gas flow through the nozzle. This resulted in an increased pressure buildup and ignition of an increasing surface of propellant. Soon the pressure was above the limits of the strength of the case (see figures 2d and 2e) and the aft end of the propulsion section was expelled aft. At nearly the same time, the expanding gas pocket had reached and broken into the forward cavity. Again, the decrease in pressure was insufficient to extinguish the fire. The pressure built rapidly within the forward cavity since the bore was completely collapsed causing about 4000 pounds (1800 kg) of propellant to be expelled approximately 50 meters aft of the incident site where it burned. See figure 2f. The reactive force simultaneously moved the head end of the motor and container forward, approximately one meter, to rest against the truck used in the assembly.

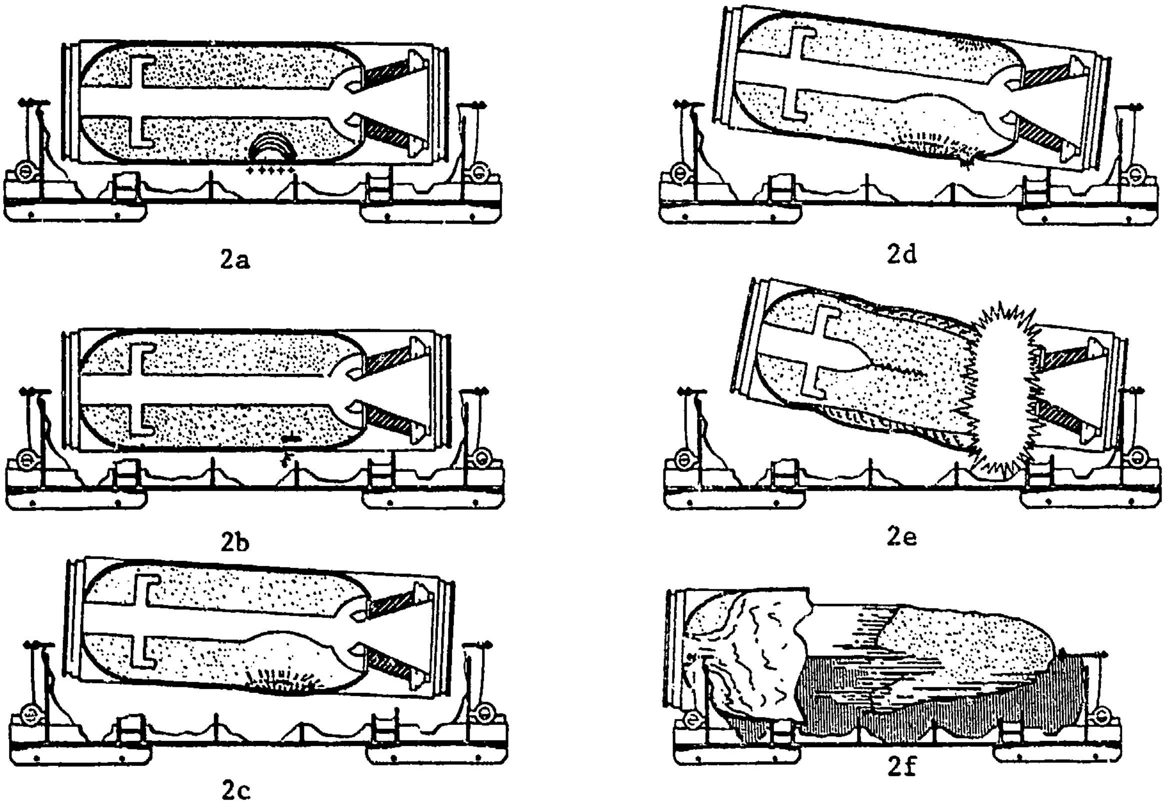

Figure 2a-f. Sequence of events as PII first stage motor was being removed from its shipping container which led to the motor fire and damage. Figure 2a shows a positively charged patch on the outer surface of the composite PII motor case created by the silicone foam rubber cradle pads of the container. An external arc discharge resulting in the internal arc is shown in 2b. Figures 2c and 2d show the progressive expansion of the localized high pressure area causing case failure which resulted in the collapse of the grain, shown in 2e, and the separation of the nozzle/aft skirt section. Figure 2f shows the result of the high pressure pocket formed in the "P-groove" area in the front of the propellant grain.

Propellant Safety Assurance Prior to Accident and New Findings

The Pershing II first stage rocket motor contains a customary ammonium perchlorate HTPB propellant which - compared with other similar propellants - is less sensitive to external stimuli. It will not detonate, but can and does burn very rapidly. This burning can cause rapid over-pressurization of the motor case if abnormal burning occurs or the exit port (nozzle) becomes blocked. This over-pressurization results in the bursting of the motor case -- as occurred in this accident.

Prior to the Pershing II accident, extensive testing was done to ensure system safety. Among these tests were those dealing with propellant sensitivity. The propellant was characterized by the existing state-of-the-art tests and determined to be insensitive to levels higher than those in any expected adverse environment, including ESD. During the course of the accident investigation, phenomena were discovered which have required the propulsion community to reassess and redesign testing techniques for propellant. It has been found that: (1) an internal electrical breakdown of the propellant, due to a transient electromagnetic field, can result in ignition of this propellant; and (2) it has been shown that propellant temperature and sample volume are critical to proper evaluation of its response to ESD.

Knowledge of the presence of these phenomena has allowed corrective actions to be taken on the present system and eliminate future accidents of this nature on this and other designs.

Replication and Verifications Tests

To confirm that the propellant was most probably ignited by ESD phenomena required evaluation based on measurements of:

(1) charges and electrical fields generated during the lift,
(2) where the charges migrate and at what rate, and
(3) the response (sensitivity) of the propellant to ESD phenomena.

Replication tests were conducted to further investigate the ESD ignition scenarios. These tests involved actual and simulated removal of a live tactical propulsion section from its container. This motor was as nearly identical in construction and history to the incident motor as possible. The tests were conducted at temperatures as near as possible to those involved in the accident. The relative humidity was also controlled to avoid frost accumulation, which did not exist at the accident site. When the motor was lifted from the container in the manner which resulted in the 11 January 1985 accident, generation of very high electrostatic charge densities was confirmed. As predicted prior to the test, the motor did not ignite due to the low probability of exactly duplicating all of the necessary events of the accident. Following the duplication phase of the test sequence, multiple lifts were conducted to determine the possible build-up of charge due to multiple contacts. In this phase, it was repeatedly shown that the charge density did not significantly increase with additional lifts. Finally, simulated lifts were conducted. This phase of testing provided more control of the charging, charge distribution, and discharging of the motor/cradle pad interface area. These tests were also conducted at low temperatures and relative humidities. When the motor pad was charged to a 50 kV potential with respect to the container structure and then discharged via an arc discharge, the propellant was ignited in the subsurface region of the grain. This demonstrated the "sympathetic" ignition scenario wherein an external ESD arc creates an electrical arc in the propellant near the case bond interface without penetrating the case.

Conclusion

In reviewing the total data base generated in the investigation, the critical events leading to the accidental propellant ignition were:

(1) Triboelectrification of the insulating motor case.
(2) Location of the charge distribution of the motor.
(3) Contact between the motor and the aft steel cradle at that location.
(4) An external ESD from the motor case to the container at the contact point creating very high E-field stresses within the propellant.
(5) Sufficiently cold temperatures of the system such that:
   a. charge generation of the motor case was enhanced,
   b. charge retention was enhaced.
   c. susceptibility thresholds of the propellant to both E-field and energy was significantly reduced.

Hence, a duplication of the accident would require more than similar conditions of temperature, humidity, and movement. It would also require exact timing, motor positioning in the cradle to produce charging at a precise location, and finally specific movements of the motor to bring the charged area within discharging distance of the steel container. Tests have confirmed that if this scenario occurred, the propellant grains could be ignited with an unmodified system. That all of these necessary conditions would coincide at one time was, indeed, a very remote possibility.

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