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The Response of Aeroshells To Lightning

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Abstract

Electrical discharges from a lightning simulator were directed at Mk12 aeroshells. Buckling of the aluminum substrate was observed after some 100-kA shots, and severe damage consisting of tearing of the aluminum and the production of inward flying aluminum shrapnel was observed after some 200-kA peak-current shots. Some shots resulted in severe damage to both the aluminum and the carbon-phenolic ablative material. It is reasonable to conclude from the experimental results that a lightning stroke with very high-peak current could, by itself, produce an opening in an Mk12 aeroshell. Because the aeroshell is part of the nuclear explosive safety exclusion region for the Mk12/W62 nuclear weapon, an opening would significantly reduce the assured safety of the weapon. It is unlikely that the observed interaction between lightning and the aeroshells would have been predicted by any form of computer simulation.

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The Response of Aeroshells To Lightning

Summary

Electrical discharges from a lightning simulator were directed at Mk12 aeroshells. The Mk12 aeroshell, which is part of the Mk12/W62 nuclear weapon, consists of an aluminum substrate (~0.060-inch-thick) and an ablative heat shield (~0.41-inch-thick); the two parts are held together by an adhesive. The aeroshells that contain the W76, W78, W87 and W88 are of similar construction.

Damage to aeroshells was seen after discharges for which the peak currents were above about 100 kA. Buckling of the aluminum substrate was observed after some 100-kA shots, and severe damage consisting of tearing of the aluminum and the production of inward flying aluminum shrapnel was observed after some 200-kA peak-current shots. Severe damage to the aluminum was more common than severe damage to the carbon-phenolic heat shield. Only one discharge produced an opening completely through the heat shield and the aluminum substrate. Damage is most likely due to the production and rapid heating of gases as the lightning current flows through the carbon phenolic and the adhesive. Buckling and tearing of the aluminum substrate was more common than damage to the carbon phenolic because the aluminum was the weaker material.

Because the output of the lightning simulator resembles, with high fidelity, negative cloud-to-ground lightning, it is reasonable to conclude that natural lightning strokes could produce the same damage as was produced by the discharges from the simulator. Hence, the experiments have shown an unexpected damage mechanism in a lightning environment. It is reasonable to conclude from the experimental results that a lightning stroke with very high peak current could, by itself, produce an opening in an Mk12 aeroshell. Because the aeroshell is part of the nuclear explosive safety exclusion region for the Mk12/W62 nuclear weapon, an opening would significantly reduce the assured safety of the weapon. The experiments showed that lightning strokes could also produce aluminum shrapnel inside the aeroshell. Unfortunately, it was not possible to determine the velocity of the aluminum pieces.

The use of actual aeroshells and of electrical discharges that closely resembled lightning led to the observation of unexpected damage. It is unlikely that this damage would have been predicted by any form of computer simulation.

Introduction

The stockpile lightning analysis and test (SLAT) program was initiated by M. E. Morris, Manager, Electromagnetic Analysis and Test Department, and others to obtain data on the responses of nuclear weapons to lightning. The program was divided into three phases. In the first phase of the program, data were obtained on the currents and voltages induced by simulated lightning in relatively simple configurations, such as metal-to-metal joints, chosen to represent structures found in weapons. When this report was being written, three reports on the Phase I work were being completed.^{1,2,3} The plan for the second phase called for three distinct sets of experiments. The first set would study the interaction between lightning and aeroshells, the second set would investigate the currents induced by lightning in ferromagnetic fire sets, and the third set would investigate certain thermal effects. This report describes the work on aeroshells. Dinallo, Loescher, and Warne will write a report on the investigation of ferromagnetic fire sets. No work was done on the third topic. Also, no work had been done on Phase III of the SLAT program at the time this report was being written.

A typical re-entry body has the shape of the frustrum of a cone. It consists of an aeroshell and whatever is contained inside the aeroshell. If the re-entry body is a nuclear weapon, the aeroshell contains a nuclear warhead. The aeroshells for most nuclear weapons consist of an aluminum shell that is ~0.060-inch thick over which is placed a much thicker shell of ablative material. A layer of adhesive connects the two shells. The aeroshells that contain the W62, W76, W78, W87, and W88 all have this basic structure.

Prior to the start of this work, Fisher and others established that a single lightning stroke without continuing current would not burn a hole in aluminum plates that had thicknesses of 0.060 inch.⁴ This result led to the expectation that a lightning stroke that was not followed by continuing current would not damage an Mk12 aeroshell, unless the stroke attached at an edge of the ablative material. If the stroke attached at an edge, damage in the form of tearing of the ablative material was expected. The nature of lightning discharges is discussed in the next paragraph.

A lightning flash consists of an initial return stroke, possibly additional return strokes, and, possibly, continuing current.⁵ The division into an initial stroke and subsequent strokes is made because the two types of strokes are initiated in different ways and important parameters of the strokes, for example, rise time and peak current, are described by different statistics. Approximately 60% of all lightning strokes connect one cloud to another cloud. The remaining 40% of the strokes connect electrical charge in a cloud to the earth. The latter strokes are referred to as cloud-to-ground strokes. The median value of peak current for the initial stroke of negative cloud-to-ground lightning is approximately 30 kA. Ninety-nine percent of all negative-cloud-to-ground discharges have peak currents that are less than or equal to 200 kA. Over 90% of lightning discharges are of the negative-cloud-to-ground type.⁶ Less than 10% are of the positive cloud-to-ground type. The terms negative and positive refer to the type of charge in the leader that initiates the lightning discharge. The largest peak currents, those in the 200-kA to 300-kA range, are due to return strokes of positive lightning; positive flashes are relatively more common in winter thunderstorms (snowstorms) than in summer thunderstorms.⁷

Apparatus and Tests

Test apparatus and test methods are described in this section. In some instances, additional details are given so that future investigations can be compared accurately with the methods used in this study.

Midsections of the Mk12 aeroshell were used for all tests described in this report. There were a number of reasons for the choice of this aeroshell: the Mk12/W62 nuclear weapon will be in the stockpile until the end of the decade; the structure of this aeroshell is similar to that for the W76, W78, W87, and W88; it was readily available; and it was not classified. The Mk12 aeroshell consists of a 0.41-inch-thick carbon-phenolic heat shield over a 0.060-inch-thick aluminum substructure. A 0.040-inch-thick layer of silicone adhesive connects the heat shield to the aluminum. A sketch of the aeroshell is given in Figure 1.

Three aeroshells were used in this work. At the end of the study, there were unexplained differences in the way the aeroshells responded to lightning. It is hoped that the following histories of the aeroshells may help a future investigator to explain the observed differences, or to conclude that the detailed histories are irrelevant. The first aeroshell was obtained in March 1993 from Dick Davis of the W76, W78, and Integrated AF&F Department, who, in January 1993, had obtained twelve aeroshells from the Director of Special Weapons at Kelly Air Force Base in San Antonio, Texas. Dick retained some of the aeroshells, sent six to the Field Command Defense Nuclear Agency (FCDNA) warehouse on Kirtland Air Force base, and sent the rest to Los Alamos. The second aeroshell was obtained from the FCDNA warehouse in May 1993 where it had been stored in an H1224 shipping and storage container. The third aeroshell was obtained, indirectly, from Los Alamos; it is speculated to be one of those that Dick had sent there earlier in the year.

Figure 1. Sketch of the Mk12 Aeroshell

On August 30, what was to be the third aeroshell was moved from the FCDNA warehouses to the lightning laboratory. On September 3, David Harding of the Transportation Systems Department asked to use the aeroshell in thermal tests that would be conducted over the Labor Day weekend. He offered to replace it with one that was at Los Alamos. On September 3, Dave took the aeroshell; later in September he provided the replacement. It is highly likely that the replacement aeroshell was one that Dick Davis had sent to Los Alamos earlier in the year.

To aid in posttest evaluation, the surfaces of the first two aeroshells were divided with chalk marks into sixteen zones, and four possible stroke attachment points were identified in each zone. This division of the surface is shown in Figures 2 and 3. The chalk lines and the zone labels appear in many of the photographs that are part of this report. The surface of the third aeroshell was divided into six zones that ran the entire length of the shell.

Throughout this report, angular separation between locations on the surface of an aeroshell will be given in degrees measured counterclockwise when the aeroshell is viewed from the aft end.

Figure 2. Division of the Aeroshell Surface Into Attachment Points. Used for the First Two Aeroshells.

Figure 3. Further Details of the Division of the Aeroshell Surface Into Attachment Point.

The Sandia Lightning Simulator (SLS) was used as a source of fast rise time, high current, electrical discharges.⁸ Previous work had shown that discharges from this machine reproduced the most important characteristics of negative cloud-to-ground lightning with acceptable fidelity.⁹ For all tests, the simulator was configured so that discharges were from a 0.25-inch-diameter tungsten rod. The axis of the rod was vertical and the tip of the rod was positioned approximately one inch from the surface of the aeroshell. The one inch spacing was chosen because Fisher and Schnetzer¹⁰ found that plasma erosion, which had not been observed after strikes by natural lightning, occurred if the electrode-to-attachment surface distance was too small. For all tests, the aeroshell was oriented so that the surface to be struck was approximately horizontal.

The simulator consists of two Marx generators; a motor-generator set; and equipment to trigger, direct, and monitor the discharge. The Marx generators are identified by their location in the laboratory; one is referred to as the north generator and the other as the south generator. Discharges from the north generator are identified with an N, e.g. N3443, and shots from the south generator are identified by an S. The north tank is used for shots that require high peak current. Because there are two Marx generators, two discharges can be fired in a short period of time; however, this feature of the simulator was not used. The motor-generator set is used to provide continuing current. This feature was used for some shots on the first aeroshell.

Four different connections were used for the conductors that carried the return current from the aeroshell to the simulator and will be referred to as bolted to aluminum (BTA), bolted to aft ring (BTAR), strapped on copper (SOC), and copper plane (CP). These four connections are shown in Figures 4 through 7. For the bolted-to-aluminum connection, four one-half-inch outside-diameter copper tubes were attached to the aft end of the aeroshell with 10-32 screws. The tubes had walls that were 0.032 inches thick and washers were placed between the screw heads and the tubes. The tubes, which were ~12 feet long, were placed approximately 90° apart. For the bolted-to-aft ring connection, an aluminum ring was threaded onto the aft end of the aeroshell. The ring, which had been obtained for use in another program, had an inside diameter of 17 inches, an outside diameter of 19 inches and was 2 inches wide. The same screws and copper tubes that were used for the BTA connection were used to connect the ring to the simulator. For the strapped-on-copper connection, a 4-inch-wide, 0.034-inch-thick copper sheet was strapped to the outside surface of the carbon phenolic material. The length of the contact area was between 5 inches and 6 inches so the contact area was approximately 22 sq. inches. The copper sheet extended beyond the aft end of the aeroshell. The same four copper tubes used for the BTA and BTAR connections were connected to the extension and routed back to the lightning simulator. For the copper-plane connection, the aeroshell was placed on a copper plate that was 3 feet wide, 6 feet long, and 0.062-inch thick. The aeroshell was placed on the plate so that there was a line of contact between the carbon phenolic material and the plate over the entire length of the aeroshell. The same four copper return conductors were attached to the four corners of the plate.

Eleven strokes were directed at the first aeroshell. Information about these strokes is given in Table 1. The first stroke was used to set up the machine. For this stroke, the aeroshell was positioned so that the attachment point would be midway between the lateral boundaries, and approximately 2 inches from the front edge of zone ID. The BTA return connection was used for all shots directed to the first aeroshell.

The first discharge to the second aeroshell was fired on May 27, 1993, shot N3459 was fired on June 3, and the last two shots were fired on July 16 (see Table 2). The simulator was used for other programs between June 4 and July 16. The first discharge to the third aeroshell was fired on October 19, 1993 and the last shot was fired on October 21, 1993 (see Table 3). There was a long delay between the last shot on the second aeroshell and first shot on the third aeroshell because both the simulator and the operator of the high speed photographic equipment were committed to other work.

Figure 4. BTA Connection of the Return Current Conductors

Figure 5. BTAR Connection of the Return Current Conductors

Figure 6. SOC Connection of the Return Current Conductors

Figure 7. CP Connection of the Return Current Conductors

Table 1. Test Matrix for the First Aeroshell

Shot	Peak Current (kA)	Continuing Current		Attachment Point
		(A)	(s)	
S3393	48	0	n.a.	ID-front
S3394	48	0	n.a.	IIA-2
S3395	48	0	n.a.	IIIA-1
N3402	95	0	n.a.	IIB-1
N3403	80	0	n.a.	IIIB-1
N3406	187	0	n.a.	IIC-1
N3407	198	0	n.a.	IIA-1
S3411	48	860	1	IID-1
S3413	48	860	1	ID-3
N3418	186	369	1	IIIA-2
N3420	192	400	1 ms	IIIA-3

The first three shots were fired on April 20 and the last shot was fired on May 5.

Table 2. Test Matrix for the Second Aeroshell, Serial 992074
 (There was no continuing current on any of the shots)

Shot	Peak Current (kA)	Attachment Point	Return Current Connection ¹
N3438	106	IIA-1	BTA
N3440	101	IIB-2	BTA
N3441	187	IIIA-3	BTA
N3442	192	IIIA-3	BTA
N3443	187	IIIA-3	BTA
N3444	198	IIIB-3	BTA
N3446	105	IIA-2	SOC
N3447	106	IIB-1	SOC
N3449	197	IIC-3	BTA
N3450	196	IID-3	BTA
N3451	200	IID-2	BTA
N3456	misfire	IID-3	BTA
N3457	201	IID-3	BTA
N3458	200	IIA-3	SOC
N3459	199	IIIA-(1-2)	SOC
N3563	211	IVA-1	CP
N3564	209	IIB-4	CP

¹The nomenclature is explained in the text.

Table 3. Test Matrix for the Third Aeroshell, Serial 370992
(None of shots included continuing current)

Shot	Peak Current (kA)	Attachment Point		Return Current Connection ¹
		Distance from aft end (in)	(degrees)	
N3766	174	10.5	120	BTAR
N3768	184	10.5	240	BTAR
N3769	185	10.5	0	BTAR
N3770	194	10.5	300	BTA
N3771	197	10.5	60	BTA
N3772	195	15.25	225	BTA
N3773	199	15.25	225	BTA
N3774	201	15.25	225	BTA
N3775	174	21.5	30	BTA

¹The nomenclature is explained in the text.

A record of simulator output current versus time was recorded for each shot. Values of current were obtained from measurements of the voltage across a 1.67-m Ω current viewing resistor. The measured voltage was transmitted to a screen room where a Tektronix model 7612 digitizer converted it to a digital signal. A graph of current versus time constructed from the digitized signals is shown in Figure 8. The data are for shot number N3406.

The aeroshells were examined visually after each shot to determine whether damage had occurred. A 35mm camera equipped with a 55mm lens was used to record test set ups, the appearance of the test object before and after simulated lightning discharges, and other test results that could be represented on photographs. Stanley and Lufkin tape measures were used to measure the dimensions of damaged regions and various distances.

Framing camera records of damage to the aluminum substrate were the major objective of the shots at the second aeroshell. Two cameras, a Cordin Model 330 and a Cordin Dynfax model 350, were used. The Model 330 was adjusted to record at frame rates between 50,000 frames per second (fps) and 60,000 fps; the exact rate was recorded for each shot. The Model 330 was used for shots N3438 through N3447. The Dynfax model 350 was adjusted to record at a rate of 35,000 frames per second. The cameras and ancillary equipment were set up and operated by Mark Nissen of the NDT, Photometrics, and Optical Data Department. Prior to all tests, the inside of the aeroshell was painted white and rectilinear grids were drawn directly below the planned attachment points. These grids are seen in Figure 18. Mark planned to use flash lamps to illuminate the inside of the aeroshell. Unfortunately, the power supplies for the lamps were damaged by the electromagnetic noise that accompanied the discharge of the lightning simulator. The supplies were completely inoperable after shot N3443. When he was no longer able to use his lamp power supplies, Mark set up a system of mirrors to focus light from the simulated lightning stroke onto the interior of the aeroshell. The mirrors provided much less light than would have been available from the flash lamps. The fact that Mark was able to obtain photographs without flash lamps is testimony to his ingenuity. Unfortunately, the photographs were not as clear as might have been obtained with the lamps.

Figure 8. The Waveforms Show Current and Charge Versus Time for Shot N3406

Framing camera records were also the major objective of the shots at the third aeroshell. For this series of shots, Mark used a Cordin model 377 framing camera that was set to operate at 120,000 frames per second. He chose flash bulbs rather than flash lamps for illumination because they would be fired by relays and batteries instead of by impulse sensitive electronic circuits. Furthermore, the flash lamps, which require milliseconds to achieve full light output, would be fired well before the lightning simulator was triggered and produced electromagnetic noise. A mechanical shutter was used to prevent double exposures.

Results

The only evidence of damage to the first aeroshell after the first three strokes was a slight change, near the point where the discharge attached to the body, in the way light reflected from the body. There was no evidence of structural damage to the carbon phenolic or to the aluminum substructure. After the next shot, for which the peak current was 95 kA, it was found that the aluminum substructure had buckled inward over a length of approximately 13 inches. The buckling started ~6 inches from the front of the body and ended approximately 19.3 inches from the same reference. The buckling was not directly under the attachment point, but instead it was ~90° clockwise from that point. This was the only time that the damage caused by a discharge was well removed from the attachment point. The damage, at the attachment point to the phenolic, was similar to that seen after the 50-kA shots. A second shot, for which the peak current was 80 kA, followed. No significant damage to the phenolic or to the aluminum was observed after this shot. Small chips were missing from the edges of the radar windows after both shots.

The next discharge, N3406, had a peak current of 187 kA. The attachment point was ~12 inches from the front of the body and approximately over the region that had been buckled by the 95-kA shot. The current and charge waveforms for this shot are shown in Figure 8. Extensive damage to the aluminum substructure was observed after this shot. The extent of the buckled region increased so that it started ~5 inches from the front and extended for ~20 inches. Also, the aluminum was extensively torn. The longest tear was along the top of the buckle. It started ~6 inches from the front and extended for ~14 inches. Approximately 7 inches from the front of the tear, that is ~13 inches from the front of the body, two azimuthal tears split off from the main tear. Each of these ran for ~3 inches, and then turned into axial tears that ran for ~5 inches. This damage is shown in Figure 9. The maximum inward displacement of the aluminum was ~1.3 inches. As can be seen in Figure 10, there was nothing other than superficial damage to the carbon phenolic near the attachment point.

The next shot, N3407, had a peak current of 198 kA. The attachment point was ~12.3 inches from the front of the body and almost diametrically opposite to the attachment point for the previous shot. Prior to the shot, there was no apparent damage near, or under, the intended attachment point. After the shot, there was extensive damage to both the carbon phenolic and the aluminum substructure. An irregularly shaped, but roughly rectangular, piece of phenolic that had approximate maximum dimensions of 4 inches by 3 inches was torn from the surface, and was found on the test bench ~3 feet from the attachment point. There were also extensive azimuthal cracks in the phenolic. The longest crack, located directly behind the place from which the piece had been torn, extended ~7 inches in each direction from the aft point of the region from which the piece was torn. The aluminum under the test point was buckled and torn. The buckle started ~5 inches from the front of the body and extended for ~11 inches. The tear started ~7 inches from the front of the body and extended for ~7 inches along the top of the buckle. The maximum inward displacement of the aluminum was ~0.8 inch. The damage to the phenolic and to the aluminum are shown in Figures 11 and 12.

Figure 9. Damage to the Aluminum Substructure of the First Aeroshell after Shot N3406

Figure 10. Lack of Damage to the Phenolic Material after Shot N3406

Figure 11. Damage to the Carbon Phenolic after Shot N3407, Peak Current 198 kA

Figure 12. Damage to the Aluminum Substrate after Shot N3407, Peak Current 198 kA

The first six shots, S3393 through N3407, consisted of a single high-current discharge. As was mentioned in the introduction, actual lightning discharges often contain a component of continuing current that can last for hundreds of milliseconds. The Sandia Lightning Simulator is able to simulate this part of lightning discharges. There is evidence that it is the continuing current, rather than the high-peak-current strokes, that burns holes in metal sheets.¹¹ A number of shots were conducted to determine how continuing current would affect the aeroshell. The first two tests were to have 50-kA peak current and 400-A continuing current. Due to an error in the set up of the simulator, the actual continuing current was close to 800 A. After both of these shots, there were blisters at the attachment point, but there was no visual evidence of damage to the aluminum substrate.

After the two 50-kA and continuing-current shots, the simulator was adjusted so that the peak current would be 200 kA, and the desired continuing current of ~400 A would be obtained. The first shot with the new peak and continuing currents resulted in severe blistering at the attachment point, but no visible structural damage. The results of the second shot with the same nominal currents were quite different.

This shot, N3420, attached at a point approximately 23 inches from the front of the body. After the shot, the substrate under the attachment point was severely deformed and torn, and pieces of aluminum were missing. The general nature of the damage to the aluminum was reminiscent of the petal-like fissures seen on ruptured discs. There was an axial tear that started approximately 19.5 inches from the front of the body and extended for ~5.5 inches. There was also an azimuthal tear that started near the middle of the axial tear and extended ~2.5 inches on each side of this tear. This damage is shown in Figure 13. After the shot, one piece of aluminum was found on the floor approximately 20 feet from the attachment point. This piece had a roughly half-oval shape with dimensions of 3.8 inches by 1 inch. There was evidence, in the form of pock marks, that electrical arcing occurred on the side of this piece that was nearest the carbon phenolic. A second piece, which had a roughly triangular shape with dimensions of ~2.2 inches by 1 inch, was found approximately six feet from the attachment point. The technicians reported hearing one or both pieces banging about the lab immediately after the simulator was discharged. A photograph of the two pieces is shown in Figure 14. The damage to the phenolic was not significantly different from that seen after the previous shots. This is shown in Figure 15.

By the end of the last test on the first aeroshell, the radar windows had been severely damaged. One window was almost torn from its mount, and chips from the windows were found scattered around on the table that supported the aeroshell.

Shot N3438 was the first shot directed at the second aeroshell. After this shot, there was damage to the phenolic at the front edge of sector IB. This damage is shown in Figure 16. There was no visual evidence of damage to the aluminum substructure after this shot. There was no visual evidence of damage, other than a slight roughening of the phenolic surface at the point of arc attachment, after shots N3440 and N3443. Shots N3439, N3441, and N3442 were used to set up the machine; they were not directed at the aeroshell.

There was severe damage to the aeroshell after shot N3444. The current versus time waveforms for this shot, and for the preceding shot are shown in Figure 17. Except that the peak current was slightly larger for N3444, there was no significant difference between the discharge currents for the two shots. The damage to the aluminum following shot N3444 is shown in Figure 18. The tears in the aluminum were similar to those seen after shot N3420, which had been directed at the first aeroshell. The distances traveled by the tips of the aluminum tears were measured. The smallest distance was 1.25 inches and the largest distance was 1.75 inches.

The framing camera provided a sequence of photographs of the inside of the aeroshell that started when the arc for N3444 attached to the aeroshell and continued for ~4 ms. A photograph was recorded every 17.6 ms. Examples of the photographs are shown in Figures 19 and 20.

Figure 13. Damage to the Aluminum Substrate after Shot N3420, Peak Current of 192 kA Was Followed for 1 ms by a Continuing Current of 400 A

Figure 14. Two Pieces of Aluminum from the Aeroshell That Were Found In the Laboratory after Shot N3420

Figure 15. Damage to the Carbon Phenolic after Shot N3420

Figure 16. Damage to the Carbon Phenolic after Shot N3438, Peak Current 106 kA

Figure 17. Plot of Current and Charge-Versus-Time for Shot N3443, after Which There Was No Observable Damage, and Shot N3444, after Which There was Extensive Damage. (No variation exists between the plots to explain the difference in the damage.)

Figure 18. Damage to the Aluminum Substrate after Shot N3444

It was possible to obtain an estimate of the velocity of the aluminum from the framing camera records. It was hoped that the records would contain clear images of aluminum shrapnel, and that the velocity of the shrapnel could be determined from measurements of distance traveled between successive records. Unfortunately, no such images were obtained. However, it was possible to identify the onset and the conclusion of deformation of the grid drawn on the inside of the aeroshell. It was found that there was little, if any, deformation visible in the photographs that preceded the one shown in Figure 19. It was more difficult to determine when the deformation was complete. It appeared that the deformation was nearing completion when the photograph shown in Figure 20a was taken. It also appeared that the deformation was essentially complete when the photograph shown in Figure 20b was taken. The interval between the photographs shown in Figures 19 and 20a was 87.9 ms and the interval between the photographs shown in Figures 19 and 20b was 211- μ s.

Figure 19. Camera Record for Shot N3444. Deformation of the rectilinear grid started at about the time the photograph was taken.

(a)

(b)

Figure 20. Framing Camera Record for Shot N3444. (a) shows deformation of the grid nearing completion; (b) shows deformation of the grid essentially complete.

No additional visible damage to the phenolic, except for local roughening of the surface, or to the aluminum was observed after shots N3446, N3447, N3449, N3450, N3451, N3456, and N3457. Shots not listed were used to set up the machine; they were not directed at the aeroshell. A radar window was damaged by shot N3449 and was blown completely out by shot N3450. After shot N3458, there was a bulge in the aluminum substrate. The bulge was 10 inches long and 2 inches wide. The center of the bulge was midway between attachment points IIIA-1 and IIIA-2. The attachment point for shot N3459 was directly over the center of the bulge produced by shot N3458. After the shot, the bulge was bigger, but there was no evidence of any tears in the aluminum.

The series of shots that began with N3438 on May 27 were terminated with N3458 on June 3 because the shots were not producing the expected aluminum shrapnel, and because both Mark Nissen and the lightning simulator were scheduled for other work. Two additional shots, N3563 and N3564, were directed at the aeroshell on July 16; no additional damage was observed.

The primary goal of the tests on the third aeroshell was to obtain good photographic records from which shrapnel velocities could be determined. As has already been mentioned, the photographic equipment included a new camera and flash bulbs. Data from the tests on the first two aeroshells was reviewed to determine whether there was any relation between attachment point and the production of flying pieces of aluminum. It was concluded that those attachment points located a few inches forward of an internal mounting ring tended to produce aluminum fliers. The mounting ring is located approximately 7.6 inches from the aft end of the aeroshell. Six attachment points were measured 10.5 inches from the aft end and equally spaced in azimuth.

It was speculated that an aluminum ring secured onto the aft end of the aeroshell might provide a better return path than the bolted-to-aluminum connection. An end ring that had been obtained for work on another program was used for shots N3766, N3768, and N3769. Female threads in this ring mated with male threads on the end of the aeroshell. Because evidence of arcing was observed between the phenolic of the aeroshell and the end ring after shot N3769, the end ring was not used for subsequent shots.

There was no visible evidence of damage to the phenolic, other than roughening of the surface at the attachment point, or the aluminum after any of the shots to the third aeroshell. Damage to the radar windows was observed.

Discussion

Peak Current and Damage

The first aeroshell was subjected to seven discharges without continuing current and four discharges with continuing current. No structural damage was observed visually after five shots for which the peak current was approximately 50 kA. Severe buckling was observed after one shot for which the peak current was 95 kA, and no damage was observed after a shot for which the peak current was 80 kA. Severe damage to the aluminum was observed after three out of four shots for which the peak current was ~200 kA.

Shot N3438, for which the peak current was 106 kA, resulted in some damage to the carbon phenolic at the front edge of the second aeroshell; however, no damage to the aluminum substrate was observed. Shots N3446 and N3447, for which the peak currents were 105 kA and 106 kA, respectively, did not produce any visible damage. The second aeroshell was subjected to ten shots for which the peak current was approximately 200 kA. After three of these shots, N3444, N3458, and N3459, there was visible damage to the aluminum substrate.

Nine shots, for which the peak currents were between 170 kA and 201 kA, were directed at the third aeroshell. The intended peak current for all shots was 200 kA; the variations in peak current were the result of minor differences in the operation of the simulator. There was no visible damage to the aluminum substrate or to the carbon phenolic, except for some roughening of the surface, after any of the shots.

None of the 50-kA peak-current shots produced any damage to the carbon phenolic, other than roughening of the surface, or to the aluminum substrate. Damage to the carbon phenolic was observed after one of the six 100-kA peak-current shots, and buckling of the aluminum substrate was observed after another shot in this series. Severe damage to the aeroshell was observed after 6 out of 23 shots for which the peak current was at least 170 kA.

None of the 50-kA shots, 33% of the 100-kA shots, and 26% of the greater than 170-kA shots produced damage. However, the data are too sparse to support the conclusion that strokes with peak currents in the 100-kA range were more damaging, or at least as damaging, as those with larger peak currents. Furthermore, when shots with peak currents of 170 kA or more produced damage, the damage was more severe than that produced by shots for which the peak current was in the 100-kA range. Also, only those shots with the higher peak currents produced shrapnel.

Multiple Return Strokes

The lightning flash of negative cloud-to-ground lightning often consists of many strokes. The separation between strokes ranges from microseconds to hundreds of milliseconds. Multiple return strokes are less common in positive cloud-to-ground lightning flashes. The lightning simulator could have been configured to produce an initial stroke and a second stroke. Although such shots were considered at the beginning of the work, they were abandoned when framing camera records of aluminum flier motion became the primary objective of the experiments; it would have been impractical to synchronize the camera with two shots from the simulator. The minimum time between discharges from the two generators was ~60 ms, while the framing camera record covered less than 2 ms. The use of two framing cameras was not considered.

Attachment Point and Damage

The attachment point for shot N3438 was near the front of the second aeroshell. As shown in Figure 17, after the shot, there was significant damage to the front edge of the carbon phenolic. There was no visible damage to the aluminum substrate. Buckling of the aluminum substrate was the most common form of damage observed after shots that attached in the aft one-half of zone I or anywhere in zone II. In some cases, the aluminum was torn as well as buckled. Such damage is shown in Figure 13.

Pieces of aluminum were torn from the substrate after two shots that attached in the aft part of zone III. Two such pieces that were torn away during shot N3420 are shown in Figure 15. The place from which these two pieces were torn was almost directly under the attachment point at location IIIA-3. As shown in Figure 14, this place was a few inches forward of a mounting ring. Similar damage, and the production of aluminum shrapnel occurred after shot N3444, which attached to the second aeroshell at location IIIB-3. Location IIIB-3 was selected because of the way in which the shot that attached at IIIA-3 in the first aeroshell produced the shrapnel. It was thought that the region of thick aluminum aft of the attachment point limited the extent of buckling; therefore, if the aluminum could not buckle to dissipate energy from the lightning stroke, the production of shrapnel was likely. This thinking was the basis for the selection of attachment points on the third aeroshell. Remember that the primary objective of the experiments on the third aeroshell was framing camera records from which shrapnel velocity could be determined. Five shots were directed at the selected attachment points. Not so much as a dimple in the aluminum was observed after any of the shots. Damage to the radar windows was observed frequently after shots that attached in zones III and IV.

Velocity of the Aluminum

The primary purpose of the tests on the second and third aeroshell was to obtain photographic records from which the velocity of aluminum pieces torn from the substrate could be determined. Unfortunately, only shot N3444 yielded any usable records. A photograph of the damage produced by the shot is shown in Figure 17, and the framing camera records are shown in Figures 19 and 20. Although a piece of aluminum was torn from the substrate, the framing camera did not capture the motion of this piece. As discussed in the Results Section, the photographic records can be used to bound the time interval over which deformation occurred to between 87.9 μ s and 211 μ s. These numbers and the distances that the tips of the tears moved can be used to calculate lower and upper bounds for the average velocity of the tips. The resulting lower bound is 490 feet per second and the upper bound is 1660 feet per second. A method to infer a velocity for the aluminum fliers from these velocities has not been determined.

Differences in the Responses of the Aeroshells

More damage was observed after shots to the first aeroshell than after shots to the second or third aeroshells. It is unknown whether the storage or handling of the aeroshells would cause the observed differences.

Return Current Connection

The connection of the return-current conductors strongly influenced the path taken by electrical current as it flowed from the attachment point back to the simulator. When the BTA connection was used, current had to flow through the adhesive layer to the aluminum layer. Although current could have arced from the edge of the carbon phenolic to the underlying aluminum, there was no evidence that such arcing occurred. Most of the damage observed occurred after shots for which the BTA connection was used. No damage was observed after the three shots for which the BTAR connection was used. After these shots there was evidence of arcing between the aft end of the phenolic material and the front surface of the ring. The evidence consisted of pits in the ring. Damage was seen after two of the four shots for which the SOC connection was used. The damage was unexpected because current did not have to flow through the adhesive and the aluminum substrate. The SOC connection was designed to simulate the path-to-ground of lightning current on an aeroshell that was oriented so only part of the heat shield touched the ground. The results show that damage could occur to an aeroshell in such an orientation. Only one test was conducted with the CP connection; no damage was observed after the test.

Mechanism of Damage

The buckling and tearing of the aluminum is most likely caused by a build up of high-pressure gas between the aluminum and the carbon phenolic. The aluminum buckles and tears because it is weaker than the filament-wound carbon phenolic material. The gas probably arises from vaporization of the adhesive that is between the two materials and from vaporization of the binder in the carbon phenolic.

Response if the Aeroshell Were Not Empty

Because all of the tests were conducted on empty aeroshells, nothing prevented the inward movement of the aluminum. If a test aeroshell had contained a warhead, parts of the warhead might have prevented such movement. However, in the Mk12/W62 and Mk12A/W78 nuclear weapons, there are relatively large regions over which the aluminum could move inward. Such movement was seen in a test conducted by Fisher *et al.* on an Mk12A aeroshell that contained a mock up of the W78 warhead.¹²

Implications for Nuclear Explosive Safety

The experiments have shown that lightning can breach the exclusion region around a W62 warhead in an unexpected way. About 25% of the time, the aluminum substrate was severely damaged when an Mk12 aeroshell was subjected to a simulated lightning stroke for which the peak current was at least 170 kA. It seems reasonable to conclude that natural lightning strokes with equally large peak currents would cause similar damage. Less than a few per cent of all lightning strokes have peak currents that exceed 170 kA. Because of the way it is stored and deployed, the Mk12/W62 nuclear weapon normally is not exposed to lightning. However, it could be exposed after an accident.

If an Mk12/W62 were hit by a lightning stroke with high-peak current, the carbon phenolic and aluminum substrate might be damaged, and one or more pieces of aluminum shrapnel might be produced. A hole through both the heat shield and the aluminum would represent a serious breach of the energy exclusion region around the nuclear explosive. Electrical energy from a subsequent lightning stroke, or from another source, could pass through such a hole. Fortunately, the experimental results show that severe damage to both the carbon phenolic and aluminum was much less likely than damage to the aluminum. In particular, both materials were severely damaged after only one of twenty three high-peak-current shots, whereas the aluminum was severely damaged after six of the shots.

The fact that the carbon phenolic often suffered much less damage than the aluminum substrate has the following disturbing implication. An Mk12/W62 that appears to have suffered little damage after being struck by lightning could, in fact, have suffered extensive damage. Explosive ordnance disposal personnel should be aware of this possibility.

The experiments did not show that the velocities of the pieces of aluminum that were torn from the substrates were below the velocity at which direct initiation of the high explosive would be possible. Hence, the possibility of direct initiation by such pieces cannot be rejected.

After a simulated lightning discharge to an Mk12A aeroshell that contained a mock up of the W78 warhead, it was found that the aluminum had been torn into sharp petals. The damage to the aluminum was very similar to that shown in Figure 13.¹³ Furthermore, it was found that an electrical cable had been cut directly under the damaged area. Detailed failure mode analysis led to the conclusion that the cable had been cut by one of the aluminum petals. If this conclusion is correct, sometime during the evolution of the damage, there was metallic connection between the substrate and the conductors in the cable. Electrical current from the simulated lightning stroke might have flowed through this connection. Tests to evaluate the likelihood and consequences of such current flow have been planned.

The Importance of Experiments

The experiments, which required a large lightning simulator that is expensive to maintain and operate, led to the observation of totally unexpected phenomena. It is unlikely that any amount of computer simulation would have led anyone to predict the damage that was observed. The observation of a new phenomena emphasizes the importance of experiments in which full-scale hardware is exposed to realistic threats.

Summary and Conclusions

Electrical discharges from a lightning simulator were directed at Mk12 aeroshells. Damage to an aeroshell was observed after 2 out of 6 shots for which the peak current was approximately 100 kA, and severe damage was observed after 6 out of 23 shots for which the peak current was at least 170 kA. In most instances, the damage to the aluminum substrate was more severe than the damage to the carbon-

phenolic heat shield. Only one discharge produced an opening completely through the heat shield and the aluminum substrate. Damage is most likely due to the production and rapid heating of gases as the lightning current flows through the carbon phenolic and the adhesive. Buckling and tearing of the aluminum substrate was more common than damage to the carbon phenolic because the aluminum was the weaker material.

Because the output of the lightning simulator resembles, with high fidelity, natural lightning, it is concluded that natural lightning strokes could produce the same damage as was produced by the discharges from the simulator. Hence, the experiments have shown an unexpected damage mechanism in a lightning environment. It is concluded from the experimental results that a lightning stroke with very high peak current could, by itself, produce an opening in an Mk12 aeroshell. Because the aeroshell is part of the nuclear explosive safety exclusion region for the Mk12/W62 nuclear weapon, an opening would significantly reduce the safety of the weapon. The experiments showed that lightning strokes could also produce aluminum shrapnel inside the aeroshell. Unfortunately, it was not possible to determine the velocity of the aluminum pieces.

The use of actual aeroshells and of electrical discharges that closely resembled lightning led to the observation of unexpected damage. It is unlikely that this damage would have been predicted by any form of computer simulation.

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