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August 1991

U.S.S. IOWA EXPLOSION

Sandia National Laboratories' Final Technical Report

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GAO

United States
General Accounting Office
Washington, D.C. 20548

National Security and
International Affairs Division

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August 28, 1991

The Honorable Sam Nunn
Chairman, Committee on
Armed Services
United States Senate

The Honorable Howard M. Metzenbaum
United States Senate

The Honorable Mary Rose Oakar
House of Representatives

As part of your broader requests concerning the April 19, 1989, explosion aboard the U.S.S. Iowa and other battleship issues, you asked that we assess the Navy's technical investigation of the explosion. Because of the complex nature of that investigation, we sought the assistance of the Department of Energy's Sandia National Laboratories.

We discussed Sandia's preliminary findings in our report BATTLESHIPS: Issues Arising From the Explosion Aboard the U.S.S. Iowa (GAO/NSIAD-90-4, Jan. 29, 1991). We are providing Sandia's final report as a supplement to our earlier report.

As arranged with your offices, unless you publicly announce its contents earlier, we plan no further distribution of this supplement until 30 days after its issue date. At that time, we will send copies to interested committees and other Members of Congress; the Secretaries of Defense and the Navy; and the Director, Office of Management and Budget. Copies will also be made available to other parties upon request.

Please contact Martin M Ferber, Director, Navy Issues, at (202) 275-6504 if you or your staff have any questions concerning this report.

Frank C Conahan

Frank C. Conahan
Assistant Comptroller General

FINAL REPORT

SANDIA NATIONAL LABORATORIES

REVIEW OF THE USS IOWA INCIDENT

AUGUST 1991

Prepared by Sandia National Laboratories
Albuquerque, NM 87185 and Livermore, CA 94550
for the US Department of Energy
under Contract DE-AC04-76DP00789

CONTENTS

	Page No.
Glossary	iii
USS IOWA Investigation Team	v
Introduction	1
Executive Summary	3
Introduction	3
Foreign Materials	4
Overram of Powder Bags	7
Initiation Sensitivity	9
Summary	11
Recommendations	12
Acknowledgments	13
Materials Characterization	14
Foreign Materials	14
Alternate Sources	14
Iron Fibers (Steel Wool)	15
Calcium (Ca) and Chlorine (Cl)	21
Glycols	24
PE-PET	28
Particulate Debris	29
Summary	29
Heat Transfer to "Foreign Material" Fibers	31
Impact Ignition Studies	34
Introduction	34
Subscale Experiments	35
Full-Scale Experiments	37
Statistical Analysis of Total Data Base	39
Trim-Pellet Statistics	45
Conclusion	48

i

CONTENTS (continued)

Explosive Materials Characterization	49
Introduction	49
Propellant Chemical Stabilizer Analysis	49
Chemical and Compatibility Studies	49
Sensitivity Testing	50
Impact	50
Thermal	50
Electrostatic Discharge (ESD)	51
Shock	52
Summary	52
Analytical Modeling	53
Summary	53
Speed Determination Powder Bag Compression	54
Gouge Analysis	54
Powder Bag Compression Modeling	54
Powder Bag Modeling Conclusions	57
Rammerhead Buffer Bore Markings	57
Buffer Mark Conclusions	63
Overram Speed from Rammer-Control Linkage Position	63
USN/BRL Scenario	63
SNL Rammerman Seat Motion Study	69
Gas Flow Analysis	69
Structural Analysis of Seat Motion	75
Geometry Considerations "As-Built"	79
Regarding Motion of the Rammerman's Seat Conclusions	80
References	81
Vitae	82

GLOSSARY

A	ampere
AES, Auger	Auger electron spectroscopy
AFFF	aqueous fire fighting foam
ARC	accelerating-rate calorimetry
A/sec.	amperes per second
BRL	Ballistic Research Laboratory
C	centigrade
Ca	calcium
Cl	chlorine
cm.	centimeters
DMC	Distinct Motion Code
DOE	Department of Energy
DPA	diphenylamine
EDPM	elemental distribution photomicrograph
EMPS	electron microprobe analysis
ESD	electrostatic discharge
ft.	foot
FTIR	Fourier transform infrared spectroscopy
ft.-lb.	foot-pound
ft./sec.	foot per second
GAO	General Accounting Office
GC/MS	gas chromatography/mass spectroscopy
ICP-AES	inductively coupled plasma-atomic emission spectroscopy
IG-1	IOWA Turret 2 center gun
IG-2,3	IOWA Turret 2 left and right gun
in.	inch
J	joule
kg.	kilogram
km.	kilometer
lb.	pound
LC	liquid chromatography
mg.	milligram
mil.	0.001 inch (thousandths of one inch)
mJ.	milijoule
MPa	mega Pascal
MRE	meals-ready-to-eat
m/sec.	meters per second
msec.	millisecond
n	number of analysis
NC	nitrocellulose
NOS	Naval Ordnance Station
NNSY	Norfolk Naval Shipyard
NSWC	Naval Surface Warfare Center (Dahlgren)
NWSC	Naval Weapons Support Center (Crane)
P-GC/MS	pyrolysis gas chromatography/mass spectroscopy

iii

GLOSSARY (continued)

PE	polyethylene
PET or PE-PET	polyethylene terephthalate
psi	pounds per square inch
R	range
sec.	second
SEM	scanning electron microscopy
SNL	Sandia National Laboratories
USN	United States Navy
VISAR	velocity interferometer system for any reflector
wt.%	weight percent
WWII	World War II

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See Vitae, page 83 v

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See Vitae, page 83 vi

Introduction

On April 19, 1989, an explosion occurred on the battleship USS IOWA in the open breech of a 16-in. gun, killing 47 crew members. In its investigation of the explosion, the US Navy (USN) concluded there was evidence of "foreign material" in the cannelure of the rotating band that spins the projectile on firing. In this incident, the projectile was driven a short distance up the barrel by the open-breech explosion, but remained in the gun.

From subsequent open-breech tests the USN concluded that the "foreign material" was replicated only when a chemical ignition device was present. The USN proposed that the explosion was initiated by a chemical ignition device consisting of calcium hypochlorite, brake fluid (or a similar material) and steel wool, and that it was placed by a crewman between the bags of propellant that were rammed into the gun. The USN report stated that, "the residue found in the IOWA rotating band cannot be duplicated by simple contamination of the gun chamber with steel wool and other chemicals normally present in a gun firing."

In late 1989, the General Accounting Office (GAO) asked Sandia National Laboratories (SNL) to examine the adequacy of certain aspects of the USS IOWA investigation. On November 22, 1989, Dr. Albert Narath, President of SNL, agreed that Sandia would consult with the GAO and undertake a technical study, pending Department of Energy (DOE) authorization. Dr. Roger L. Hagengruber, Vice President of Defense Programs, SNL, was assigned responsibility for managerial oversight for this activity and for coordination with the DOE. Dr. Richard L. Schwoebel, Director of Systems Evaluation, SNL, was assigned the technical lead. SNL was asked to: 1) examine pieces of rotating band and the 16-in. projectile from the gun for evidence of "foreign material" that might be related to a chemical ignition device; 2) test gun powder from the USS IOWA's magazine and from the same lot obtained elsewhere to ascertain the stability of the material; and 3) review the scope and methodology of the USN's technical investigation and examine other physical evidence that the USN believed supported its conclusions about the probable cause of the explosion. SNL first reported its findings at a Senate Armed Services Committee hearing on May 25, 1990, and released its initial report, Sandia National Laboratories' Review of the USS IOWA Incident, June 1990.

The initial Sandia National Laboratories' report concluded: 1) the presence of a chemical ignition device could neither be proved nor disproved, although all the "foreign materials" except the steel wool fibers were shown to be normal components of battleship turrets; 2) the stability of both the propellant and black powder was within acceptable limits and there was only a remote possibility the black powder could have been initiated by friction, electrostatic discharge or electromagnetic radiation; 3) the powder bags were overrammed against the projectile and the extent of the overram was determined; and 4) that a potentially important factor in the explosion was a previously unrecognized sensitivity of the powder bag train to overram when there is a reduced number of pellets in the trim layer(s) of the powder bags. SNL experiments indicated that a reduced number of trim layer pellets lying next to the black powder pouch could result in an explosion if overrammed, and that the probability of an explosion increased with the speed of the overram. SNL recommended that these experiments be extended to actual 16-in. gun conditions to establish the validity of this ignition mechanism.

At the conclusion of the hearing before the Senate Armed Services Committee, SNL was asked to continue its work and to participate with the USN in the reopened investigation of the incident.

This final report documents SNL findings of work performed since May 25, 1990. Detailed documentation of work described here will be found in SNL reports that were in preparation at the time this report was written.

Executive Summary

Introduction

Sandia National Laboratories' continued investigation of the explosion in the center gun in Turret 2 of the USS IOWA on April 19, 1989, has had three important thrusts.

The first has been to establish reference measurements for "foreign materials" found on the rotating band of the projectile in the center gun. These measurements were used to examine the US Navy's conclusion that these materials were the fingerprint of a chemical ignition device placed between the powder bags that were rammed into the breech of the gun.

The second has been to examine impact initiation of propellant caused by the fracture of pellets adjacent to a black powder pouch. These analyses were used to reexamine the USN's conclusion that "impact and compression of the bag charges were not contributing factors in the IOWA incident."

The third has been to further examine the overram that occurred in the center gun. This included studies of rammer motion as it was blown out of the breech, internal markings produced by the buffer in the rammerhead, powder bag compression and rammer handle motion. The results of these analyses were relevant to determining the extent of powder bag compression against the base of the projectile and helping to establish if a static overram occurred. In addition, analyses of the displacement of the rammerman's seat have been used to better understand damage to the rammer handle quadrant.

The studies reported here have drawn heavily on the extensive USN investigation of the incident, and that work served as a valuable basis on which to extend certain elements of the SNL investigation. The SNL investigation did not include, for example, exhaustive studies of the operating mechanisms in the gun room such as the rammer, powder hoist and powder door. These mechanisms were found by the USN to be in proper operating condition at the time of the explosion and were apparently not associated with the cause of the explosion. An unexplained observation related to these mechanisms was the unlowered position of the powder car at the time of the explosion. This observation will be briefly discussed in the conclusion of this section of the report.

Foreign Materials

Further studies have shown that all of the so-called "foreign materials" found in the cannelure of the rotating band of the projectile in the center gun of Turret 2 are also found in the forward grooves of the projectile, i.e., in a region protected from the explosion. These materials are also found to varying degrees in the same regions of the projectiles that had been rammed into the left and right guns of Turret 2 prior to the explosion in the center gun. That is, the presence of "foreign materials" identified by the USN is not a unique indicator that the hypothetical chemical ignition device was present in the center gun.

1. The hypothetical chemical ignition device was postulated by the USN to be the source of iron fibers found on the rotating band of the center gun projectile. However, steel wool has been found in key locations on all three of the projectiles removed from the 16-in. guns of Turret 2.

2. Steel wool fibers found on the rotating bands of these projectiles cannot be distinguished from each other based on their morphologies. Size distributions of fibers found in various locations are also statistically indistinguishable. Compositional details of the steel wool indicate that it came from more than one source. That is, the steel wool apparently came from more than one pad of steel wool, not from a single pad as would be expected had a chemical ignition device been present.

3. Iron fibers found in the forward grooves of the rotating band of the center gun projectile are indistinguishable from fibers found in the cannelure. Fibers in the grooves could not have resulted from explosion products because the grooves were protected from the explosion by the seal formed by the rotating band fin. It is also unlikely that steel wool in the forward grooves could have resulted from contamination following the explosion because the grooves were sealed when the projectile was forced forward in the barrel.

   Conclusion: Steel wool was found in the cannelures and forward grooves of the rotating bands of all three projectiles in the gun rooms of Turret 2. The steel wool in the cannelure of the projectile in the center gun was indistinguishable from that found in the forward grooves, and was also indistinguishable from that found on the other two projectiles. The observation of iron fibers in the rotating band of the projectile from the center gun is not a definitive indicator of the presence of the hypothetical chemical ignition device.

4. Ballistics modeling indicates that iron fibers of the size found in the cannelure would have been physically altered by the high-temperature explosion. Had any fibers been deposited in the cannelure, it is expected that they would have had a melted appearance and exhibited rounded surface features consistent with exposure to temperatures in excess of the melting point. None of the fibers recovered from the cannelure of the center gun projectile had such an appearance. Ballistics modeling also indicates that the flow of rapidly expanding gases from the point of ignition would tend to carry fibers away from the cannelure. This modeling is consistent with the observation that very few steel wool fibers were found in the rotating bands of projectiles used in full-scale tests in which a chemical ignition device was used to initiate an explosion.

   Conclusion: The physical appearance of fibers found in the cannelure is not consistent with that expected of fibers exposed to temperatures above the melting point. The relative absence of steel wool in the cannelure following full scale field tests using a chemical ignition device to initiate an explosion is consistent with ballistics modeling that predicts the general flow of gases away from the cannelure. These and other results regarding fibers suggest that the steel wool in the rotating band of the center gun projectile was present before the explosion and is unrelated to its cause.

5. The presence of an encrusted iron fiber in the cannelure was emphasized by the USN as being a unique signature of the presence of a chemical ignition device based on their field tests. USN measurements of higher-than-normal quantities of calcium on a single encrusted fiber were not corroborated because that fiber and any similar ones were not available for analysis by SNL.

   Conclusion: The encrusted fiber described in the USN report appears to be one of a kind and is not representative of the many other fibers found in the cannelure.

6. With the exception of the single encrusted fiber, all measurements of the surface quantities of chlorine and calcium on iron fibers taken from the cannelure of the center gun projectile are comparable. These quantities are similar to the surface quantities of these elements observed on iron fibers from the projectiles that were in the left and right guns of Turret 2. These quantities are also similar to those found on fibers recovered from the forward grooves of the rotating band from the center gun projectile, i.e.,

fibers that were isolated from the explosion. Substantially higher quantities of chlorine were measured on iron fiber and cannelure surfaces of projectiles from field tests using chemical ignition devices than on fibers taken from the cannelure of the center gun projectile.

7. Debris and grease from the forward grooves and cannelures of projectiles from the left and right guns of Turret 2 contain significant levels of calcium and chlorine. These levels are similar to the levels found in the debris taken from the cannelure of the center gun projectile.

   Conclusion: The observed quantities of chlorine and calcium on iron fibers and in debris from the cannelure of the center gun projectile are similar to the quantities of these elements on iron fibers and in debris found elsewhere in the turret. The observed quantities of calcium and chlorine are not definitive indicators that the hypothetical chemical ignition device proposed by the USN was present in the center gun. If a device of this kind had been present, substantially higher quantities of chlorine on surfaces of fibers in the cannelure would have been expected based on USN field tests.

8. The USN found glycols in the cannelure and concluded that they were constituents of brake fluid or a similar material that may have been used in the hypothetical chemical ignition device. It has been found that these same glycols are present in Break-Free™, a liquid routinely used to maintain the 16-in. guns on the USS IOWA.

9. A large quantity of Break-Free™ was used to help remove the projectile from the center gun following the incident. Break-Free™ apparently leaked into the cannelure, contaminating it with several of the constituents that the USN concluded came from the hypothetical chemical ignition device.

10. These glycols are also constituents of grease residues found on other projectiles from Turret 2.

    Conclusion: The glycols are constituents of Break-Free™ used in the routine maintenance of the guns, and are also found in grease residues on the projectiles. A large quantity of Break-Free™ was used to help free the projectile and apparently leaked into the cannelure. The presence of these glycols does not demonstrate that the hypothetical chemical ignition device was present.

11. The USN postulated that a single PE-PET fragment, believed to have been found in the projectile's cannelure, came from a plastic food bag that contained the hypothetical chemical ignition device. It has been found that the sampling procedure used by the USN did not document that the fragment came from the cannelure of the projectile. Further study also shows that Dacron™ fibers covered with Break-Free™ can produce a P-GC/MS spectrum indistinguishable from that of the PE-PET fragment identified by the USN. Such a fragment could have come from several sources, including the Dacron™ bore brush sock used to clean the gun.

    Conclusion: The USN did not document that the PE-PET fragment came from the cannelure of the projectile. The PE-PET fragment does not support the presence of the hypothetical chemical ignition device.

12. SNL found inorganic particulate materials in debris from the forward grooves of projectiles from the center gun and one other gun in Turret 2. These particulates were similar to many of the materials identified in the cannelure of the center gun projectile and included paint chips, sand and/or glass, metal fragments, iron fibers, and high-temperature graphite.

13. The high-temperature graphite particles found in the cannelure and forward grooves of the center gun projectile and the forward grooves of IG-2, are indistinguishable from graphite inclusions in the cast iron projectiles.

    Conclusion: Similarities in the inorganic particulate found in both the forward grooves and the cannelure of the projectile from the center gun also suggest that this debris, along with the steel wool, was present before the explosion. The observation of inorganic particulate does not support the presence of the hypothetical chemical ignition device.

Overram of Powder Bags

In normal operation, the powder bags are pushed slowly with the rammer (1 to 2 ft./sec.) until the rear of the last bag is just inside the breech of the gun. For a five-bag charge, such as was used at the time of the incident, this leaves a space of at least 17 in. between the front of the bags and the base of the projectile. In the USS IOWA incident, it was found that the powder bags were overrammed so that there was no space between the bags and the projectile.

1. The position of the rammerhead at the time of the explosion was determined by correlating gouges in the spanning tray with specific links in the rammer chain. The overram was determined to be 45.75 $\pm$ 0.1 in. beyond the breech face if there was no compression of the rammerhead buffer, or 48.25 $\pm$ 0.1 in. if there was full compression of the buffer.

   Conclusion: The extent of the overram was approximately 5.5 in. beyond that determined by the USN, and compressed the five powder bags approximately 1.1 in. against the base of the projectile. A substantial overram of the powder bags occurred in the center gun.

2. The USN observed after the explosion that the rammer handle was in a position corresponding to a ram speed of approximately 1.7 ft./sec. and concluded that ramming occurred at normal speed. However, possible collision of the rammerman's seat with the rammer handle and transients introduced into the rammer system by the explosion could have produced substantial movement, resulting in virtually any position of the rammer handle after the explosion.

   Conclusion: The position of the rammer handle following the open breech explosion cannot be definitively related to the ram speed prior to the explosion.

3. The USN has suggested that ramming took place at slow speed based on marking of the quadrant by impact of the rammerman's seat. SNL analyses of the rammerman's seat motion shows that the first impact of the seat occurs with the aft quadrant mounting pad. This appears to be supported by a photograph of this region of the quadrant mounting pad. In addition, these analyses show that the aft leg of the seat contacts the rammer control lever. Both of these contacts occur before the front of the seat has rotated sufficiently to cause impact with and marking of the quadrant.

   Conclusion: The marking of the quadrant is not a definitive indicator of ramming speed because the quadrant could have been dislodged from the bulkhead by the impact of the seat. In addition, the rammer lever could also have been moved prior to the marking of the quadrant.

4. Measurements by the USN have determined the average uncompressed length of five powder bags and the nominal projectile seating distance. A refined dynamic model by SNL has been used to show that it is impossible to

establish the speed of the overram because of the large variability in the length of the powder bags.

Conclusion: The uncertainties of powder train length and projectile seating distance make it impossible to determine the rammer speed from the compression of the powder bags and the gouges in the spanning tray.

5. The SNL interpretation of gouges on internal surfaces of the buffer in the rammerhead is that the buffer was 1/4 in. short of full compression when the open breech explosion occurred. That is, the buffer was not fully compressed at the time of the explosion. However, it was observed in one of the open breech field tests that the statically held rammerhead moved forward after ignition but prior to the blast.

   Conclusion: The buffer marks cannot be used to conclusively determine the speed of the overram.

Initiation Sensitivity

1. The propellant and black powder were both found to be within the acceptable range of stability. Stabilizer levels in propellant pellets were also within acceptable limits based on USN requirements. SNL evaluations indicate that the possibility that the explosion could have been caused by electrostatic discharge, electromagnetic radiation, and thermal or friction effects is negligible.

   Conclusion: The age and stability of the propellant and black powder were not factors in this explosion.

2. A powder bag is brought to the correct weight by placing several pellets on their side in a trim layer at the front of a powder bag. SNL postulated from reduced-scale tests that powder bags in 16-in. guns could be initiated by a high-speed overram, a process that can fracture pellets in the trim layer of one bag, igniting the black powder pouch of the adjacent powder bag. The USN confirmed this effect in full-scale tests.

   Conclusion: Trim layer pellets fractured by a high-speed overram can ignite the black powder of the adjacent powder bag and lead to an explosion.

3. It was found that trim layers containing one to approximately twelve pellets are more sensitive to ignition in an overram than trim layers containing larger numbers. The lot of D846 propellant aboard the USS IOWA at the time of the explosion included bags with trim layers containing from zero to sixty-three pellets. The distribution of the trim layer pellet count was such that, in five bags randomly selected from this lot, the probability was 0.166 (one in six) that one or more of the rear four bags would contain from one to twelve pellets in the trim layer.

   Conclusion: The probability was 16.6 percent (one in six) of selecting a group of five-bag charges from the propellant lot aboard the USS IOWA that was sensitive to ignition by overram.

4. The probability that an overram at 14 ft./sec. will initiate a five-bag powder train that includes at least one bag with one to twelve trim pellets is nominally 0.087 (one in eleven). Given the statistical uncertainties, this probability could be as high as 0.39 (approximately one in three). These probabilities were calculated using data provided by the USN from full-scale studies in a gun simulator and also data from the other (approximately 600) tests.

   Conclusion: The probability of initiating a five-bag powder train with at least one bag with one to twelve trim pellets is nominally 0.087 (one in eleven) in a high-speed overram.

5. The probability of an explosion in a high-speed overram is the product of the probability of having a sensitive combination of powder bags (that is, at least one powder bag with one to twelve trim pellets next to a black powder pouch) and the probability of initiating such a combination.

   Conclusion: The probability of an explosion in a high-speed overram was nominally 0.0144 (one in seventy) for five powder bags randomly selected from the lot aboard the USS IOWA at the time of the explosion. Given the statistical uncertainties, the probability could be as high as 0.0639 (one in sixteen).

6. There is another sensitive configuration of pellets that does not involve the trim layer. Initiation occurred in one of five full-scale tests at high ramming speeds when a single pellet was misplaced at the rear of the bag adjacent to the black powder pouch. Subsequent examination of all the D846 propellant bags showed that 3.39 percent of them had a misplaced pellet at the rear of

the bag. There may be even more sensitive configurations that can lead to initiation of an open-breech explosion in an overram situation.

Conclusion: The presence of a reduced number of pellets in a trim layer is only one configuration that can lead to an explosion in an overram. At least one other configuration, the single misplaced pellet at the rear of the bag, can also lead to an explosion. The probability of explosion with this and other configurations has not been fully explored.

Summary

The following summary statements of the SNL investigation are presented with respect to the USN conclusion that a chemical ignition device was placed between the powder bags by the gun captain and then initiated by a static overram.

The USN reported that "the residue found in the IOWA rotating band cannot be duplicated by simple contamination of the gun chamber with steel wool and other chemicals normally present in a gun firing." This included the presence of calcium, chlorine, various glycols, inorganic particulate, and steel wool fibers found in the cannelure of the center gun projectile and associated by the USN with a hypothetical chemical ignition device. Studies at SNL show that the foreign materials identified by the USN in the cannelure of the projectile of the center gun are indistinguishable from those found in other key locations within Turret 2. Chemical constituents and steel wool fibers indistinguishable from those in the cannelure were found in the forward grooves of the rotating band of the projectile in the center gun; that is, in a region of the cannelure that was isolated from the explosion. In addition, the same chemical constituents and steel wool fibers were also found in the cannelures and forward grooves of the rotating bands of projectiles that were in the left and right guns of this turret. These fibers were also indistinguishable from those in the cannelure of the center gun projectile. These and other facts suggest that the fibers and the various chemical constituents found by the USN on the center gun projectile are unrelated to the explosion.

A substantial overram of the powder bags occurred for reasons that have not been determined. That is, the powder bags were forced against the base of the projectile by the rammer. This was determined from an analysis of the position of gouges on the spanning tray. Based on the observation that the buffer in the rammerhead was apparently not fully compressed at the time of the explosion, the overram may have occurred at a higher-than-normal-speed. A further observation that tends to support the concept of a higher-than-normal-speed overram was the unlowered position of the powder car. The normal procedure aboard the USS IOWA was to lower the powder car immediately after closing the powder door. If the ramming of the powder bags occurred at high speed, the upper powder hoist operator may not have had time to begin the lowering of the car. If the ramming occurred at low speed, the operator would have had approximately 20 to 30 seconds to begin this process.

After the explosion, the rammer control handle was found in the 1.7 ft./sec. position. However, SNL analyses show that the position of the handle and damage to the quadrant are not definitive indicators of the ramming speed.

It has been demonstrated in a full-scale simulator that a high-speed overram can initiate powder bags and result in an open-breech explosion. This previously unrecognized safety problem with 16-in. guns occurs when hot particles from fractured propellant pellets ignite nearby black powder. While impact initiation cannot be proven to have been the cause of the explosion, these results raise serious questions about the USN conclusion that "impact and compression of the bag charges were not contributing factors in the IOWA incident." Impact initiation could have been involved since a significant overram occurred.

A variety of scenarios for this incident have been explored, but they remain unproven for lack of evidence, partially due to the violence of the explosion and fire. Because of this, it may be difficult to ever fully resolve the many unknowns and develop a clear and unambiguous explanation of the events that occurred within the center gun room of Turret 2.

It is concluded that there is no explicit physical evidence that the hypothetical chemical ignition device was present in the center gun of Turret 2. It is also concluded that a high-speed overram is a possible cause of the April 19, 1989, explosion aboard the USS IOWA.

Recommendations

Following are recommendations if future operation of 16-in. guns aboard the battleships is anticipated:

1. Mechanisms for positive control of rammer speed and distance should be implemented as recommended in the interim report.

2. Various other pellet displacements, including those at the rear of the powder bags, should be explored to determine if there are additional sensitive configurations that could lead to an explosion in an overram.

The USN has already implemented an earlier recommendation that powder bags be redesigned to eliminate trim layers.

Acknowledgments

The SNL study was facilitated by the extensive cooperation of USN personnel. Of particular value were interactions and discussions with personnel at the Naval Ordnance Station, Indian Head, Maryland; the Naval Weapons Support Center, Crane, Indiana; and the Naval Surface Warfare Center, Dahlgren, Virginia. USN personnel at these and other locations supported the Sandia team throughout its investigation. Their contributions are gratefully acknowledged.

Materials Characterization

Foreign Materials

As a result of its investigation of the (April 19, 1989) explosion aboard the battleship USS IOWA, the USN concluded there was evidence that "foreign material" was present in the gun chamber of Turret 2 center gun during the USS IOWA incident. From open-breech tests, the USN concluded that the "foreign material" deposited in the cannelure of the USS IOWA projectile rotating band was replicated only when a chemical ignition device was used to initiate the tests. This chemical device incorporated calcium hypochlorite, brake fluid, and steel wool. The USN stated that "the residue found in the IOWA rotating band cannot be duplicated by simple contamination of the gun chamber with steel wool and other chemicals normally present in a gun firing."

In the initial report, Sandia National Laboratories' Review of the USS IOWA Incident, June 1990, it was concluded that the presence of a chemical ignition device could neither be proved nor disproved. Some of the "foreign materials" identified by the USN were shown to be normal constituents of a battleship turret environment and evidence for the presence of a chemical ignition device was found to be inconclusive.

Continuing studies at SNL show that the foreign materials identified by the USN in the cannelure of the projectile of the center gun are indistinguishable from materials found in other key locations in Turret 2. These materials were present in Turret 2 of the USS IOWA as part of the ship-board environment, either as a result of post-incident operations or as a result of pre-incident contamination. SNL studies show that none of these "foreign materials" can be uniquely associated with a chemical ignition device. Supporting data will be contained in a more comprehensive SNL report that is in preparation.

Alternate Sources

The conclusions in the initial SNL report of May 1990 were largely based on analyses of materials primarily from three sources: 1) background samples from gun rooms and turrets on the USS IOWA, USS NEW JERSEY, and USS WISCONSIN; 2) materials (for example, Break-Free™) from USN stores that are normally used in battleship gun rooms; and 3) materials found in or associated with the cannelure of the rotating band from the projectile recovered from the center gun of Turret 2.

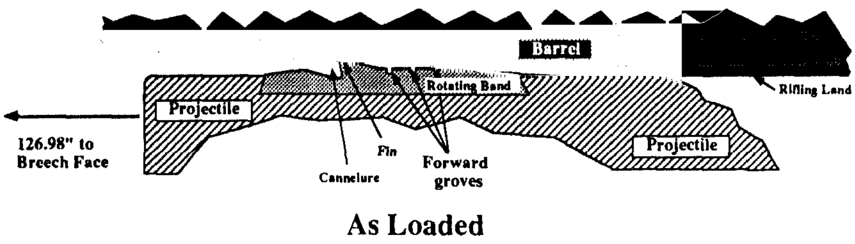
At the time of SNL's initial investigation, SNL personnel were unaware of the location of the projectiles that had been loaded in the left and right guns of Turret 2 at the time of the USS IOWA explosion. The subsequent location of these projectiles has led to studies of materials present on these projectiles and, in particular, in specific locations on their rotating bands. For clarification, a nomenclature assigned by Naval Weapons Support Center, Crane, Indiana (NWSC-Crane) to identify the Turret 2 projectiles is used: IG-1 (IOWA Gun - center, the projectile from the USS IOWA incident from which most of the "foreign materials" data and conclusions were drawn), IG-2 and IG-3 (left gun and right gun - which projectile was in which gun is not documented). These three BLP (blind loaded and plugged) projectiles were part of a group of nine known projectiles that had been reworked at a USN facility in Keyport, Washington, in 1982. The fact that three projectiles from the same rework group were loaded in the three guns of Turret 2 on April 19, 1989, suggests that they had been subjected to the same environment (i.e., contamination sources) from the time they left Keyport. The evidence recovered from these projectiles, has an important bearing on the significance of "foreign materials" found by the USN in the cannelure of IG-1.

Iron Fibers (Steel Wool)

SNL's initial investigation revealed iron fibers embedded in the rotating band cannelure of IG-1 that had the appearance and composition of steel wool. Subsequently, the cannelures and forward grooves (see Figure 1) of IG-2 and IG-3 rotating bands and the forward grooves of IG-1 have been examined. A wide variety of particulate materials, including iron fibers, were found associated with grease recovered from these areas. A photograph of some of the iron fibers found in the forward grooves of IG-2 is shown in Figure 2.

The forward grooves of IG-1 would not be contaminated by materials from an explosion in the gun chamber because of the gas seal formed by the rotating band fin. These forward grooves of IG-1 constitute a repository of background material caused by pre-incident contamination of the projectile. The forward grooves of IG-1 rotating band samples were opened by SNL and were found to contain the same material contaminants, including iron fibers, as were found in the cannelure of IG-1. The forward grooves and cannelures of IG-2 and IG-3 contained similar materials, but were not exposed to the blast because the breeches of the left and right gun were closed.

Materials Characterization



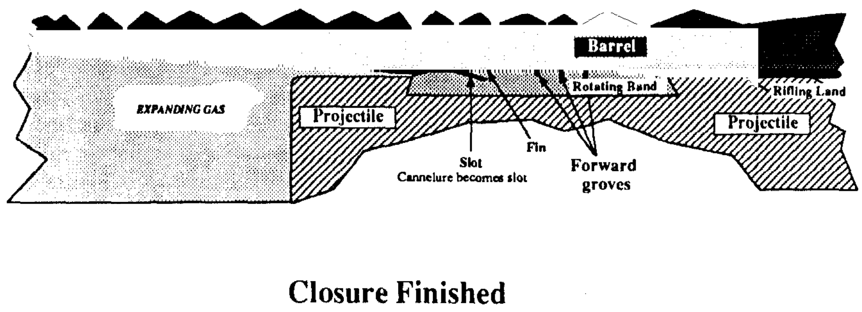


Figure 1. Schematic cross-section diagram of a 16 in. projectile rotating band.

top: as loaded
bottom: after closure of the cannelure and forward grooves

16

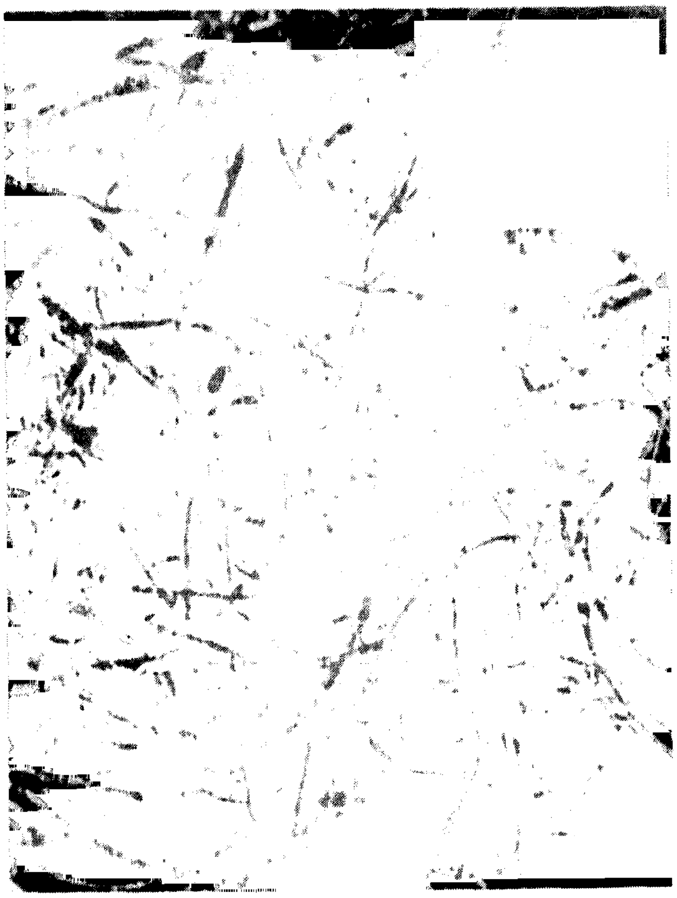


Figure 2. Iron fibers recovered from IG-2 forward grooves.

Table 1 shows the location and number of iron fibers recovered from the Turret 2 projectiles and analyzed by SNL. These are compared with the total number (thirty-seven) of fibers found in the IG-1 cannelure by SNL, NWSC-Crane, and Norfolk Naval Shipyard (NNSY).

Table 1

Iron Fibers from Turret 2 Projectile Rotating Bands

Projectile	Location	No. of iron fibers	Band Length* Sampled (in.)
IG-1	forward groove	77	12
IG-1	cannelure	37	32
IG-2	forward groove	hundreds	6
IG-2	cannelure	12	25
IG-3	forward groove	14	25
IG-3	cannelure	1	25

* The entire length (circumference) of a rotating band is 50 in., but sampling was limited either to the amount available (IG-1) or to lengths that had not been previously sampled (IG-3, IG-2 cannelure). The exception was the IG-2 forward grooves where sufficient material for analysis was obtained in 6 in. of groove length.

The iron fibers were analyzed by optical microscopy and scanning electron microscopy (SEM) to determine their morphology and size distribution, and by electron microprobe with wavelength dispersive x-ray spectroscopy to determine their bulk composition. All of the iron fibers analyzed at SNL from IG-1 forward grooves, and from IG-2 and IG-3, have the appearance, composition, and microstructure of steel wool. SNL analyses show that the concentration of manganese, the principle alloying element, varies sufficiently to indicate that the steel wool fibers found in the cannelure and forward grooves of IG-1 and IG-2 came from a source involving more than one pad of steel wool. That is, the fibers in the cannelure of the center gun projectile were not the result of a single pad of steel wool as would be expected if the hypothetical chemical initiator were present.

SNL measured the size distribution of the 77 fibers found in the forward grooves of the IG-1 projectile. These data were obtained using the same measurement and sampling techniques as were used on the IG-1 cannelure. In Figure 3, the distribution of the sizes of the fibers in the forward grooves (Figure 3b) is compared to the distribution of fiber sizes found in the IG-1 cannelure (Figure 3a). Within experimental uncertainty, these distributions are identical. Our conclusions from the fiber size data are that there is no difference in the sizes of the various fibers found in the cannelure and in the forward grooves of the IG-1 projectile.

Subsequent to this work, NWSC-Crane has examined debris from the forward grooves of IG-1 and IG-2 with a modified sampling technique and with increased magnification. This work has located fibers or fiber fragments of smaller diameters than previously found. However, size distributions that include these fibers should not be directly compared with fiber size distributions for the IG-1 cannelure, since significantly different sampling methods were used to generate that data.

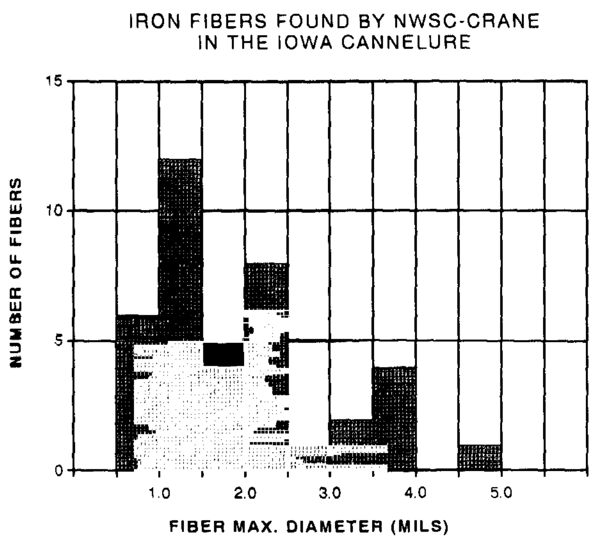


Figure 3a. Size distribution of iron fibers found in the USS IOWA cannelure by NWSC-Crane.

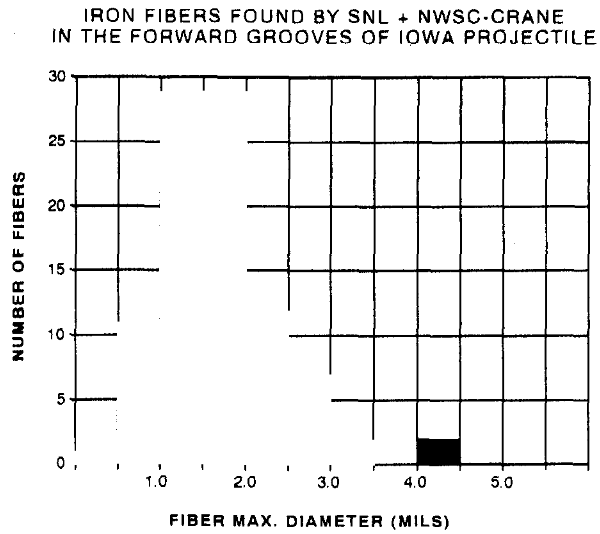


Figure 3b. Size distribution of iron fibers found in the forward grooves of USS IOWA projectile (SNL + NWSC-Crane).

The almost total absence of iron fibers in the rotating-band cannelures of the chemical-device-initiated test fires is evidence that fibers are unlikely to be deposited in the cannelure if they originate in the powder charge. This conclusion is supported by ballistics modeling (see the following section), which indicates that few iron fibers of the diameter used in the tests would survive the fireball if present in the powder charge. This conclusion is also supported by the morphology of the fibers found in the cannelure of IG-1. The fibers found in the IG-1 cannelure have sharp edges, which are attributed to the cutting process used in the manufacture of steel wool, and do not show evidence of surface melting. Based on this evidence, SNL concludes that the iron fibers found in the cannelure of IG-1 were present in the cannelure before the explosion and did not originate from a chemical ignition device.

Calcium (Ca) and Chlorine (Cl)

The initial SNL report demonstrated that small quantities of Ca and Cl are found on most metal surfaces in the turrets of the USS IOWA, including rotating-band cannelure surfaces and iron fibers from IG-1. Auger data obtained from analyses at SNL, joint analyses with NWSC-Crane, and from the original NWSC-Crane analyses all showed small quantities of Ca and Cl. The one exception was the surface analysis of a single point on a single encrusted fiber reported by NWSC-Crane, which showed high Ca concentration. This spectrum was atypical because it was the only one out of approximately 40 spectra recorded that showed high Ca. A number of points were analyzed along an iron fiber from the IG-1 cannelure to determine the point-to-point variation. These data indicated that the Cl concentration was always low on iron fibers from the IG-1 cannelure, but particles with high Ca concentrations could be found. Spectra obtained a few micrometers distance from these particles showed low levels of Ca. That is, significant statistical variation was observed depending on where the measurement was made. Figures 4 and 5 show a summary of Auger measurements of the concentrations of Ca and Cl on the surfaces of iron fibers from sources related to the IOWA incident. From these data, it is concluded that there is substantial variability in the concentrations of Ca on iron fibers. The "encrusted" fiber that was used by the USN to assert high Ca levels exist on the surfaces of fibers found in the IG-1 cannelure is not typical. The only examples of high Cl concentration were found on surfaces of the rotating band cannelure from chemical device tests at Dahlgren, and on an iron fiber from one of those tests.

Subsequent to SNL's initial report, additional joint experiments were performed with NWSC-Crane to analyze iron fibers for Ca and Cl. In addition, all of the Energy Dispersive Analysis (EDA) data from SNL, NNSY, and NWSC-Crane with respect to Ca and Cl on iron fibers from the IG-1 cannelure were examined, (approximately 160 spectra in all). SNL also analyzed iron fibers from IG-1 and IG-2 forward grooves using Auger electron spectroscopy and electron microprobe analysis (EMPA). These data further supported the initial results; i.e., low levels of Ca and Cl are found on all of the iron fibers. This includes the fibers from the IG-1 cannelure and the forward grooves of both IG-1 and IG-2. Again, microscopic particles with high concentrations of Ca can be found. However, when the analysis is performed on a spot just a few micrometers from the particle, low levels of Ca are observed. Elemental distribution photomicrographs (EDPM) show that these particles are not associated with Cl.

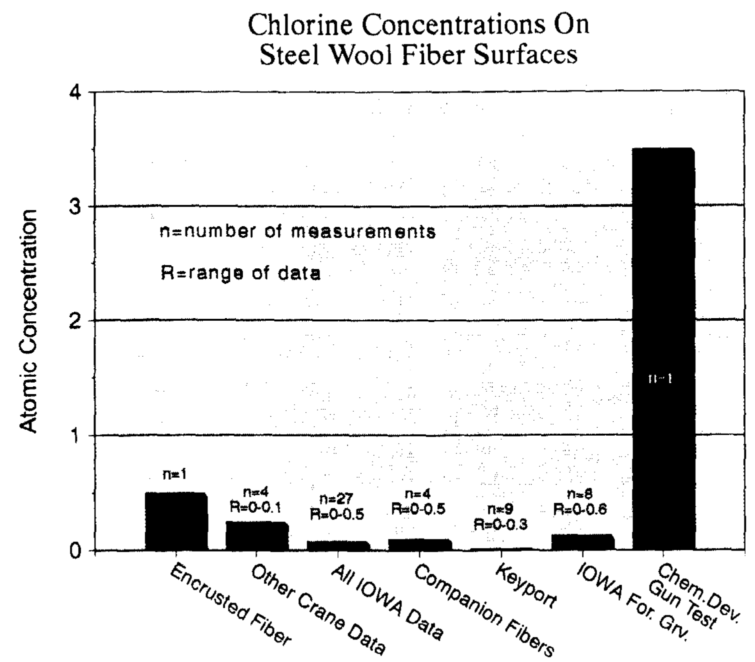


Figure 4. Calcium concentrations measured on steel wool fiber surfaces by Auger spectroscopy.

22

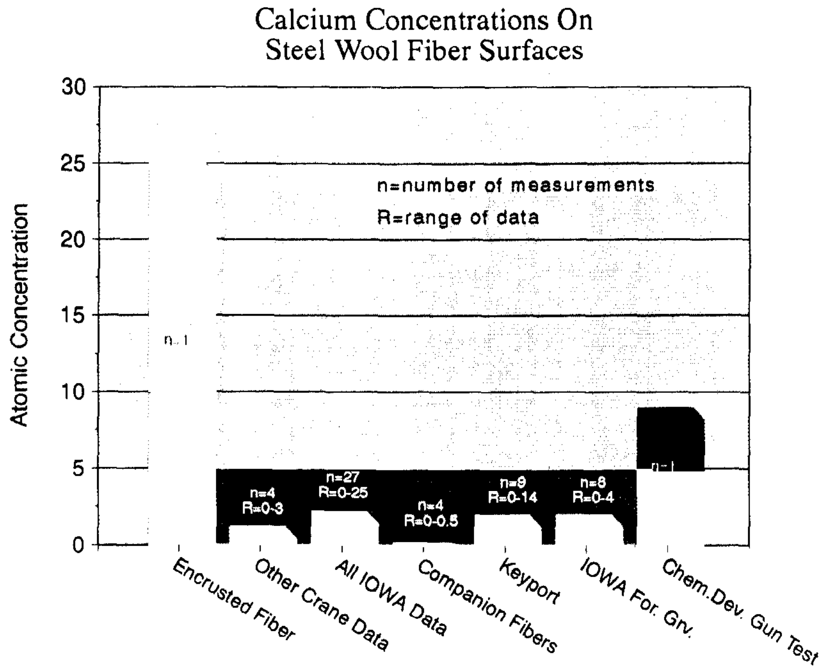


Figure 5. Chlorine concentrations measured on steel wool fiber surfaces by Auger spectroscopy.

The debris that is found associated with the iron fibers from the forward grooves of IG-1 and IG-2 has been quantitatively analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) and found to contain significant levels of Ca. These results indicate that the debris, which consists of grease and particulates, may be a source of localized high concentrations of Ca on iron fibers. The debris was also quantitatively analyzed by ion chromatography and found to contain significant levels of Cl. The results of these analyses are shown in Figures 6 for Ca and 7 for Cl. These figures also show data from debris found in the rotating band cannelure of the projectile from one of the chemical device gun tests.

These data indicate the variability of the concentrations that can be measured in this nonuniform debris. They also indicate that the levels found in the IG-1 cannelure are generally consistent with those found in the forward grooves of IG-1, and on IG-2 and IG-3 and with those found on rotating-band cannelure samples from NSWC-Dahlgren open-breech tests initiated with a chemical ignition device.

SNL concludes that highly localized surface concentrations of Ca can be found on iron fibers from the USS IOWA projectiles. Microparticles with high calcium concentrations are present both on iron fibers from the IG-1 cannelure (exposed to the explosion) as well as on iron fibers from the forward grooves of IG-1 and IG-2 (not exposed to the explosion). Thus the presence of localized concentrations of Ca on the iron fibers cannot be uniquely related to the blast environment or to a hypothetical Ca-containing chemical ignition device. In addition, SNL finds that the surface concentrations of Cl measured were much larger on surfaces exposed to a chemical ignition device in the Dahlgren open breech tests than were measured on any of fibers or surfaces from the IOWA projectiles. From these additional data and our original results it is concluded that the available information does not support the presence of a chemical ignition device containing calcium hypochlorite in the powder charge of the center gun of Turret 2 of the USS IOWA.

<u>Glycols</u>

Because of their age and previous handling, it was not possible to analyze the IG-1 rotating-band samples for materials with a volatile component such as glycols. SNL therefore concentrated on examining the data obtained by NWSC-Crane and NNSY laboratories, and characterizing the background contaminants on the ship to determine the relevance of any findings. This investigation showed that much of the data obtained in these early analyses can be explained by background constituents and analytical or environmental variations.

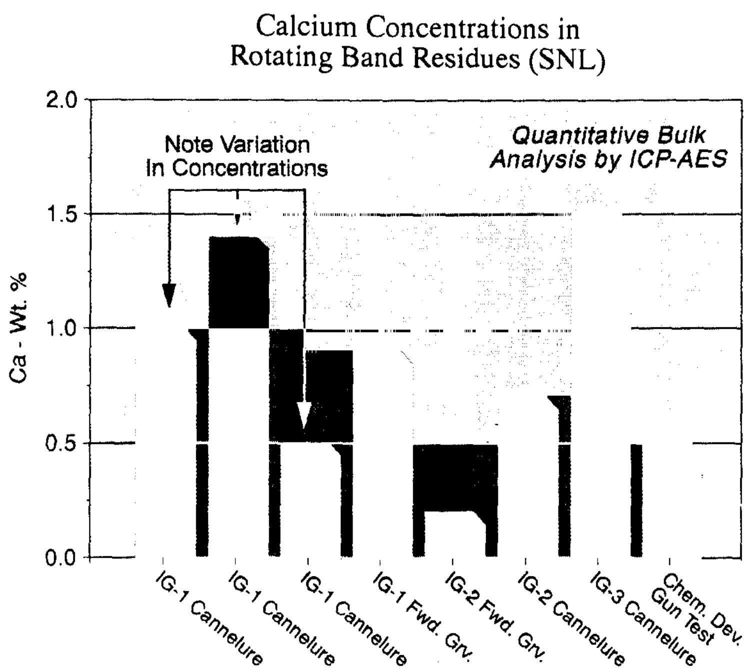


Figure 6. Calcium concentrations in debris from rotating bands.

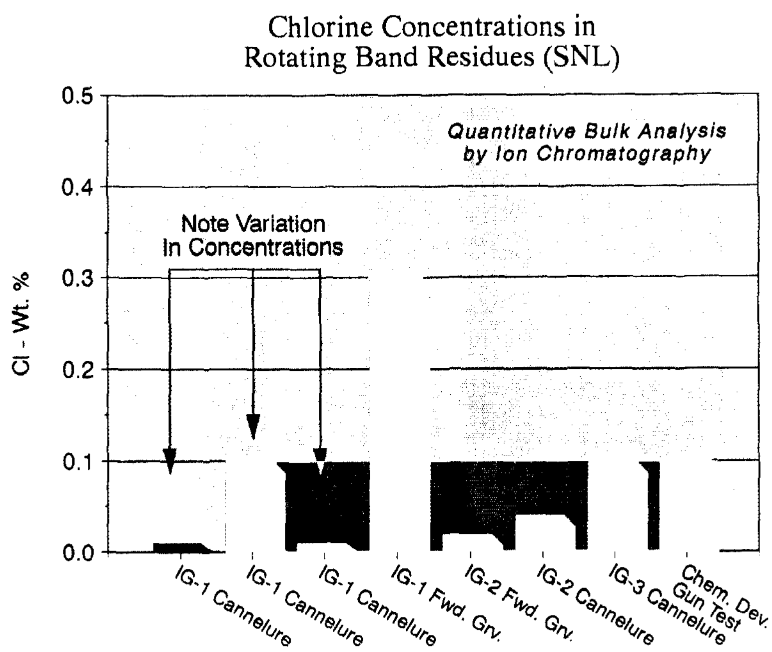


Figure 7. Chlorine concentrations in debris from rotating bands.

26

SNL's initial report showed that of the three glycol compounds identified by NWSC-Crane, two are found in known background materials. Butyl carbitol, also known as diethylene glycol butyl ether, and butyl ether glycol are both present in Break-Free™, which was used in great quantities in post-incident attempts to remove the lodged projectile from the Turret 2 center gun. Butyl carbitol acetate is a major component of Break-Free™ and butyl carbitol is found associated with the acetate. Butyl carbitol is also a major component of aqueous fire-fighting foam (AFFF), which was used in Turret 2 immediately following the incident. Butyl ether glycol, the second glycol identified by NWSC-Crane, is also found in ink from the marking pens used to identify the band samples.

The USN identified the third compound as ethylene glycol phenyl ether. Working from gas chromatography/mass spectroscopy (GC/MS) data obtained from NWSC-Crane, SNL determined that the compound was phenol, a trace contaminant in Break-Free™ and also a known breakdown product of the Tenax™ concentrating trap used in the GC/MS analysis of these samples at NWSC-Crane.

Subsequent analyses at SNL showed that the grease found in the forward grooves of IG-1 and IG-2 rotating bands was also a possible source of butyl carbitol. Grease samples from IG-1 and IG-2 were analyzed with Fourier transform infrared spectroscopy (FTIR) and GC/MS. Butyl carbitol and butyl carbitol acetate were found in the grease from these forward grooves.

The USN has suggested that the ratio of butyl carbitol to butyl carbitol acetate found in the two samples that were analyzed at NWSC-Crane were much higher than that found in Break-Free™. The butyl carbitol/butyl carbitol acetate ratio found in methanol washes of the grease from the forward grooves of IG-1 and IG-2 (0.6) is higher than that found in the methanol washes of Break-Free™ soaked rotating-band experiments (0.2) or a direct injection of Break-Free™ (0.06). This ratio is also close to the ratio measured by NWSC-Crane on one of two methanol wash solutions from IG-1 rotating band cannelure samples. The other sample appears to have an additional unresolved component that enhances the apparent ratio of butyl carbitol to butyl carbitol acetate. In either case, the data were obtained for the purpose of qualitative identification of the components. SNL concludes that the qualitative data obtained from the two measurements by NWSC-Crane cannot be used to resolve relatively small quantitative differences (X2 - X3) in these ratios. SNL investigations have also shown that several analytical and environmental conditions further impede such a comparison. These statistical, environmental, and analytical variations will be detailed in a comprehensive report on foreign materials.

Additional SNL studies to characterize brake fluids showed that these fluids are composed of several different glycols in addition to butyl carbitol. The NWSC-Crane data from the IG-1 rotating band samples were carefully scrutinized for any such corroborating chemical evidence but none was found. These results suggest that brake fluid was not a source of the glycols.

These results, plus the variety of alternate sources for these glycols, do not support the identification of the glycols as "foreign materials."

PE-PET

One of the "foreign materials" identified by the USN was a single fragment of poly(ethylene)/poly(ethylene) terephthalate (PE-PET) presumed to have come from a Seal-a-Meal™ or Meal-Ready-to-Eat (MRE) plastic bag. Following the release of the initial SNL report, it was learned that the PE-PET fragment had been found in filtered residue that remained after a sample from the rotating band had been dissolved in nitric acid at NWSC-Crane (i.e., the fragment could not be uniquely traced to the cannelure). Because the original location of the PE-PET fragment cannot be determined, it cannot be considered "foreign material." SNL did not find any PE-PET on samples of the IG-1 rotating band cannelure.

SNL personnel reviewed NNSY analyses of IG-1 samples for evidence of PE-PET. Of seven particles that appeared to be "plastic" and were analyzed by direct insertion probe/mass spectrometry, three spectra showed only air background. Data from the other materials indicated only the presence of hydrocarbons. SNL personnel, in cooperation with NNSY personnel, analyzed Seal-A-Meal™ (PE-PET) at NNSY, using NNSY instrumentation. None of the spectra from the seven IG-1 particles, previously analyzed at NNSY, resembled Seal-A-Meal™.

There is no evidence to indicate that particles or fragments of a PE-PET sealable bag were found in the IG-1 cannelure. Experiments at SNL have also shown that materials known to have been in the gun can produce data similar to that for PE-PET. A combination of Break-Free™ (which contains poly-alpha-olefin oil, a low molecular weight analog of polyethylene) and fibers from the bore brush sock (PET) produces a pyrolysis/GC/MS spectra similar to PE-PET.

Finally, SNL found a fragment of PE-PET on the rotating band of one of the NSWC-Dahlgren open-breech tests initiated with a chemical device. According to USN records, polyethylene (PE) not a PE-PET laminate was used in this chemical device. SNL believes that this observation of PE-PET in a test where no PE-PET was used is another indication of background contamination.

Particulate Debris

SNL analyzed particulate materials found in the IG-1 cannelure and compared these results with those obtained from analyses of debris found in the forward grooves of IG-1 and IG-2. A variety of particulates were observed as contaminants associated with the grease found in these grooves. These particulates were similar in appearance to many of the materials previously identified in the cannelure of IG-1 and included paint chips, sand/glass, metal chips, polymer/organic materials, and steel wool fibers.

The presence of "Pyrex™" type glass particles was reported by NWSC-Crane as possible evidence of a chemical ignition device. The evidence for this identification was semiquantitative analyses of insulating particles found in the cannelure of IG-1 for silicon and aluminum. However, no structural information was obtained to distinquish crystalline minerals from glass particles and there was no attempt to measure the boron content of the particles. The presence of boron is a distinguishing feature of "Pyrex™" glass. SNL analysis of particulate materials from the IG-1 cannelure, found most of the insulating particles to be crystalline silicate or alumino-silicate minerals. Only one glassy particle was detected. SNL concludes that there is no available data to support the presence of "Pyrex™" type glass particles in the IG-1 cannelure.

As mentioned in the initial SNL report, flakes of graphite were also observed in debris from the IG-1 cannelure. The graphite was identified as a high-temperature material by Raman spectroscopy and Raman analysis showed it to be indistinguishable from graphite in the cast iron projectile. Similar graphite flakes associated with the grease were found in the forward grooves of IG-1 and IG-2.

The presence of similar types of particles in the forward grooves of the IG-1 and IG-2 rotating bands and the similarities to those observed in the cannelure of IG-1 suggest a common source of contamination for these projectiles.

Summary

SNL's continuing investigation has determined that the materials classified by the USN as "foreign materials" in the cannelure of the center gun projectile were also found in other locations in Turret 2 that were not exposed to the explosion. With the exception of the material identified by NWSC-Crane as PE/PET, all of the "foreign materials" found in the IG-1 cannelure, identified by the USN as unique to a chemical ignition device, were also found in the forward grooves of IG-1 and IG-2. The presence of these materials in the forward grooves as well as the IG-1 cannelure, argues that pre-incident contamination, was a source of these materials. The incident of April 19, 1989, would have affected only the IG-1 cannelure. Additionally, SNL modeling studies suggest that iron fibers, of the diameter recovered from IG-1, could not have been deposited in the cannelure by the explosion.

The evidence from SNL chemical analyses and modeling studies suggests that the "foreign materials" found in the IG-1 cannelure were not produced by a chemical ignition device, but were the result of pre- and post-incident contamination.

Heat Transfer to "Foreign Material" Fibers

This section addresses the effects of heat transfer on the "foreign materials" removed from the projectile rotating-band cannelure following the USS IOWA incident. Iron fibers were recovered as possible evidence of a hypothetical chemical ignition device placed within the propellant powder charge. The significant feature of these fibers is their small size, typically, 1.5-mil. diameter. These fibers were observed to have irregular surfaces and sharp edges (see Figure 8) and show no evidence of surface melting. Furthermore, they retained sufficient mechanical integrity to indent the copper cannelure during closure. If the origin of these materials was a chemical ignition device, fibers would have been exposed to a violent combustion environment and subjected to intense heat transfer. SNL studied the extent of the heat transfer and estimated the temperature histories of the fibers that would have, according to the USN scenario, passed through the combustion environment to the projectile cannelure.

Figure 8. A photograph of an iron fiber.

From earlier interior ballistic modeling of the combustion within the open breech gun, it was determined that the onset of rapid combustion, sufficient to produce closure of the projectile cannelure, occurred after a time duration of approximately 50 msec. as given in the initial report, Sandia National Laboratories' Review of the USS IOWA Incident, June 1990. (The delay time of ignition is not included hence; the time duration of the combustion event is longer.) The combustion environment is conservatively estimated to be approximately 1750°C.

It has been proposed that fibers, originating from a hypothetical chemical ignition device, could have been transported to the rotating band cannelure by two means. If the fibers were ejected ahead of the flame fireball, they would have escaped the heat transfer from the combustion gases. However, ballistic calculations of fibers with approximately 1.5-mil. diameter, propelled at the speed of sound (approximately 300 m/sec.), indicate that fibers would not reach the cannelure unless the chemical ignition device was within a few inches of the cannelure. Small fibers would more likely have been transported by the combustion gases. These fibers would have been immersed in the hot turbulent environment and exposed to temperatures above the fiber melting point. Furthermore, the most probable gas flow path was out of the open breech of the gun rather than toward the stagnation region of the projectile base. Significant gas flow into the cannelure requires that the seal between the cannelure fin and the gun barrel be incomplete. Blowby of combustion gases in these flow paths is considered to be unlikely.

Beyond the question of the transportability of the fibers into the cannelure, the fibers must have experienced some effects from heat transfer associated with the propellant combustion. Heat transfer calculations incorporating the effects of convective and radiative exchange were made assuming the fibers had cylindrical geometry of various diameters. The effects of ablation and phase change were not included in these calculations.

Figure 9 is a plot of the temperature history of various diameter iron fibers exposed to the combustion environment. Fiber surfaces with sharp edges will experience enhanced heat transfer and may have higher localized temperatures. This figure shows that fibers with approximately 1.5-mil. diameters will approach (or even exceed) a temperature near the melt temperature of iron (approximately 1550°C) during the 50 msec. they are exposed to the combustion gases. Iron fibers <4-mil. diameter will experience heat transfer sufficient to undergo some degree of metallurgical change. Such changes were not observed in these fibers.

The survivability of these fibers can be argued to have occurred due to thermal protection by a viscous fluid coating, i.e., grease. However, it seems unlikely that this coating could remain intact in an environment so violent. Furthermore, a series of open-breech gun tests has been conducted at NSWC-Dahlgren in which grease-coated steel wool was placed on the projectile. These tests revealed that most of the steel wool was consumed by the combustion or was expelled out of the open breech. Unfortunately, these tests used a gun with high barrel wear (favoring blowby of the combustion gases) and the steel wool was not tagged to ensure that recovered fibers were uniquely linked to the material in the chemical ignition device. Fibers that preexisted on the cannelure would have been protected and survived the intense heat transfer of the combustion within the gun.

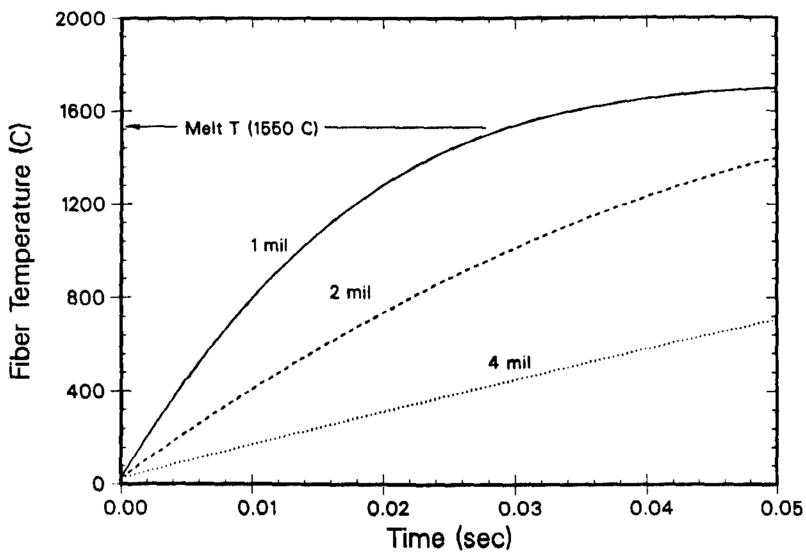


Figure 9. The temperature history of iron fibers with various diameters.

In summary, the propellant combustion environment produced sufficient heat transfer to partially melt small fibers and thus would have modified fibers originating within the powder charge. No recovered fiber exhibits a surface morphology indicative of intense heat transfer. It is concluded that the surface morphology of the iron "foreign material" fibers is not indicative of their having come from a hypothetical chemical ignition device in the propellant powder bags.

Impact Ignition Studies

Introduction

In the initial report, Sandia National Laboratories' Review of the USS IOWA Incident, June 1990, the Ignition Experiments Section described experiments on impact initiation of whole propellant pellets and assemblies of pellets and black powder. Those experiments showed that D846 propellant pellets could be initiated by impact and, in association with black powder, lead to an explosion. The most sensitive configuration appeared to be one where trim pellets in a bag of D846 propellant were adjacent to the black powder igniter pad in the next bag. This is the normal or prescribed manner in which the bags are loaded into the 16-in. gun. It was further shown that in this configuration the probability of ignition from impact increases with increasing ramming speed, and also increases with the decreasing number of trim pellets in any one of the bags (except the first bag, nearest the projectile). These results were based on subscale tests where little or no impact energy is lost in the test fixture system. In a full-size 16-in. gun, energy is lost in compressing and swelling of the bags, tearing of stitching, and motion or displacement of pellets in the bags and breech.

Because the amount of energy lost in a 16-in. gun system was unknown at the time of the initial report, only trends could be established. Extrapolation of the subscale test data to the operation of an actual gun was not quantitatively possible. It was only possible to speculate on the probability of ignition in a gun system and establish minimum boundary conditions necessary for ignition by impact during an overram of the bags into the gun.

Since the submission of the initial report, many additional experiments have been conducted, some at SNL, but most at NOS-Indian Head and NSWC-Dahlgren. The NOS-Indian Head tests expanded the data base in subscale impact fixtures. The NSWC-Dahlgren experiments involved full-scale drop tests and full-scale ramming tests, which represented the conditions in a 16-in. gun system.

This report incorporates all of the results from the three laboratories. This complete data base shows that the subscale data can be used to demonstrate ignition from impact over a range of trim pellet loadings and impact velocities and that this data can be extrapolated to actual gun conditions. These data also yield significant probabilities that ignition would occur from an overram of the D846 bags into the 16-in. gun at high speeds obtainable by the rammer.

Subscale Experiments

Subsequent to SNL's subscale impact testing, NOS-Indian Head also began subscale tests on an impact fixture similar to the 8-in. diameter fixture used at SNL. The first test configuration explored at NOS-Indian Head had seven trim pellets adjacent to a black powder ignition pad. (This configuration was described in the SNL initial report.) The results of these tests showed a mean impact energy to achieve ignition of approximately 1635 ft.-lbs. This was considerably higher than the mean of 959 ft.-lbs. found at SNL for this same configuration.

During previous tests at SNL, ambient humidity ranged from approximately 20 to 30 percent, while the humidity during the tests at NOS-Indian Head was in the mid-90 percent range. The ratio of mean energy from NOS-Indian Head's seven-pellet test to that of SNL's previous seven-pellet test was approximately 1.7. This agreed with independent humidity studies conducted at SNL with single pellets in a small fixture. To correct for humidity test conditions, the SNL data were, therefore, multiplied by a factor of 1.7 in order to correlate it with the subsequent NOS-Indian Head test results.

NOS-Indian Head also tested, in addition to the impact tests on D846 configurations, four similar configurations using D839 propellant pellets. D839 is one of the other 16-in. gun propellants used on the IOWA-class battleships. The mean ignition impact energy for the D839 was higher for each pellet configuration than that for the corresponding D846 configurations. This should be expected because the D839 pellets are larger. The forces required to fracture the pellets are proportional to the fracture surface area. In the case of these pellets this is the longitudinal cross-section area. The ratio of the longitudinal cross-section area of D846 to that of D839 is approximately 0.71. The average ratio of the mean impact ignition energy for the four sets of tests where both types of propellant were used (five, seven, twelve, and twenty trim pellets) was found to be 0.738. Using this last ratio, the D839 data was corrected to equivalent D846 values and used to expand the ignition energy data base.

SNL thus compiled a fairly extensive set of data that could be correlated to establish the relationship between the mean impact ignition energy and the number of trim pellets. This is shown in Figure 10. The total mean ignition impact energy remains essentially constant over the approximate range of one to twelve trim pellets and then increases rapidly as the number of trim pellets increases.

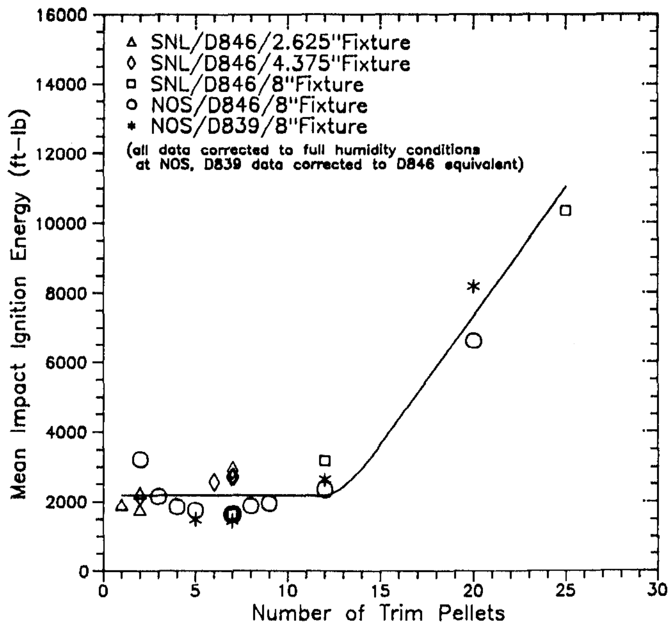


Figure 10. Mean impact ignition energy versus number of trim pellets for all subscale tests at both SNL and NOS-Indian Head.

This relationship between ignition energy and number of trim pellets appears to be independent of the diameter or size of the impact fixture. This data base should be applicable to the full-size gun with one additional correction. In these test fixtures, pellets are held rather firmly in place and there is little loss of energy in the system. That is, all or most of the impact energy is transmitted through the trim pellets. In a 16-in. gun this is not the case. When an impact occurs on a train of propellant bags, the individual bags compress and swell and often burst side-stitching of the bag. The pellets are then free to move. This movement consumes energy, and this energy is lost from the impact ignition process. Therefore, the ignition energy versus trim pellet curve seen above shifts upward in energy by an amount determined by bag losses during actual operation of a gun. These losses were determined by performing similar types of impact experiments on full-size bags and in multiple bag configurations as they are used in the 16-in. gun. Such experiments were conducted by the USN at NSWC-Dahlgren.

Full-Scale Experiments

NSWC-Dahlgren conducted two types of full-scale impact experiments: vertical drop tests and horizontal ramming tests. In the drop test series, several powder bags were strapped together, forming a train as they would in a normal gun loading, and an 800-lb. weight was placed on top of the bag stack. This weight was used to simulate the effective mass of the gun rammer system. The assembly of weight and powder bags was raised and then dropped from a predetermined height onto a steel pad.

As in the subscale tests, this procedure was repeated from a number of different heights such that both ignitions and nonignitions were obtained in sufficient number to estimate the mean ignition impact energy and other statistical parameters.

In the second type of tests, a 16-in. gun rammer system (the one removed from the center gun, Turret 2) was used to ram powder bags along a spanning tray into a simulated 16-in. gun breech and a stop that simulated the base of a seated projectile. Ramming speed was varied from test to test such that a series of ignitions and nonignitions was obtained and could be analyzed as in the drop tests.

Impact ignition data were obtained on four different test series. First, drop tests were conducted of five powder bags of D846 with five trim pellets in the second from bottom bag. Second, drop tests were conducted of six powder bags of D839 with twenty trim pellets in the second from bottom bag. Third, horizontal ram tests were conducted of five powder bags of D846 with five trim pellets in the second bag. Fourth, horizontal ram tests were conducted with five powder bags of D846 where the second bag had five trim pellets and the fourth powder bag had one pellet at the end, which was upset and moved onto its side such that it lay directly under the black powder ignition pad in the same bag. The mean ignition impact energy was determined for each of these series of tests and is plotted along with the subscale data on Figure 11.

Note that the results are essentially the same, i.e., there is a similar data spread compared to the subscale set for both the horizontal ram and vertical drop tests using five trim pellets. This indicates that the full-scale drop tests simulate the conditions obtained in horizontal ramming and, therefore, represent conditions in a gun. The data point shown for the mean ignition impact energy for a single trim pellet was obtained by extrapolating to the mean from the full-scale horizontal ram test data for that condition (one ignition in five tests at 14 ft./sec.) by using the standard deviation obtained from the total data base shown in the next section.

When the data in Figure 11 are analyzed, they show an approximately constant offset between the subscale and full-scale data. This offset is the energy that is lost in powder bag compression and swelling and subsequent mass pellet motion.

The data in Figures 10 and 11 represent the mean or average ignition energy. To estimate the probabilities of ignition at other conditions of energy or velocity, other statistical parameters such as the standard deviation of the experimental data obtained are required. These parameters were also determined from the entire data pool and are presented in the following section.

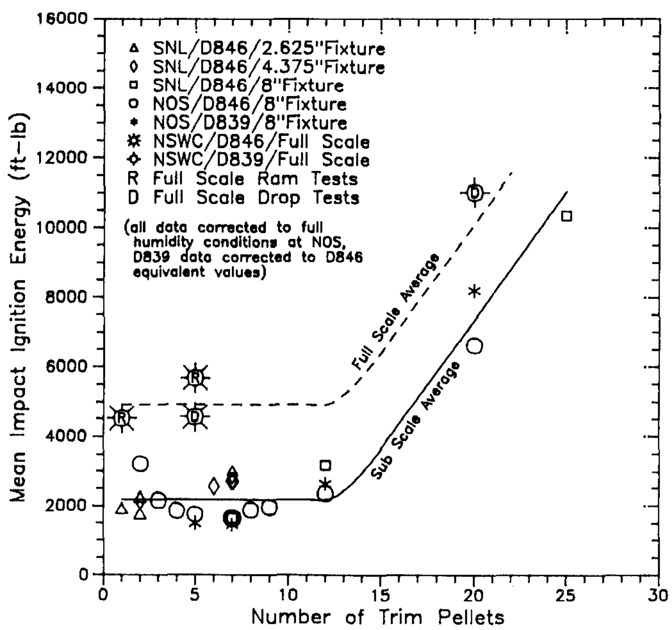


Figure 11. Full-scale ramming and drop test result compared to subscale test results.

Statistical Analysis of Total Data Base

From each series of "go" or "no-go" experiments for each configuration tested at all three laboratories, four important statistical parameters could be obtained. These are: 1) the mean of the particular data set, 2) the variance of the mean, 3) the standard deviation of the data set, and 4) the variance of the standard deviation. A total of forty-three test configurations were run in this manner and the results are shown in Table 1 [1-4].

Test Series 1 through 25 in Table 1 were from SNL test configurations described in the initial SNL report. Series 27 through 40 were conducted at NOS-Indian Head in an eight-inch subscale drop test fixture similar to the one at SNL with the pellet/black powder/buffer stack up used in Series 23 through 25. All the tests at NOS-Indian Head used dried black powder ignition pads, except Series 32. Series 41 and 43 at NSWC-Dahlgren were full-scale drop tests; 42 was a full-scale horizontal ram test.

Those series shown in Table 1 that lack data for standard deviation and variances had insufficient data range to determine those parameters. All of the data sets were analyzed using the ASENT [5] statistical computer code at SNL. Values estimated by the code closely matched similar analyses made at both NSWC-Dahlgren and NOS-Indian Head.

Because some series had more data points than others, the best averages are obtained by weighting the parameters by the number of shots in each series. This was done and the results, all in log transform, are shown in Table 2.

Impact Ignition Studies

Table 1

Compendium of Impact Test Data

Test Series	Confign.	Fixture Diameter (inches)	Black Powder Pouch Included	Number of Trim Pellets	Number of Shots	Mean Height (log in)	Variance of the Mean (logs)	Stndrd Devn. (logs)	Variance of the std dev (logs)	Mean Impact Energy (ft-lb)	Mean Impact Velocity (ft/sec)	Ref
1	1/73.5# wt	.8 X 1.8	no	1	50	1.609	2.32E-04	7.01E-02	3.86E-04	249	14.8	1
2	1/179.5# wt	.8 X 1.8	no	1	50	1.239	4.40E-04	1.05E-01	1.20E-03	259	9.6	1
3	2	2.625	no	1	25	1.272	3.49E-04	6.73E-02	8.32E-04	2011	10.0	1
4	3	2.625	yes	1	15	1.017	2.91E-03	1.44E-01	8.36E-03	1117	7.5	1
5	4	2.625	yes	2	20	1.087	5.10E-04	7.29E-02	1.20E-03	1311	8.1	1
6	5	2.625	yes	2	13	0.983	2.96E-04	4.05E-02	4.59E-04	1034	7.2	1
7	6	4.375	no	0	4	>1.9	---	---	---	>8540	>20.7	1
8	7	4.375	no	1	11	1.825	---	---	---	7179	18.9	1
9	8	4.375	no	4	20	1.673	1.21E-03	1.14E-01	4.47E-03	5064	15.9	1
10	9	4.375	no	7	14	1.562	---	---	---	3918	14.0	1
11	10	4.375	no	7	16	1.482	1.88E-04	3.42E-02	2.39E-04	3257	12.8	1
12	11	4.375	yes	0	9	1.890	2.21E-03	8.83E-02	1.16E-02	8336	20.4	1
13	12	4.375	yes	0	19	1.579	5.26E-04	6.47E-02	1.08E-03	4071	14.3	1
14	13	4.375	no	0	12	1.743	6.12E-04	5.13E-02	9.43E-04	5937	17.2	1
15	14	4.375	yes	0	12	1.506	1.20E-03	8.55E-02	3.00E-03	3445	13.1	1
16	15	4.375	yes	7	18	1.447	8.98E-04	9.50E-02	2.74E-03	3008	12.3	1
17	16	4.375	yes	7	15	1.400	---	---	---	2698	11.6	1
18	17	4.375	yes	6	8	1.375	---	---	---	2547	11.3	1
19	18	4.375	yes	2	16	1.300	4.60E-03	1.69E-01	1.53E-02	2142	10.3	1
20	19	4.375	yes	7	8	1.400	---	---	---	2698	11.6	1
21	19a	4.375	yes	7	9	1.429	3.74E-04	3.85E-02	5.51E-04	2885	12.0	1
22	20	4.375	yes	7	8	1.475	---	---	---	3207	12.7	1
23	21	8	yes	7	23	0.951	1.98E-03	1.20E-01	6.10E-03	959	6.9	1
24	22	8	yes	12	11	1.238	3.75E-04	4.36E-02	5.71E-04	1859	9.6	1
25	23	8	yes	25	18	1.752	1.43E-03	1.09E-01	4.56E-03	6070	17.4	1
27	NOS846-2	8	yes	2	4	1.381	---	---	---	2602	11.4	2
28	NOS846-3	8	yes	3	10	1.206	---	---	---	1741	9.3	2
29	NOS846-4	8	yes	4	8	1.141	---	---	---	1498	8.6	2
30	NOS846-5	8	yes	5	9	1.117	9.99E-04	6.56E-02	1.89E-03	1418	8.4	2
31	NOS846-7	8	yes	7	18	1.088	7.99E-04	8.44E-02	1.45E-03	1327	8.1	3
32	NOS846-7 wet	8	yes	7	10	1.179	1.46E-03	7.90E-02	1.96E-03	1635	9.0	3
33	NOS846-8	8	yes	8	8	1.148	---	---	---	1523	8.7	3
34	NOS846-9	8	yes	9	8	1.164	1.00E-03	6.58E-02	1.90E-03	1581	8.8	2
35	NOS846-12	8	yes	12	9	1.244	---	---	---	1898	9.7	2
36	NOS846-20	8	yes	20	8	1.695	1.93E-03	8.22E-02	4.92E-03	5370	16.3	2
37	NOS839-5	8	yes	5	8	1.180	9.84E-04	5.56E-02	1.24E-03	1638	9.0	2
38	NOS839-7	8	yes	7	10	1.167	5.75E-03	1.81E-01	2.05E-02	1590	8.9	2
39	NOS839-12	8	yes	12	8	1.427	---	---	---	2893	12.0	2
40	NOS839-20	8	yes	20	4	1.920	---	---	---	9011	21.1	2
41	NSWC846-5D	18	yes	5	16	1.631	5.36E-04	6.54E-02	1.12E-03	4560	15.1	4
42	NSWC846-R*	18	yes	5	30	1.719	1.30E-03	5.86E-02	1.13E-03	5678	16.8	4
43	NSWC839-20D	18	yes	20	12	1.954	1.03E-03	5.29E-02	1.62E-03	11016	22.0	4

(*converted from velocity data)

40

Table 2

Shot Weighted Average Results
(In Log Units)

Standard Deviation	0.06802
Variance of Standard Deviations	0.002418
Variance of Mean	0.0008906

Using the shot weighted values given above, in conjunction with the mean impact ignition energy as a function of number of trim pellets (Figure 11 in previous section), probability maps were determined for impact ignition as a function of both ramming speed and number of trim pellets.

The mean ignition energy and standard deviation were used to calculate the nominal or point estimate probabilities. The mean ignition energy, standard deviation, variance of the mean, and variance of the standard deviation were used to calculate the confidence limits. The 95 percent confidence limits means that 95 times out of 100 if any of these series of tests were repeated, the experimentally determined point estimates would lie within those limits. Another way to consider the confidence limits is that the measured mean in any given set of experiments is only an estimate of the true mean for the entire lot of propellant if it were tested in that particular configuration. The true mean can be anywhere between the confidence limits. The broader the limits, the more certain it is that the true mean lies between them.

In the extreme, it is clear with 100 percent confidence that the mean ignition energy is greater than zero and less than infinity. The 95 percent confidence limits are chosen because they represent a sufficiently broad range that most likely includes the true value, yet is still narrow enough to yield workable values. This also holds for any other point estimate of probability; i.e., 1, 10, 75 percent, etc.

These statistical parameters were used to examine the impact ignition of the five-bag powder train of D846 propellant that is overrammed into the base of the projectile seated in the 16-in. gun. The two most critical cases are: 1) finding the probability of ignition as a function of ramming speed where there are a small number of trim pellets (one to twelve) in any of the powder bags, and 2) finding the probability of ignition as a function of the number of trim pellets in any of the powder bags where there is a maximum ramming speed (14 ft./sec.).

The two cases are shown in Figures 12 and 13. The ignition probability is plotted on a log scale in order to discern the magnitude of the probabilities at very low values. A probability of 1 is the same as saying the event is 100 percent certain, a probability of 10^{-1} is one out of ten, 10^{-2} one out of a hundred, 10^{-3} one out of a thousand, 10^{-6} one out of a million, etc.

An alternative to the above analysis is to completely discount all of the subscale data, trends, and statistics and consider only the full-scale ramming tests where sufficient data were obtained to allow a statistical analysis of at least one single condition. The full-scale ramming tests of the five-bag load with five-trim pellets in the second bag is the only such data set. From Table 1, the mean, standard deviation and variances for this set have been determined and the statistical map of probability of ignition versus ramming speed calculated for the five-trim pellet configuration. These results are shown in Figure 14 where they are compared to the previous analysis that employed the global data set.

In either case, it is seen that there is a significant probability of ignition when a load of five bags with a small number of trim pellets in one of the bags is overrammed at high speed (but within the operating limits of the gun) into the base of a seated projectile. As the ram speed is reduced, so is the probability of ignition. Although the probability of ignition becomes extremely low at mid-range ramming speeds, it is not zero. It should be noted that in subscale tests (test Series No. 23, Table 1) ignition was obtained at 6.5 ft./sec. impact speeds.

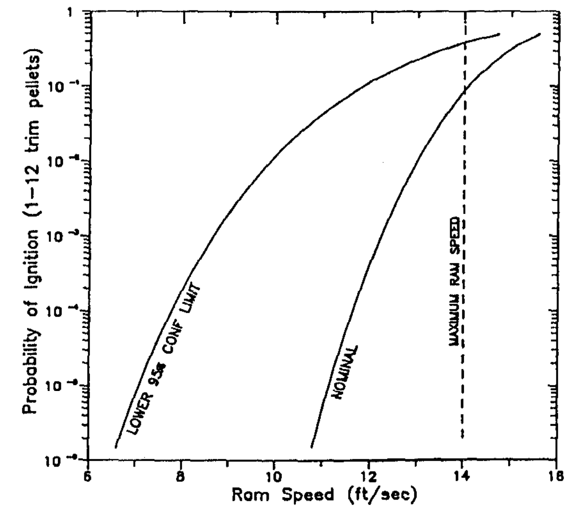


Figure 12. Probability of ignition versus speed of ram (for five-bag load of D846 with one to twelve trim pellets in at least one bag).

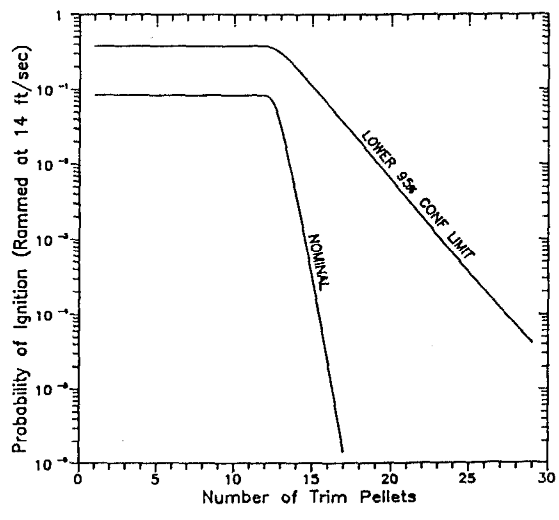


Figure 13. Probability of ignition versus number of trim pellets at ramming speed of 14 ft./sec.

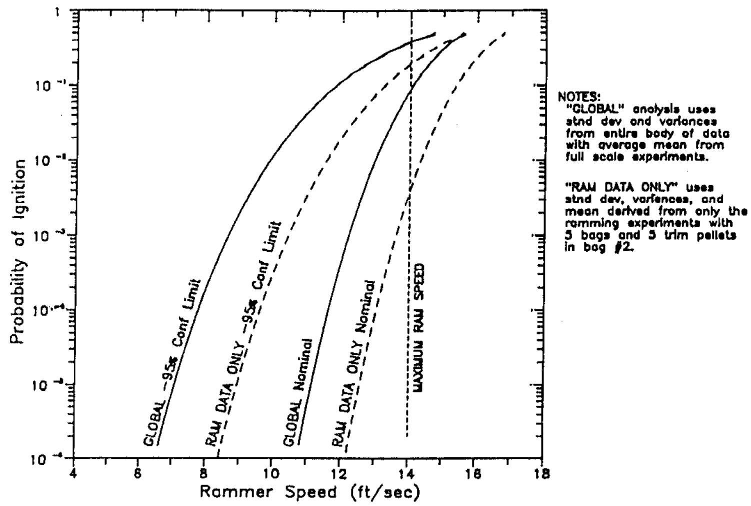


Figure 14. Comparison of ignition probability versus ram speed maps from global data and trends, to that from ram data for five bag/five pellets only.

Trim-Pellet Statistics

Between June 1 and October 1, 1990, more than 3,000 D846 powder bags were inspected by the USN. These were powder bags from the incident lot aboard the USS IOWA, as well as bags from the same lot stored at other locations. The powder bags were examined and the number and position of the trim pellets was determined and recorded.

The number of trim pellets per powder bag varied from 0 to 63. Also, there were 105 bags in which a single pellet had been dislodged from the stack at the rear of the bag and was found lying on its side in the fold of silk beneath the black powder punch. This is a configuration that was tested in full-scale ramming and is considered here to be equivalent to a trim layer with only one pellet. These bags, therefore, are included in the following data as bags with one trim pellet. The trim pellet count data received from the USN [6] is shown in Table 3. A plot of the data is shown in Figure 15.

The data in Table 3 can be used to calculate the cumulative fraction of bags that contain specific counts of trim pellets. This is shown in Figure 16, where cumulative fraction is plotted versus the number of trim pellets per bag.

In an earlier discussion it was shown that the most impact-sensitive bag configuration is one containing from one to approximately twelve trim pellets. That portion of the cumulative distribution curve is enlarged and shown in Figure 17.

Figure 17 shows that the fraction of powder bags containing from one to twelve trim pellets is 0.0443 (or 4.43 percent). This means that if one powder bag were selected at random from the lot of D846 bags, there is a 4.43 percent chance that it would contain between one and twelve trim pellets.

It was stated earlier that impact ignition could occur during a higher-than-normal-speed overram if the powder bag containing the low number of trim pellets was any bag other than the first one. Therefore, when considering the probability of ignition, the probability of selecting a low-trim pellet powder bag for any of the other four positions must be considered. The probability of having from one to twelve trim pellets in any of four powder bags selected at random is approximately 16.6 percent.

Table 3

Trim Pellet Counts per USN Inspections

Total Number of Powder Bags Containing Given Number of Trim Pellets, All Data

Number Pellets	Number Bags	Number Pellets	Number Bags	Number Pellets	Number Bags	Number Pellets	Number Bags
0	13	16	24	32	108	48	31
1	* 105	17	32	33	140	49	34
2	0	18	24	34	161	50	35
3	1	19	45	35	212	51	33
4	4	20	71	36	194	52	40
5	2	21	72	37	201	53	19
6	0	22	81	38	178	54	18
7	3	23	75	39	133	55	16
8	2	24	71	40	113	56	11
9	3	25	82	41	77	57	8
10	11	26	76	42	66	58	2
11	4	27	57	43	45	59	0
12	8	28	60	44	36	60	3
13	13	29	64	45	30	61	0
14	14	30	68	46	35	62	1
15	19	31	93	47	25	63	1

* Single pellet upset and lying under Ignition Pad

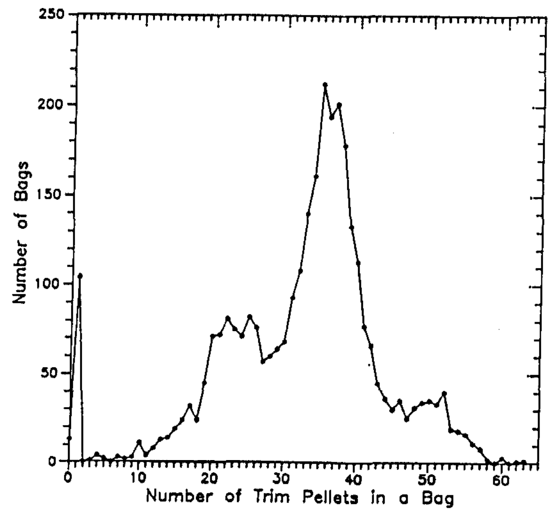


Figure 15. Population distribution of trim pellets in D846 powder bags.

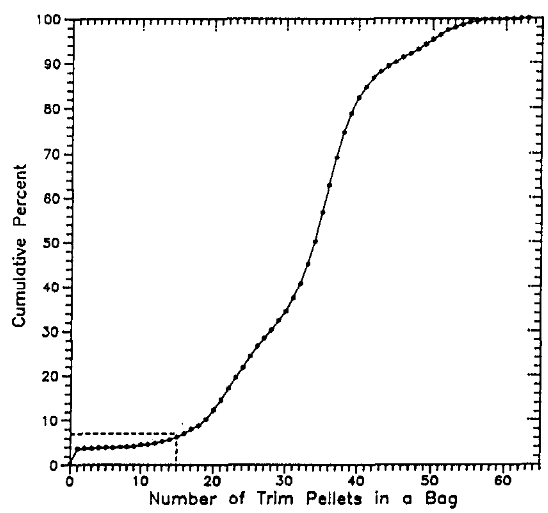


Figure 16. Cumulative distribution of trim pellets in D846 powder bags.

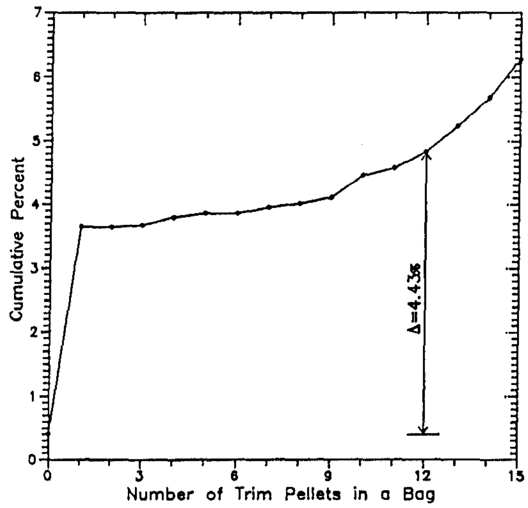


Figure 17. Cumulative distribution of trim pellets in D846 powder bags.

Conclusion

From the preceding, it is apparent that there is no single or unique combination of trim pellets and ramming speed that would lead to an explosion, but rather a broad range of combinations with a reasonable probability of occurrence. Certainly a most probable case can be found based on this data. That case is where there are a low number of trim pellets (one to twelve) in one of the powder bags and maximum ramming speed (14 ft./sec.). In that case the probability of the occurrence of an explosion could be as high as 39 percent, which is the probability value at the lower 95 percent confidence limit.

In relation to the explosion on the USS IOWA, if there were a low number of trim pellets (but not necessarily the minimum) in any of powder bags two through five and a higher-than-normal powder ramming speed (but not necessarily the maximum), then there was a finite probability that an ignition and subsequent explosion would occur. Further, in a possible case where there were the minimum number of trim pellets and the overram was at the maximum speed, then the probability of an explosion could be as high as 39 percent stated with 95 percent confidence.

Lastly, there was a 16.6 percent (approximately one in six) chance that at least one bag containing from one to twelve pellets would be present in a critical position in any randomly drawn load of five D846 propellant bags.

Explosive Materials Characterization

Introduction

In this section, the individual initiation properties of nitrocellulose (NC) propellant and black powder are discussed. In addition, analyses concerning the effect of chemical stabilizer levels on sensitivity and material compatibility issues are described. All testing was performed using propellant and black powder removed from the USS IOWA. None of the analyses indicated any obvious safety problems related to the individual sensitivities of these materials. Key results from this study are summarized below and, where applicable, summaries of USN testing are also indicated. All of this information was discussed in the previous report.

Propellant Chemical Stabilizer Analysis

Because of the age of the USS IOWA propellant (44 years old), the amount of chemical stabilizer (DPA) present has gradually decreased since it was manufactured. Twenty-four NC propellant pellets were randomly chosen for a stabilizer analysis. Representative samples showing high- and low-chemical stabilizer levels were then chosen for much of the sensitivity testing so that the effect of known stabilizer levels on sensitivity and performance could be assessed. This testing served to confirm the USN's more extensive study in this area. Liquid chromatography (LC) was used to determine stabilizer levels and the results showed that these levels varied between 0.150 and 0.353 percent, with an average level of 0.273 percent. This agrees with the USN analysis and indicates that the propellant from the USS IOWA has sufficient chemical stabilizer to prevent any premature fuming associated with storage in a higher-than-normal-temperature environment. The data indicate that the material has not aged to the point where it is no longer acceptable, based on historical USN requirements. The highest and lowest stabilizer samples were chosen for the sensitivity testing discussed below. They will be referred to as the "high-DPA sample" (0.353-percent stabilizer) and the "low-DPA sample" (0.150-percent stabilizer).

Chemical and Compatibility Studies

Analyses were performed on the NC propellant pellets to determine the ether-evolution rates as a function of temperature, and material compatibility studies were conducted to investigate whether any chemical interactions could occur between the propellant and the wear-saver material surrounding the bag charges. The results of the propellant ether-evolution rate studies indicated that it is unlikely the ether levels in the D846 storage canisters would rise above the lower explosive limit under normal storage conditions. This indicates an even lower likelihood of reaching potentially dangerous ether levels outside the storage canisters. In the material compatibility studies, no significant chemical interactions were found. Finally, an investigation of the propellant and wear-saver material was conducted to search for the presence of explosive peroxides that can form when ether and water vapor are mixed together. No peroxides were detected.

Sensitivity Testing

Several types of sensitivity tests were performed on NC propellant and black powder to determine how these energetic materials respond to various stimuli. The tests performed included impact, shock, thermal, and electrostatic discharge (ESD). A brief summary of the results of this testing is given below.

Impact

Impact testing was performed on an apparatus patterned after an Explosive Research Laboratory tester developed during WWII. This tester consists of a 2.5-kg. weight that can be dropped from 0 to 200 cm. on the explosive or propellant sample. A test series was performed on a black powder sample and with the high- and low-DPA, NC samples. A test series consisted of 25 to 30 drops with the results of each drop recorded as a "go" (the material reacted) or "no-go" (no reaction). The Langlie statistical test method was used to determine appropriate drop height. The final results of this testing showed that black powder is much less sensitive to impact than NC. The testing on NC indicates that the propellant is slightly more sensitive to impact at low-chemical stabilizer levels than at high levels. This increased sensitivity does not, however, indicate that the material is unsafe.

Thermal

Various thermal tests investigated the behavior of the NC propellant under different heating conditions. These included the Henkin and accelerating-rate calorimetry (ARC) tests. In the Henkin test, an 80 mg. NC sample is loaded into a primer cup and lowered into a Wood's metal bath that is at a preset temperature. The test provides the time-to-explosion for various metal bath temperatures. The time-to-explosion for the high- and low-DPA samples at various temperatures was too close to discern any stabilizer effects. In general, the effect of stabilizer decreases the sensitivity of the propellant to high temperatures as compared to pure NC. The results for the high- and low-stabilizer ARC testing of NC samples were more pronounced. The ARC tests showed that the propellant with low-stabilizer levels begins to chemically react at lower temperature than the propellant with high-stabilizer levels. Although differences between propellant samples with low-and high- stabilizer levels were noted, none of the results from the thermal tests indicated that the USS IOWA propellant was thermally unstable.

Electrostatic Discharge Testing (ESD)

Several tests were performed to investigate the ESD sensitivity of black powder and the NC propellant taken from the USS IOWA. The possibility of triboelectric effects was also explored. Because some energetic materials have shown different ESD sensitivities to different current rates, the black powder and high- and low-stabilizer NC samples were tested at current rates, varying from 7×10^9 to 6×10^{10} A/sec. The results indicated that none of the samples could be initiated with ESD current levels above 7×10^9 A/sec. At this current rate, black powder was initiated with an energy of about 0.6 J, while the high- and low-stabilizer level NC samples were initiated with energies of approximately 0.7 and 0.8 J, respectively. The energy levels for the black powder are consistent with the USN results, but the NC results showed lower initiation energies than those reported by the USN. These results are not completely unexpected, because the tests were designed to examine a worst-case scenario of a completely confined sample. As a point of reference, the USN measured maximum electrical-energy levels of 0.126 mJ. in a gun turret during normal operations. This is less than a thousandth of the energy required to initiate black powder or NC.

Along with ESD, another scenario considered as a possible cause for the USS IOWA incident was triboelectric effects in the NC propellant pellets. When some materials are fractured, they discharge electricity which could possible ignite an energetic material or ether, if present. Triboelectric materials exhibit this type of behavior which is often called the "lifesaver effect." If the fracture of a propellant pellet produced an electrical discharge of any significance, a light emission would be observed. Twenty pellets were fractured in a completely darkened chamber while high-speed video cameras recorded the events. These cameras were capable of detecting extremely low light levels. None of the tests resulted in detectable light emissions, so triboelectric effects induced by propellant grain fracture was ruled out as possible cause of the blast.

Shock

Testing was performed to obtain equation-of-state (Hugoniot) data and to determine the shock pressure reaction threshold for the USS IOWA propellant (NC). In addition, these test results can be used to predict the shock pressure in NC at different impact velocities. To test the propellant, 1/4-length pellets were mounted in the end of a projectile and accelerated in a gas gun into a target material composed of plexiglass, fused silica or sapphire. The velocity of the NC propellant at impact ranged from 0.4 to 1.4 km./sec. A laser measurement system, VISAR (Velocity Interferometer System for Any Reflector), was used to measure the motion of the back of the target. The velocity of the back of the target was used to calculate the impact pressure. At the highest shock pressure of greater than 1,000,000 psi, no reactions were observed in the NC under these planar impact-test conditions. The results of this testing show that NC behaves similarly, under shock conditions, to NB (a double-base NC/nitroglycerine propellant).

Summary

No obvious sensitivity problems were found during tests of the black powder and NC propellant taken from the USS IOWA. The NC samples with low-stabilizer levels consistently showed slightly higher initiation sensitivities than samples with high-stabilizer levels. However, the difference in initiation sensitivity between these two NC samples was not considered to be significant and would pose no safety problems under normal conditions.

Analytical Modeling

Summary

As noted in Sandia National Laboratories' Review of the USS IOWA Incident, June 1990, it was established from gouge marks on the spanning tray that "the face of the rammerhead, with the rammerhead buffer completely compressed, was some 45 3/4 in. into the breech as measured from the face of the breech." With this information and using the best available data at the time for the position of the rear of the projectile (seating distance) and the average length of five powder bags, it was concluded that the powder bags must have been compressed 1 1/4 in. by the rammerhead. It was also estimated that a minimum rammer speed of 6 ft./sec. would be required to produce the 1 1/4 in. bag compression.

A refined dynamic model of the rammerhead and powder bags has subsequently been developed and used along with revised data on seating distance and bag lengths. This model has shown that it is impossible to use powder bag dynamics to establish the speed of the overram because of the large variability in the seating distance and the variability of the average bag length. Furthermore, there does not exist a criterion for the necessary propellant bag compression required to cause an explosive event.

As an alternate approach to determining the speed of the overram, studies were made of gouges and chips formed inside the buffer cylinder of the rammerhead during the explosion. These studies showed that the buffer was not collapsed at the time of the blast. The extended position of the buffer head is consistent with the position observed when explosions occurred in the dynamic overram tests conducted at NSWC-Dahlgren. However, in one test it was observed that the bufferhead moved into the breech prior to the blast. Therefore, the extended position of the buffer head could, in one case, be consistent with a statically held overram. This means that the buffer cylinder gouge marks cannot be used to determine whether a statically held overram occurred.

Although the rammer control handle was found in approximately the 2 ft./sec. position after the explosion, many transient forces could have altered the position of the rammer control handle. The USN believes that the deformation of a quadrant guide that encloses the control handle was caused by impact of the rammerman's seat early in the blast sequence, and hence provides an indication of the rammer speed at the time of the incident. However, an analysis presented here shows that the seat motion could have changed the lever position and dislodged the quadrant from its mount. From these results, it is concluded that damage to the quadrant is not a definitive indicator of the ramming speed.

Speed Determination from Powder Bag Compression

Gouge Analysis

The original SNL analysis of the overram was based on the association of gouge marks on the spanning tray with specific links of the rammer chain. This association was made by noting that the female (even numbered) links are slightly longer than the male links. Characteristic chatter marks are made as the edges of the links contact and scrape the sides of the spanning tray. These marks were aligned with the edges of the links and the lengths of the marks can be used to determine the positions of male and female links. Using this procedure on the aft gouge on the left side of the tray, it was concluded that it was made by a female link (Link 2). On the right side of the tray the foremost gouge is incomplete, the next has no chatter marks, but the third is both complete and has faint chatter marks that allow one to conclude it was made by a female link. By elimination, this gouge could not have been made by Link 2 or 4 and hence must have been made by Link 6. The mark ahead of it, made by Link 5, was the gouge closest to the centerline of the tray. It was used to determine the position of the rammer chain at the time of the blast.

Further consideration has led to the conclusion that the original SNL analysis of the gouges and link associations is still the most credible explanation. It is possible that the link numbers could be off by two links to retain the proper male and female link order. This would imply either a very large bag compression or a complete loss of the structural integrity of the powder bag train after ignition. (A similar behavior was observed in NSWC-Dahlgren open-breech burn Test #23.) An attempt is now in progress by the USN to correlate the scratches on specific links with the gouges, but, secondary impacts and damage of the links may complicate this effort.

Powder Bag Compression Modeling

The purpose of the dynamic powder bag model is to determine peak forces between individual bags and the rammerhead during an overram and to quantify the speed of the overram. Validation of the model was accomplished with measurements from NSWC-Dahlgren [7]. The model results can then be used to determine the rammerhead position at various overram speeds. This position can then be compared with the physical data from the gouge analysis.

NSWC-Dahlgren conducted an investigation to better determine the seating distance of the projectile at the time of the incident and the average length of the powder bags. To determine the seating distance, measurements were made on the deformed rotating bands on the projectiles that had been rammed into the left and right guns of Turret 2. Calculations were used to establish where the deformed rotating bands would have been had they been rammed into the center gun. This analysis makes the reasonable assumption that all three of the guns have about the same wear, and that the three rammers produce approximately the same ramming force. Based on these measurements and calculations, it was established that the seating distance was 127.6 ± 0.2 in. This is 0.6 in. farther forward than the position used in analysis described in Sandia National Laboratories' Review of the USS IOWA Incident, June 1990.

NSWC-Dahlgren measured 368 powder bags and determined that the average bag length was 16.536 in. with a standard deviation of 0.178 in. A five-bag charge would have an average uncompressed length of 82.68 in., which is slightly longer than the 82.5 in. used in Sandia National Laboratories' Review of the USS IOWA Incident, June 1990. If the rammerhead buffer was fully compressed, the distance available for the powder bags is 81.85 in., requiring an average compression of 0.83 in. If the rammerhead buffer was not fully compressed, the bags could be compressed more. The sum of the bag compression and rammer compression at the time of the blast would be about 3.33 in. (2.5 + 0.83 in.).

The original model used to predict the dynamic powder bag and buffer compression was modified to include individual powder bags instead of the combined bag stack used previously. The buffer collapse model was also modified to include the effects of an air-compression chamber in the buffer that is pressurized during compression. The size of the annular gap between the piston and cylinder was varied until the model matched the displacement time histories measured at NSWC-Dahlgren. The damping in the powder bags was adjusted to 44 percent of critical to closely match the predicted force-time history observed at a given rammer speed. The validated model was then used to predict the peak forces on the rammerhead over the entire range of rammer speeds. These predictions were within ± 10 percent of the data provided by NSWC-Dahlgren.

As indicated above, the buffer and bags must compress 3.33 in. in order for the rammerhead to be in the position that matches the gouges in the spanning tray. Figure 18 is a plot of the sum of the buffer and bag compression at four different rammer speeds as predicted by the model. For times greater than 0.3 sec., all four of the compression curves approach the static compression of the rammer, 3.33 in.

At times < 0.3 sec., the rammerhead is in the required compression position at different instances, depending on the rammer speed. The variability in bag length and the uncertainty in the measurements of seating distance contribute to a large band of uncertainty in the compression. To illustrate this uncertainty, the cross-hatched band centered about the 3.33 in. compression represents the range of ± 0.88 in. caused by a two-sigma variation in bag length. Additional uncertainty bands could be plotted to account for the ± 0.2 in. and ± 0.1 in. uncertainty in the measurements of seating distance and rammerhead position, respectively.

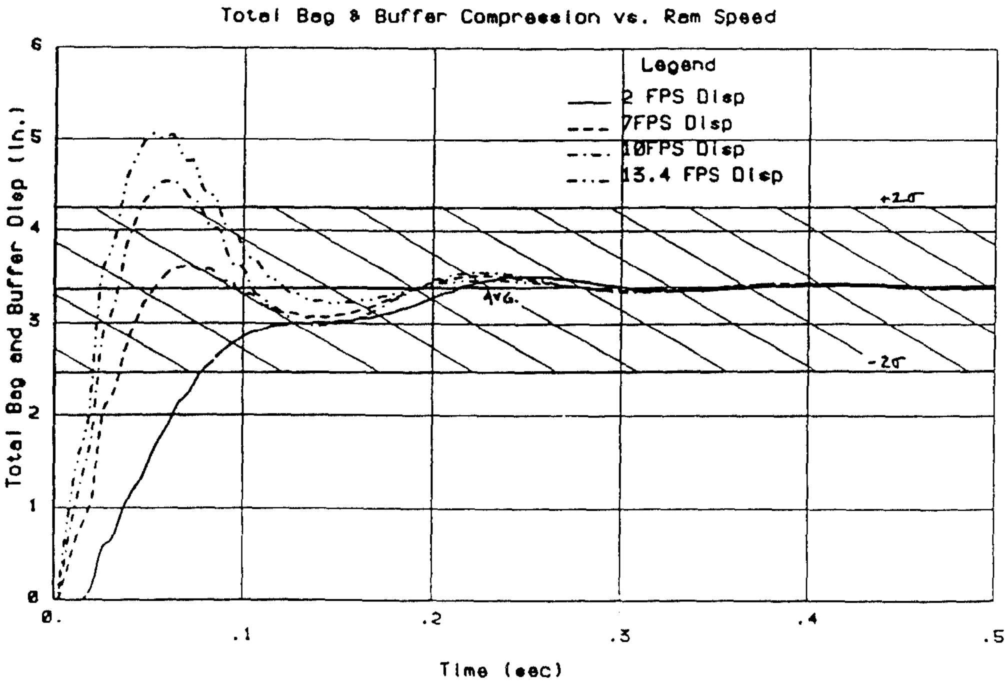


Figure 18. Predicted total powder bag and buffer compression for various ram speeds.

Recent powder bag compression tests reported by NSWC-Dahlgren agree with this model. In these tests, the initial length of the powder train was determined with a 100 lb. precompression, greatly reducing the variability in the measurement of initial bag lengths. High-speed photography was then used to determine the change in bag compression for ramming speeds between 2 and 14 ft./sec. These measurements show that the compressibility change is small compared to the variability in initial bag length and are in agreement with the SNL conclusion.

Powder Bag Modeling Conclusions

It is concluded that these uncertainties, when coupled with the lack of a time-resolved ignition criterion, make it impossible to determine the rammer speed from the compression of the powder bags and the gouges found in the spanning tray.

Rammerhead Buffer Bore Markings

The rammerhead, shown in Figure 19, incorporates a spring-loaded, fluid-filled buffer assembly that acts as a shock absorber during projectile seating. When the force exceeds the preload in the spring, the head moves into the body, compresses the spring, and forces fluid around the piston. The fluid is forced through three decreasing area slots and the annular gap between the piston and the cylinder and into an expansion chamber above the piston. The spring reaches maximum compression at 2 1/2 in. and stops the head motion. The force of approximately 1100 lb., required to fully compress the buffer, is readily supplied by the rammer hydraulic drive. Tests by the USN have shown that the head takes about 0.4 sec. to fully compress at a rammer speed of 2 ft./sec., and about 0.2 sec. to fully compress at a rammer speed of 14 ft./sec.

In the USN's dynamic overram tests that caused ignition, it was observed that ignition occurred before the rammerhead buffer was completely compressed. In contrast, most of the open-breech burn tests that involve a statically held ram show no loss of load on the rammer chain, implying that the buffer was fully compressed at the time of the blast. The only exception to this observation was Test #23, in which the chain moved into the chamber prior to the blast, implying that the buffer could have been moving out or extending.

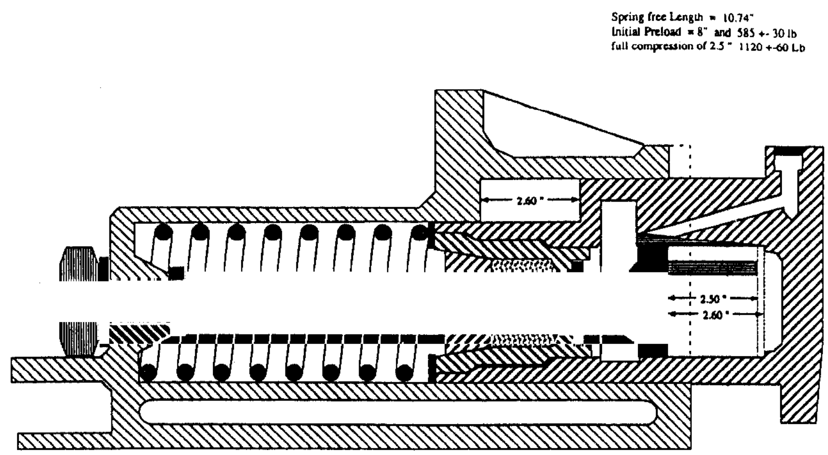


Figure 19. Cross-section through rammerhead buffer assembly.

It was reasoned that the rammerhead might exhibit marks that would indicate the position of the rammerhead buffer at the time of the incident. To investigate this, the rammerhead was sectioned, as is shown in Figure 20. The forward section on the left side of the rammerhead was also cut horizontally near the center of the bore. Examination of the bore of the rammerhead buffer (Figure 21) showed two gouges.

It is concluded that these gouges and chips were produced during the incident and were not the result of ordinary wear, for two reasons. First, the chip on the left side has clearly been raised beyond the normal limit of buffer stroke. This requires that the spring break and, by a lateral offset of the broken ends, allow slightly more axial travel of the rammerhead relative to the piston. Second, the constant churning of fluid in the buffer should ultimately have caused the relatively delicate chips to bend, fatigue, and break off if they had been formed at an earlier time.

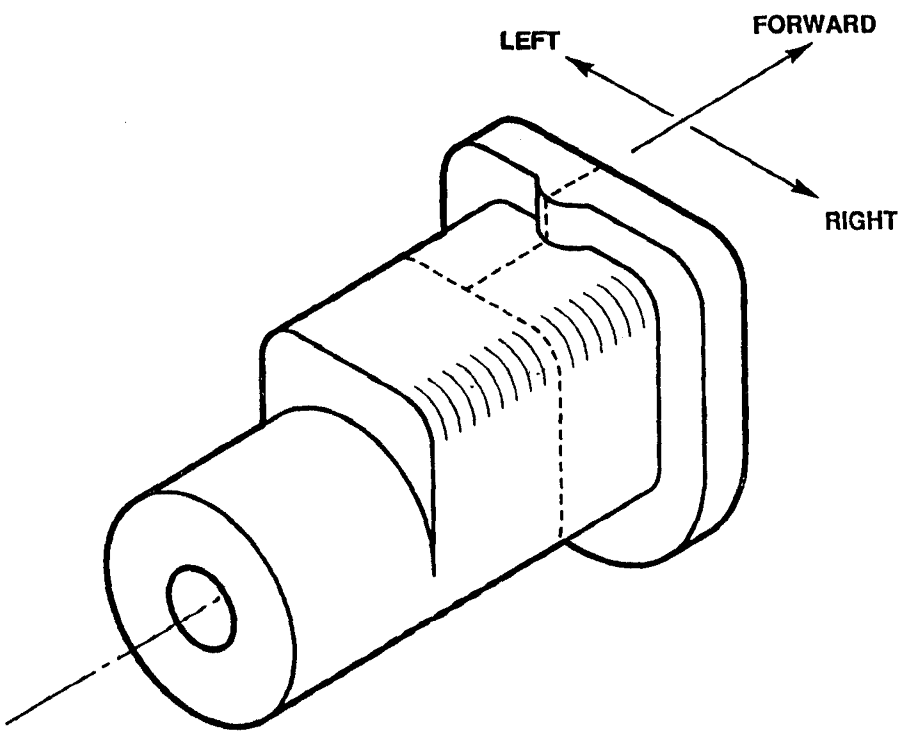
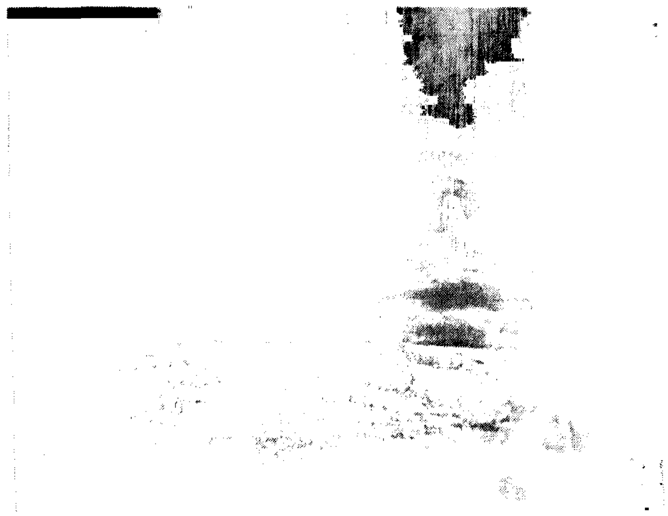


Figure 20. Orientation and sectioning of rammerhead.

Figure 21a shows the gouge marks observed on the lower part of the left side of the rammerhead bore. There is a chip that has been gouged by the piston and driven past the normal end-of-stroke position to a shoulder at the end of the machined bore. This chip was driven approximately 0.14 in. beyond the normal end of stroke. Straight striations are due to normal wear. However, where the chip has started to form, approximately 1/4 in. before the normal end-of-stroke, the striations associated with the chip deviate from the straight-line pattern. This shows that the lower left part of the rammerhead moved upward relative to the piston as this chip was being formed. Additionally, there appears to be a mark which was made by the aft surface of the piston.

(a)



(b)

Figure 21. Photographs of gouges on (a) left side and (b) right side of rammerhead buffer cylinders.

The right side of the sectioned rammerhead also shows a chip, shown in Figure 21b. This chip has not been driven up to the shoulder in the bore, but instead is stopped at approximately the normal end-of-stroke position. The striations from formation of this chip do not seem to show any upward movement. They instead show a series of impact-like marks that may be caused by the edge of the piston being repeatedly forced into the bronze rammerhead casting.

Figure 22 shows a schematic layout of the chips in the bore. The chips on the right side are located as one looks forward, between the 2 and 4 o'clock position. The chips on the left side are located between the 7 and 9 o'clock position. Three observations indicate that these chips were not made at the same time or, conversely, two separate events were required to produce these chips. The arguments for this interpretation are as follows. First, since the chips are on the opposite side of the bore, they could not be made simultaneously. Clearance of the piston in the bore prevents this. Second, the axial positions of the chips are such that it is physically impossible for the piston to produce these chips at the same time (the left chip is at the shoulder, while the right chip is at the normal end of the position). Finally, the points overlap where the gouges start and end, thus the left gouge does not start at the axial position at which the right gouge ends. These factors lead to the conclusion that the two chips were made by two different compressive events, separated in time so that the buffer could extend between them. Two large compression events that could have produced these gouges are the initial blast and the impact of the rammerhead with the bulkhead.

Examination of the front of the rammerhead shows that the right side of the buffer had received considerable damage caused by the impact with the bulkhead. On this side, the marks clearly show that the upper right side of the rammerhead impacted the small buffer located on the bulkhead. It is reasonable to associate the formation of the chip on the right with the impact of the rammerhead into the bulkhead, and the chip on the left with the initial blast force.

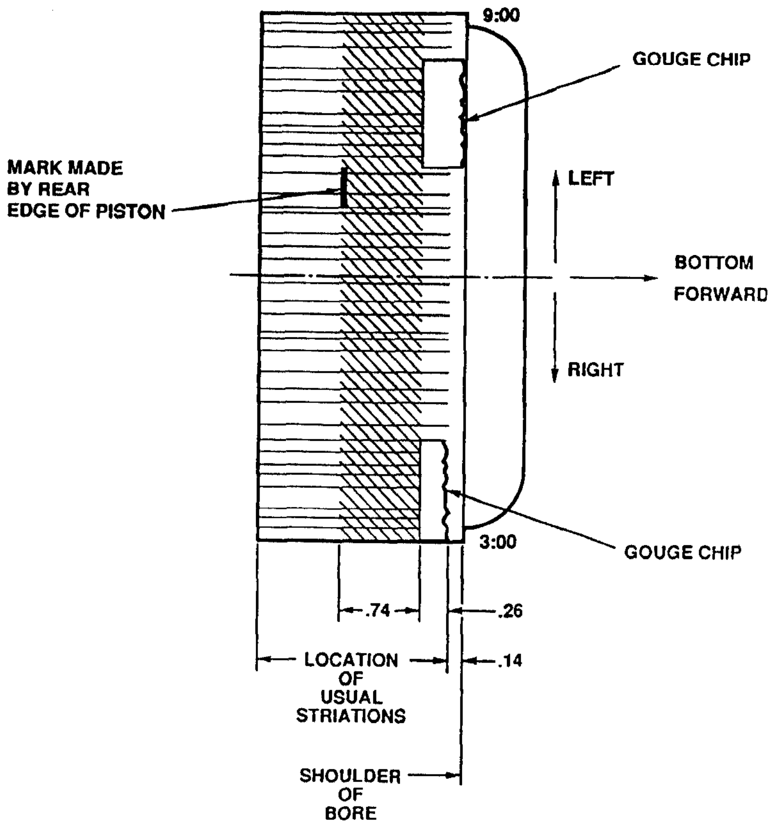


Figure 22. Developed surface of lower half of rammerhead bore.

Buffer Mark Conclusions

An examination of the bore of the rammerhead buffer shows that two gouges were probably formed during the dynamic events surrounding the incident. The two chips are associated with compressive motions of the rammerhead buffer and were apparently made at different times: the one on the left side was made at the time the blast was applied to the rammerhead and the one on the right side when the rammerhead impacted the bulkhead. From the location of the onset of the chip on the left, it is surmised that the rammerhead buffer was not fully compressed at the time of the blast. Examination of the data from the high-speed horizontal rammer tests shows that when ignition occurred the buffer was not fully compressed. In the majority of open-breech burn tests employing a shipboard rammer, the rammer chain did not move into the chamber before the blast. However, in Test #23 the rammerhead moved forward into the breech prior to the blast. Based on the anomaly of one test, the bore markings cannot be used to establish if an overram occurred.

Overram Speed from Rammer-Control Linkage Position

USN/BRL Scenario

After the explosion, the rammer control linkage was found in the 1.7 ft./sec. position, held by a frozen packing gland located where the linkage enters the pump control. The handle that controls the operation of the rammer was surrounded by a guide or quadrant tack-welded to the bulkhead. The quadrant and its mounting pads were found dislodged from the bulkhead after the explosion. The quadrant had been bent by an impact in the forward portion of the quadrant, and its forward mounting flange had sheared off. The deformation of the quadrant has been investigated by Naval Research Labs personnel and they conclude that the deformation is only consistent with the control lever being in a ram position of approximately 2 ft./sec. These two pieces of evidence form the basis of the USN position that the ram speed was normal. However, these conclusions assume that the quadrant deformation occurred before movement of the control linkage and before the quadrant was dislodged.

The USN has advanced the scenario that deformation and breakage of the quadrant was caused by the forward edge of the rammerman's seat. To investigate this scenario, the U. S. Army's Ballistics Research Lab (BRL) conducted calculations using an internal ballistics code to predict the pressures within the gun chamber. This information was transferred to the Hull hydrodynamic code in order to predict the pressures from the blast in the gun room. Finally, this loading was applied to the rammerman's seat using a finite element code to predict the resulting motion of the seat. This sequence of calculations has not been completed, so only preliminary comments are possible at this time.

Viewed from above, the motion of the rammerman's seat was predicted to be a rotation of the seat about its outboard rear edge into the quadrant with the top of the seat remaining essentially horizontal during the movement (Figure 23). The time the seat impacts the quadrant after the start of the blast loading was about 15 msec. Thus, the forward edge of the seat impacts the quadrant at a speed of approximately 75 ft./sec. and at a very low angle, about 24 degrees between the plane of the seat plate and the plane of the quadrant. At such a low impact angle it would be expected that the unsupported leading edge of the rammerman's seat would be deformed. However, the only photograph (Figure 24a) that contains the leading edge of the seat shows no detectable deformation of the forward edge. Since the seat was discarded, detailed deformation and the "as-built" geometry cannot be definitively resolved.

Figure 23 also shows the relationship between the seat and the quadrant when viewed from the side. The front edge of the seat slopes upward at an angle of 51 degrees from the deck, beginning at a point about 19 3/4 in. forward of the rear gun room bulkhead. The indentation on the quadrant slopes upward at about 35 degrees from the deck and begins at a point about 18.5 in. forward of the aft bulkhead. Clearly, if the seat rotates into the undisturbed quadrant with its top remaining horizontal, it will not hit the quadrant at the right point or orientation to make the indentation noted on the quadrant.

To further explore this, a one-quarter scale model of the rammerman station was constructed. This model clearly showed the only way that the forward seat edge could have made the indentation (assuming the quadrant remains fixed to the bulkhead) would have been for the seat to pitch so that its top rear edge moves forward and upward while its bottom moves aftward (it did not move downward because the front leg wasn't bent). As this motion occurs, it must also move outward in order to indent the quadrant. Even with this complex motion, the rear leg must bend for the front edge to reach the correct point on the undisturbed quadrant. But the close clearance between the rear leg and the rammer operating handle implies that the upward and rearwards motion of the rear leg will lift the handle, thus moving it to slower speed positions. Indeed, Figure 24a shows that the aft leg has bent outward and only very slightly forward. This suggests that, if the pitching motion of the seat were to occur, the rammer handle would be moved.

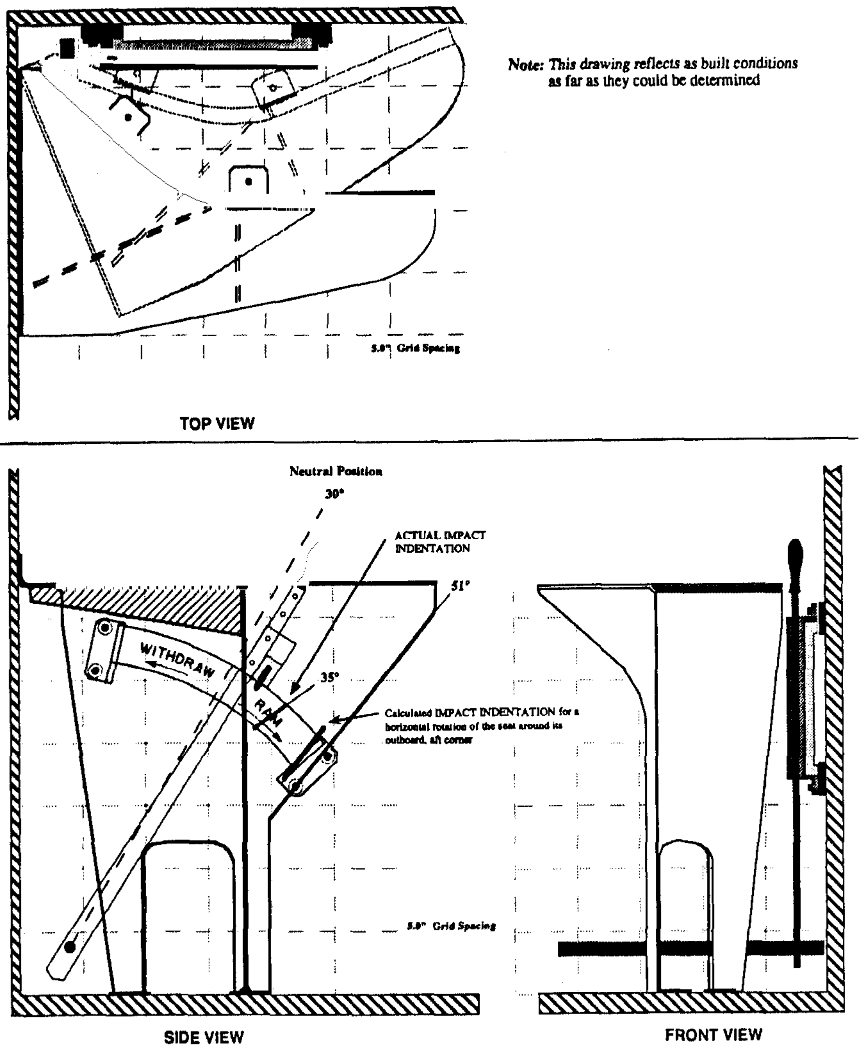
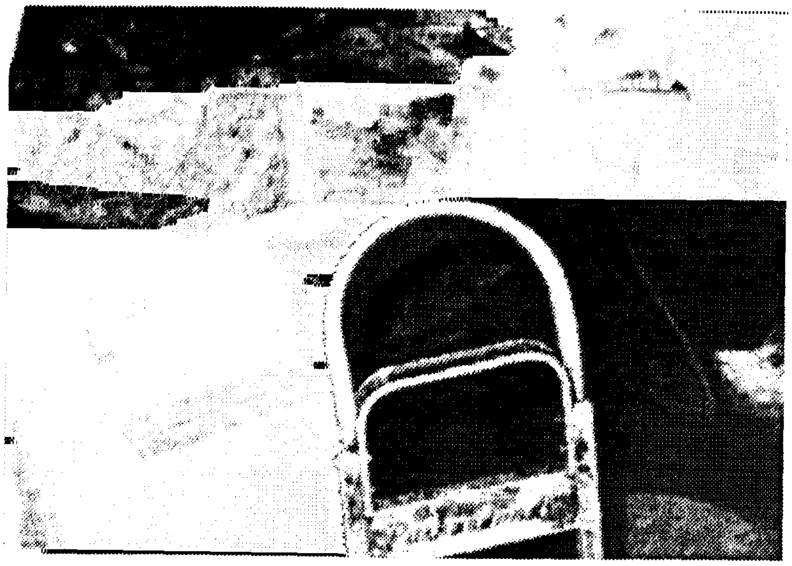


Figure 23. Layout of rammerman station.



(a)

(b)

(c)

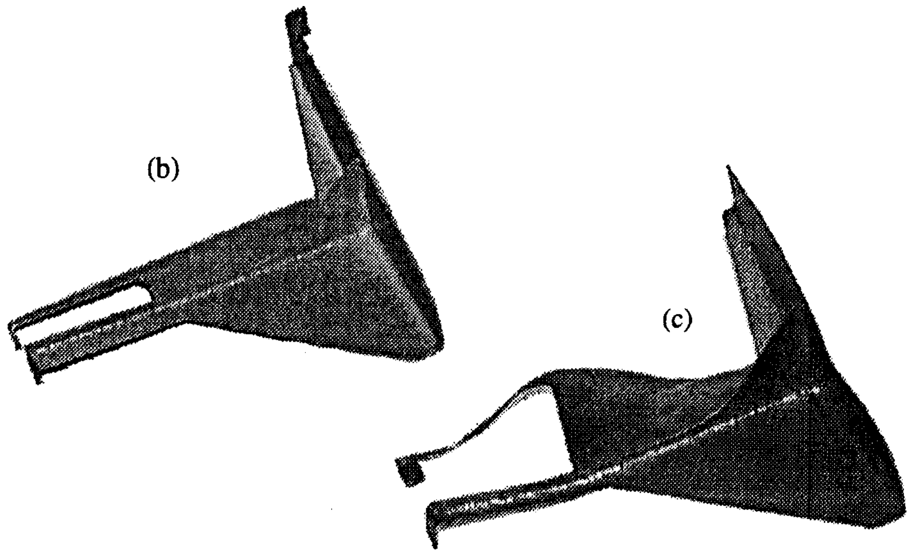


Figure 24. Photograph of:
(a) deformed rammerman's seat
(b) scale model of "as-designed" seat and
(c) scale model of "as-built and bent" seat

A second important observation made from the model was that the "as-built" seat differs from the "as-designed" seat. Figure 24b shows the "as-designed" seat model in a similar position to the incident seat (Figure 24a). Examination of the distance between the two legs shows that the "as-built" seat has its rear leg further aft than that of the "as-designed" seat. Furthermore, the tab at the bottom of the aft leg is also different in that it projects forward of the leg. This repositioning of the aft leg suggests an even stronger interaction with the rammer control handle. It could be reasoned that the bolts that secure the legs to the deck would prevent the aft leg from moving outward and striking the handle. However, examination of the gun room deck plates has shown that there were no bolts securing the legs to the deck. The holes in the deck were located about 1 3/8 in. closer to the side bulkhead than designed. This implies that the seat was actually closer to the bulkhead and rammer control handle than the model and computer calculations have assumed.

A final observation made with the scale model involved constructing an "as-built and bent" seat (Figure 24c) to try and match the deformed seat of Figure 24a. Even with the rear leg of the model seat moved aft, it was found that the lower edge and rear portion of the model seat needed to be significantly deformed in order to match Figure 24a. This suggests that the lower edge of the seat could possibly have indented the dislodged quadrant.

The top aft edge of the "as-built" seat also differs from the "as- designed" in that about one-half of the inboard side of the mounting flange had to be removed to clear piping mounted on the bulkhead. Figure 25 shows the location on the rear gun bulkhead where the seat mounting flange was secured by two 1/2 in. bolts. Directly outboard of the seat is a sheet metal mounting clip that secures two pipes in the corner of the gun room. Since this clip is undamaged, it can be concluded that the seat motion could not be directly outward since this would have crushed the clip and pipes. The rammerman foot rest also constrains the motion of the seat in the forward direction. The aft face of this foot rest on the USS IOWA was located 25 in. forward of the rear bulkhead. This permits about 5 1/4 in. of forward motion before the forward leg (which according to Figure 24a is virtually unbent) of the seat strikes the foot rest.

Figure 25. Photograph of rear corner of gun room with seat removed showing undisturbed piping in corner and bent, dislodged quadrant.

Figure 23 shows that the seat has a large area that is 47 degrees to the center line of the gun room. When this area is loaded by the blast pressure, it will produce both an outward and forward motion of the seat. The outward and forward motion of the seat allows the rear end of the seat to quickly close the 2-3 in. distance between it and the rear end of the quadrant. The quadrant mounting pads were secured to the bulkhead with very weak welds. Thus, only a modest impact could dislodge the quadrant from the bulkhead. Once it is dislodged, the position of a secondary impact determines a handle position relative to the displaced quadrant but does not indicate rammer speed. It must also be recognized that the welds could fail when the pressure load is applied to the transverse bulkhead. This bulkhead was plastically deformed by the overpressure and must have undergone a large transient motion which would have put the welds in tension as the quadrant moved with the bulkhead.

SNL Rammerman Seat Motion Study

An independent assessment of the rammerman's seat motion was undertaken at SNL to better approximate the pressure pulse from the gas flow and to see what effect this has on the resulting seat motion. To accomplish this, the gas and propellant flow seat must first be approximated, and the resulting pressure loading is applied to the seat. These two main areas of study are described separately below.

Gas Flow Analysis

Examining the details of the calculations performed by BRL, it is noted that the pressures determined from the hydrodynamic calculation contain a spurious pressure spike. This is due to an artificial initial condition in which burning propellant gases were recompressed to couple interior ballistic calculations with the Hull hydrodynamic code. Additionally, a fixed seat was modeled in the code and the limitations of coarse numerical gridding compromised accurate determination of differential pressures required to estimate the loading on the seat. Finally, it is pointed out that the hydrodynamic code resolves a continuum flow. Continuum flow describes a homogeneous media, i.e., solids and gases are assumed to coexist in space. The bulk of the kinetic energy of the open breech burn is produced by the motion of propellant grains dispersed beyond that required for a continuum approximation. Indeed, 60 percent of the kinetic energy exiting the breech is represented by motion of the propellant grains. These grains also impact the seat, the rammerman, and the lever, moving them. Accordingly, a better analysis of this event preserves the two-phase pellet/gas interaction including the reactive nature of the gas dynamics caused by the burning propellant. A calculation of this type is extremely computer intensive and require codes unavailable at this time.

An experimental analysis code DMC [8] was used to approximately the open-breech event. This analysis code preserves the discrete two-phase nature of the flow, while approximating the gas dynamics, and models individual propellant grains as two joined spheres. Drag and pressure forces from coupled gas dynamics define the forcing functions for a collection of propellant grains that collide and interact as the two phase flow develops. These processes are brought together in DMC to analyze the gas and propellant flow out of the gun, and their subsequent interaction with the rammerman's seat. Contrary to the BRL calculations, a time varying pressurization within the gun was included so that the resulting hydrodynamic calculations were consistent with interior ballistic calculations.

Testing and physical evidence from the USS IOWA were used to validate the gas flow portion of the analysis. The internal gun pressurization necessary to push the projectile into the gun in the USS IOWA incident resulted in 21 kg. of propellant being burned as calculated using an interior ballistic code. This was verified by testing from NSWC-Dahlgren. This interior pressure was applied to the open-breech tests, which included air blast gages at various distances away from the breech. The ballistic calculation very accurately reproduced these pressure measurements. With this validated pressure/gas flow description, the two-phase representation of the gun room was then possible.

Figure 26 shows the initial setup for the DMC calculation. The axisymmetric model of the breech and gun room are clearly visible, as well as the position of the rammerman's seat. Figure 27 displays representative gas flow velocity vectors at various times during the event. The spherically expanding flow is evident early, but the interaction with the walls of the gun room quickly complicates the flow field. Also, a jet of gases impinges very quickly on the rear of the gun room. The onset of gas loading occurs approximately 10 msec. from the start of the event.

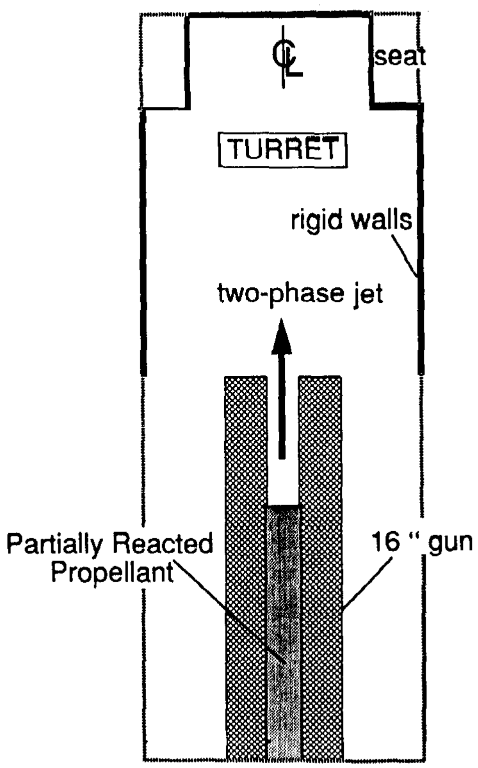


Figure 26. Initial geometry for radial symmetric DMC calculation.

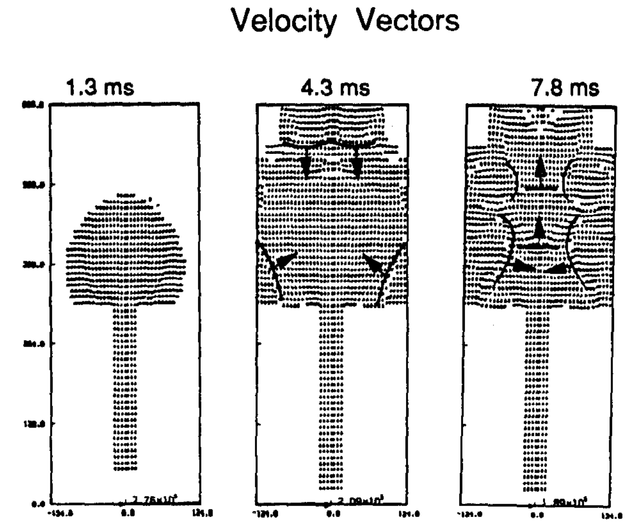


Figure 27. Gas flow field predictions from DMC.

A plot of the pressure/history on the rammerman's seat is given in Figure 28. The peak pressure was estimated to be 187 psi, which occurred over 4 msec. of time. Because the pressure loading is due to gas flow impinging on the rammerman's seat, a loss of differential pressure occurs when the flow has arrived on the other side of the seat. It is thus assumed that no additional loading exists on the seat after this initial peak pressure of 187 psi.

A series of plots from the later time response due to the propellant flow is shown in Figure 29. These plots provide some understanding of the propellant grain interaction with the gun room and rammerman's seat and the time required for this response. The propellant grains form a coherent jet that arrives at the rear bulkhead approximately 30 msec. after the gas loading is finished. As these grains ricochet off the bulkhead, they impact additional grains arriving from the breech; impact with the rammerman's seat doesn't occur until 100 msec. after the start of the event.

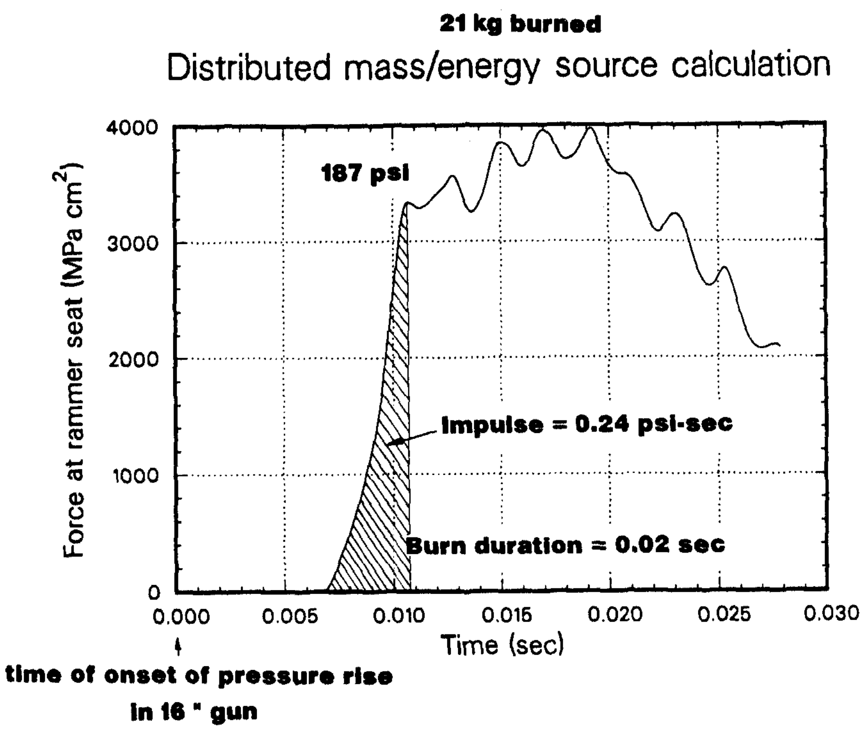


Figure 28. Pressure at rammerman's seat predicted by distributed mass/energy source calculation. Note the absence of a pressure spike at the leading edge of the pulse.

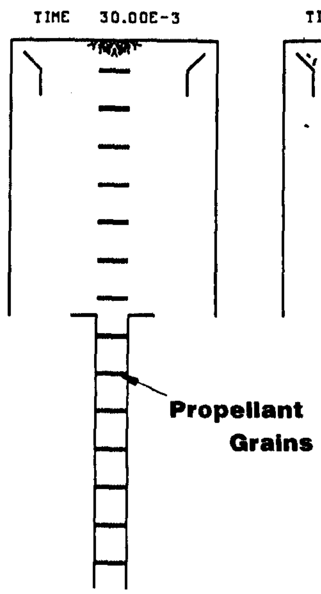


Figure 29. Propellant motion predicted by DMC.

Shielding of the rammerman's seat is provided by the close proximity of the cradle and its ancillary equipment used to load the projectile. Because the loading on the seat is due to the impingement of gas flow, the shielding provides a restriction to the total impulse applied to the seat. Areas of the seat that are assumed to be loaded by the gas flow are shown in Figure 30. The arrows denote the location and direction of the forces applied to the seat following the loading history described above. This loading is shown graphically on the finite element model used to complete the structural analysis of the rammerman's seat motion. The seat motion is described in the next section.

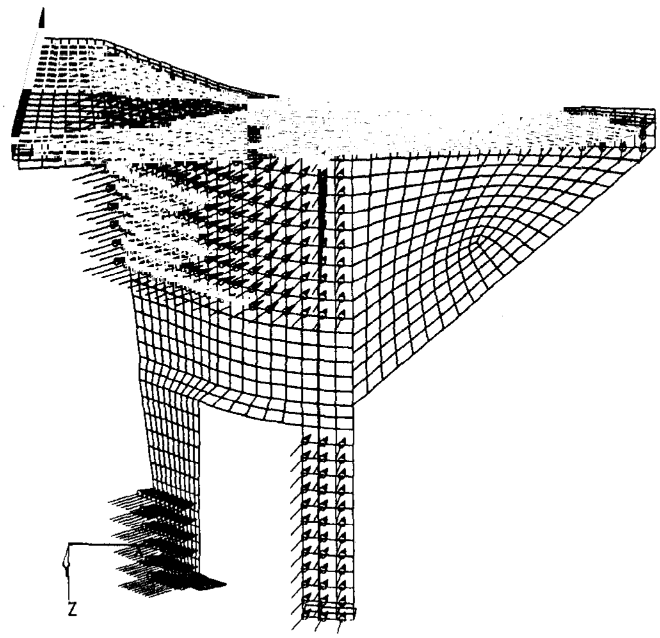


Figure 30. Pressure loading assumed on rammerman's seat.

Structural Analysis of Seat Motion

The explicit analysis code ABAQUS Explicit [9] was used for the analysis of the rammerman's seat motion. A realistic representation of the seat was constructed from the drawings of the structure; thus the rear leg was not corrected to reflect the geometry of the "as-built" seat. The finite element model used in the analysis is shown in Figure 31. The quadrant, positioned from the drawings of the gun room, is modeled with a contact surface so that the interaction with the seat can be monitored. The bulkhead was modeled as a rigid surface. The bolts attaching the seat to the rear bulkhead were modeled as a strain softening material so that failure after yield is approximated. The initial analysis also used elements to simulate bolts, to connect the legs to the floor.

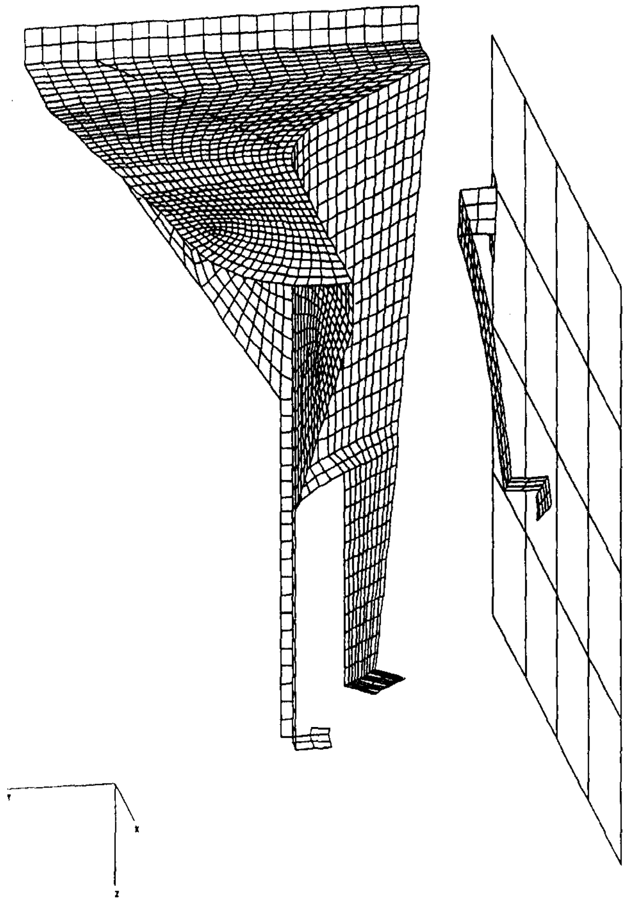


Figure 31. Initial finite element code geometry of seat, bulkhead and quadrant.

The model does not include a rammerman sitting on the seat. His body could have influenced the rotation of the seat since his legs were trapped between the seat, control handle and quadrant, further complicating the modeling of this event.

The results from the analysis show that the seat has translated and deformed over to the point of first contact with the quadrant at approximately 8.0 msec. after the initial loading. The seat plastically deforms and moves such that the first contact occurs at the lower aft mounting point of the quadrant. This is shown in Figure 32, which shows the deformed plot of the structure at this time from behind and to the side of the rammerman's seat (the bulkhead has been removed for clarity). The seat has deformed and extends over to the quadrant. Also, forward and outward motion of the seat is evident by the deformation of the bolts attaching the seat to the rear bulkhead.

It is seen that the seat has contacted the quadrant at the aft rear portion of the mounting pad. This is important because it corresponds with damage to the quadrant from the incident, where a bolt head was apparently removed and a flat surface was evident at this same position.

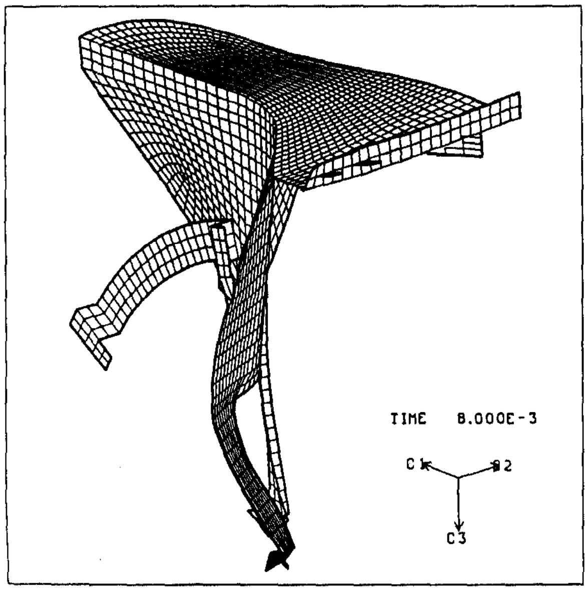


Figure 32. Predicted contact between rammerman's seat and aft end of quadrant 8 msec. after start of pressure loading.

Of particular interest is the direction that the seat impacts the quadrant. Figure 33 shows the view of the seat from above. It is clear from this plot that significant forward directed forces exist on impact. The stresses shown in the plot are the VonMises stresses in these parts, and show that some yielding of the quadrant material has been caused by the impact. Because of these similarities with the physical evidence, it is concluded that these physical phenomena discovered from the analyses resemble the event and can be used to form the basis for a reasonable seat motion scenario.

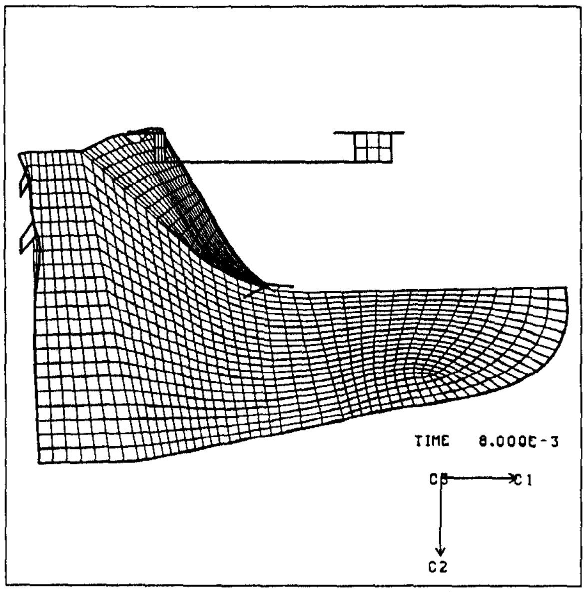


Figure 33. Top view of seat when contract is first made with quadrant.

However, it can be seen from Figure 32 that the calculation also predicts a large deformation of the aft leg that does not appear consistent with the photo of the deformed seat (Figure 24a). The calculation was repeated to include the control handle and to remove the bolts holding the legs to the deck, but the geometry of the aft leg was still modeled "as-designed." This analysis displayed a different bending of the aft leg and showed that the aft leg contacted the control handle slightly before the seat contacted the quadrant. This indicates another phenomena that would probably influence the handle position. In the SNL model, the front end of the seat is slowly rotating into the bulkhead. As this motion continues, the front inner surface of the seat could contact the control handle and possibly move it. Without the exact initial geometry of the aft leg, seat, and handle, and without considering the effects of the rammerman, complete correlation with the physical evidence will be very difficult.

Geometry Considerations "As-Built"

During the week of July 22, the USN made measurements aboard the USS IOWA to determine how the actual rammerman station differed from that as designed. It was found that:

1. The quadrant was rotated aft of the "as-designed" position with the neutral position of the handle being at approximately 30 degrees to the vertical, instead of 35 degrees.

2. The rammerman's seat deck mounting holes were found approximately 1 3/8 in. closer to the transverse gun room bulkhead. No remnants of bolts were found in the holes and probing of the holes suggested that no bolts were installed.

Figure 23 has been modified in accord with these observations. However, the computer calculations have not been redone, except to remove the leg bolts. These observations imply that the initial distance between the seat and the rear of the quadrant was about 2-3 in., instead of the 4 in. assumed in the earlier calculations. Also, they confirm that the aft leg of the seat must have been modified otherwise there would have been interference between the leg and the control handle because the "as-designed" seat had been moved 1 3/8 in. closer to the bulkhead.

Regarding Motion of the Rammerman's Seat Conclusions

The seat appears to make first contact at the rear, underside of the quadrant mounting pad. Accordingly, there is a strong possibility that the quadrant would have been dislodged from the bulkhead early in the event. Deformation of the aft support leg of the seat causes contact with the rammer handle slightly before the seat contacts the quadrant. This means that the rammer handle would also have been knocked out position. From the photograph of the actual seat, the front edge of the seat appears undamaged, making it difficult to correlate the potential quadrant impact at the damage site. Large deformation of this edge would probably be necessary to cause damage to the quadrant. Also, the pressure loading is complex, making it difficult to definitively determine seat motion. Interaction of the aft leg and control handle appears likely. These factors all combine to make the damage to the quadrant an inaccurate indicator of the ramming speed.

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VITAE

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83

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84

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87

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