

**DAHLGREN DIVISION
NAVAL SURFACE WARFARE CENTER**

Panama City, Florida 32407-7001



CSS/TR-94/38

**SUDDEN IMPACTS IN NAVAL SPECIAL
WARFARE HIGH-SPEED BOATS**

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ADMINISTRATIVE INFORMATION

The contributions of the Naval Special Warfare Development Group, its boat cadre, and Captain Frank Butler, USN, MC, of the Naval Special Warfare Command, were essential to the successful completion of this effort.

Released by
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CONTENTS

	<u>Page</u>
ABSTRACT	i
ACKNOWLEDGEMENT	v
BACKGROUND	1
PURPOSE	2
APPROACH	2
INSTRUMENTATION SELECTION	2
INSTRUMENTATION/DATA VERIFICATION	3
INSTRUMENTATION INSTALLATION AND DATA COLLECTION	3
RESULTS	5
DISCUSSION	7
RECOMMENDATIONS	9
REFERENCES	10
 APPENDIXES	
A INSTRUMENTATION	A-1
B DATA TEST EXPOSURE 1	B-1
C DATA TEST EXPOSURE 2	C-1
D DATA TEST EXPOSURE 3	D-1
E DATA TEST EXPOSURE 4	E-1
F DATA TEST EXPOSURE 5	F-1
G DATA TEST EXPOSURE 6	G-1
H LESSONS LEARNED	H-1
DISTRIBUTION	(1)

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	SOC Instrumentation Layout for Validation Testing	4
2	Sample Shock vs. Speed Comparison for NSW HSBs from Exposure	8
B-1	SOC Instrumentation for Exposure 1	B-3
B-2	Distribution of Shocks by Frequency and Magnitude During Exposure 1	B-4
C-1	SOC Instrumentation for Exposure 2	C-3
C-2	Distribution of Shocks by Frequency and Magnitude During Exposure 2	C-4
D-1	SAC Instrumentation for Exposure 3	D-3
D-2	Distribution of Shocks by Frequency and Magnitude During Exposure 3	D-4
E-1	SAC Instrumentation for Exposure 4	E-3
E-2	Distribution of Shocks by Frequency and Magnitude During Exposure 4	E-4
F-1	SAC Instrumentation for Exposure 5	F-3
F-2	Distribution of Shocks by Frequency and Magnitude During Exposure 5	F-4
G-1	SAC Instrumentation for Exposure 6	G-3
G-2	Distribution of Shocks by Frequency and Magnitude During Exposure 6	G-4

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Summary of Impacts for Each Trial	5

ACKNOWLEDGEMENT

The contributions of the Naval Special Warfare Development Group, its boat cadre, and Captain Frank Butler, USN, MC of COMNAVSPECWARCOM, were essential to the successful completion of this effort.

BACKGROUND

Whole body deceleration forces suspected to challenge human tolerances are generated during routine Naval Special Warfare (NSW) high-speed boat (HSB) operations. These repeated sudden impacts or shocks (defined to have a duration of less than 1 sec) are reported to result in a wide range of visceral and musculoskeletal injuries and fatigue. Additionally, these impacts may interfere with operator/passenger tasks of maintaining craft control, vessel navigation, and inter/intraboat communications. While professional boat racers might experience similar repeated "g" forces during training and competition, several factors distinguish the quality, quantity, and severity of professional racing from NSW exposures. NSW boat operators and passengers endure longer underway periods; operate in higher sea states, more diverse light and weather conditions; and place a decreased emphasis on comfort and protective equipment due to operational constraints. Perhaps most importantly, for NSW HSB operators/passengers, the boat operation is not the task to be performed but rather the method of transit to the operational area where subsequent warfare demands will occur.

The consequences of this unique occupational exposure are not well defined. While musculoskeletal injuries as a result of HSB operations have been reported in NSW medical records, the actual incidence of such injuries is not known. Informal observations of NSW personnel suggest that HSB operators/passengers do experience a degradation in both physical and mental performance capabilities after HSB-impact exposure. However, objective information detailing the effect of prolonged or repetitive underway exposures on operational readiness and mission success does not exist. Such data would be relevant to pre-mission planning, operator/passenger training, mission force strength determination, and operator/passenger task determination both aboard the HSB and at the mission site. Also, such data could be used as a baseline for future efforts to mitigate the operators/passengers shock exposure.

NSW initiated a program to determine the operating environment of NSW HSBs, the resulting effect on their operators/passengers, and the implementation of possible solutions. Three phases were identified in the program: (1) problem definition, (2) problem solutions identification, and (3) problem solution selection and implementation. The problem definition phase was further divided into three areas of investigation: (1) quantification of the HSB's operating environment (shocks, sea state, boat speed, hours of exposure, weather); (2) determination of the exposure effects on the acute physical well-being of the operators/passengers; and (3) determination of the exposure effect on the psychological and cognitive/motor skill performance of the operators/passengers. The ultimate objective of this NSW program is to allow the successful operation of the NSW HSB in all required sea states without operator/passenger injuries or performance degradation, or boat/equipment failure due to sudden environmentally induced shocks. This report deals only with the quantification of the HSB's shock environment.

PURPOSE

The purpose of this effort is to investigate and present objective information on the repetitive impacts that NSW personnel experience in HSB operations. Additionally, this report collates information useful in the design of the hull, control/display, operator/passenger protection equipment, and other methods or devices to improve HSB operability, efficiency, and operator safety.

APPROACH

Little objective baseline information was available on the shock operating environment of NSW HSBs. The approach chosen to investigate this problem was simple and straightforward. Instead of developing complicated models of the HSBs and their operating environment, actual NSW HSBs were instrumented to measure and collect data during actual sea operations. This was the most feasible and accurate way to attain the necessary data, and provided a baseline for future modeling, data collection, and system analysis. The approach was divided into three sections: instrumentation selection, instrumentation/data verification, and instrumentation installation and data collection.

INSTRUMENTATION SELECTION

A review of the open literature and discussions with engineers from commercial and military agencies revealed little was known about how to collect, analyze, and apply relevancy to repeated sudden impacts in high-speed platforms. Numerous studies were conducted on the effects of vibration and a singular sudden impact on humans.¹ Exposure to vibration and sudden impacts is well documented and is associated with performance decrements (stress, reduced vigilance, fatigue, interrupt and/or distort perception), injury (bruises, tissue damage, skeletal fractures), and interference with the ability to perform tasks due to displacement relative to controls and displays.²

The literature does suggest that humans are sensitive to shocks or sudden impacts of a duration between 50 and about 500 msec.³ Impacts of a duration shorter than 50 msec lack significant displacement amplitude, and impacts longer than 500 msec have a long enough onset rate to be well tolerated. For this study, shocks or sudden impacts are defined to be greater than 2 gs with a duration between 40 and 500 msec. The appropriateness of this definition was confirmed during actual performances of the craft at high speeds.

Previous attempts to quantify the shocks experienced by NSW personnel aboard HSBs were unsuccessful due to instrumentation inadequate for use under field conditions. The forces encountered during previous testing were far greater than anticipated. Therefore, the selection of an instrumentation package capable of collecting, recording, and analyzing all shock aspects

of the NSW HSB shock environment was of primary importance. This package was required to collect amplitude, direction, deviation, and frequency for the shock environment. Several instrument packages were considered for the task. Peak Acceleration Loggers (PALs) from Dallas Instruments were found most suitable. PALs are self-contained, battery-powered, microprocessor-controlled data loggers with internal memory (see Appendix A for details). Other instruments were also used during testing to augment the PALs data. These were a TrimPack Global Positioning System (GPS) used to get boat speed and heading, and an LTC 386 Compaq personal computer (used to record GPS data). Information on the instruments installation and settings is presented in Appendix A, Instrumentation.

INSTRUMENTATION/DATA VERIFICATION

One week was used for verification testing of the Navy procedures and equipment. Instruments from the Navy, Dallas Instruments, and the Oak Ridge National Laboratory (ORNL), Instrument and Controls Division, Reactor Systems Section, were placed onboard a NSW HSB for a side-by-side test. Dallas Instruments, the company that built the Navy's instrumentation (PALs), brought a more sophisticated type of shock measuring instrument (IS4) for the verification. Both Dallas Instruments and ORNL sent highly skilled and experienced engineers/technicians to help install sensors, define the requirements, and help analyze the data. Figure 1 shows the placement of the instruments during the verification week. The PALs were programmed to record peak shock lasting longer than 40 msec within intervals of 1 sec. Each PAL contained three accelerometers, one in each axis that sampled 2000 times/sec. The IS4 assisted in the recording of real-time, wave-form data from four shock/vibration sensors throughout the test. IS4 and GPS data were recorded by a computer. No special setup was required for the IS4 or GPS instrumentation. Typical locations of shock/vibration sensors are shown in Figure 1. During testing, all instruments were mounted to prevent water damage (see Appendix A for details). Upon conclusion of the week's testing, both Dallas Instruments and ORNL verified the Navy's equipment, procedures, and data. The verification test data are available upon request.*

INSTRUMENTATION INSTALLATION AND DATA COLLECTION

During testing, two types of NSW HSBs were instrumented, the SAC and SOC type. The SAC is 37 ft long. The SOC is 43 ft long. The instrumentation on both types of HSBs consisted of three PALs, a TrimPack GPS, and a Compaq LTE 386 computer. The instrumentation layouts used during testing for both boat types are shown in Appendixes B through G. Note that three different PAL units were used during the investigation. One PAL was located directly behind the operators at the base of the center bolster, and the other two at the stern of the boat, port and starboard. The TrimPack GPS used to record the heading and speed of the HSB was mounted in the front section of the boat. The PALs were programmed to record peak shock

*Call Richard Roach, Code 2310, Coastal Systems Station, (904) 235-5281.

lasting longer than 40 msec within intervals of 1 sec. Each PAL contained three accelerometers, one in each axis that sampled 2000 times/sec. GPS data were recorded by a computer programmed in C language. The program recorded GPS data and time so that the GPS data could be correlated with PALs data. During testing, all instruments were mounted to prevent water damage, as in the Instrumentation/Data Verification week (see Appendix A for details).

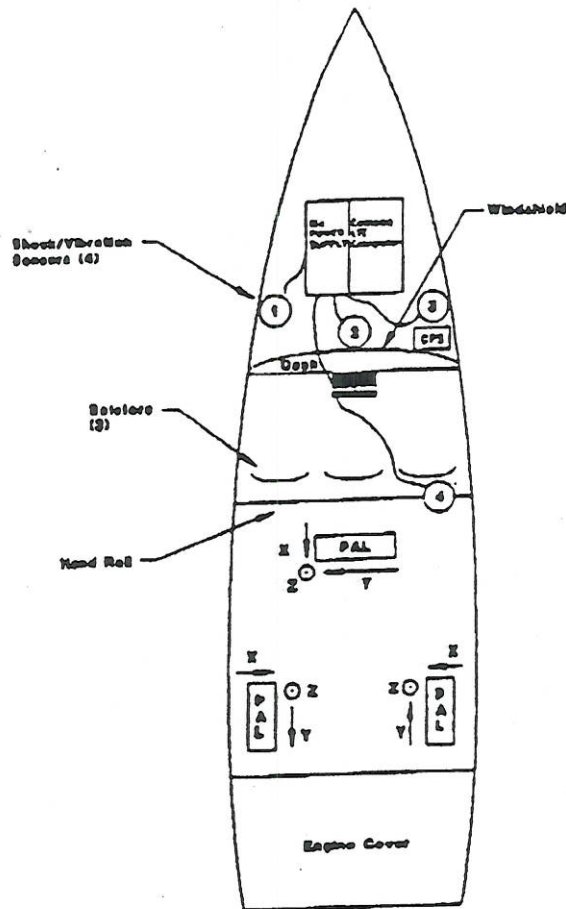


FIGURE 1. SOC INSTRUMENTATION LAYOUT FOR VALIDATION TESTING

After the final installation procedures, equipment setup, and data analysis methods were established, tests were conducted on six different days in various environmental conditions with several NSW SOC and SAC vessels. Information on the six test days is presented in Table 1. Appendixes B through G present that data collected for each individual test. Test data collected consisted of PAL (X, Y, and Z accelerations) and GPS readings as function of time. Although data were recorded on three PALs and a computer, the data collected from the PAL amidships (behind the center bulster), were considered most relevant because this PAL was nearest to the operator/passenger location, and near the vessel's center of buoyancy and center of gravity. This PAL was mounted firmly on the same deck padding the operator/passenger stood on.

TABLE 1. SUMMARY OF IMPACTS FOR EACH TRIAL

EXPOSURE DAY	1	2	3	4	5	6
SEA SURFACE	CALM	CALM	FLAT	ROUGH	VARIED	VARIED
EST. WAVE HEIGHT (ft)	3.5	2.5	≤ 2	UP TO 8	1-2 TO 5-6	1-2 TO 5-6
HOURS RUN	5	5	5	7	7	7
BOAT	SOC	SOC	SAC	SAC	SAC	SAC
TIME	DAY	DAY	DAY	DAY/NIGHT	NIGHT	NIGHT
WEATHER	COOL	COOL	WARM	T. STORMS	WARM, CLEAR	WARM, RAIN
IMPACT FREQUENCY (g)						
≥ 2 < 4	210	267	504	991	824	1318
≥ 4 < 6	191	249	202	1012	696	653
≥ 6 < 8	41	84	32	416	237	157
≥ 8 < 10	9	31	5	176	87	38
≥ 10 < 12	0	14	2	63	20	9
≥ 12 < 14	0	1*	0	21	12	2
≥ 14 < 16	0	1*	0	14	6	4
≥ 16 < 18	1*	1*	0	2	2	0
≥ 18 < 20	0	0	0	2	0	0
≥ 20 < 22	0	1*	0	0	0	0
≥ 22 < 24	0	0	0	0	0	0
≥ 24 < 26	0	0	0	2	0	0
TOTAL IMPACTS	452	649	745	2699	1884	2181

*These impacts were likely generated when the HSB struck another platform and are not due to the seas.

Data were combined to form the vector sum of the X, Y, and Z impact components. These are the data presented in this report. These data were also analyzed to allow subsequent correlation with the medical and performance tests administered to boat personnel. A synopsis of lessons learned during testing is provided in Appendix H.

4.0 RESULTS

Six days of testing under a variety of weather and sea conditions were conducted over a period of 8 mo. Testing was conducted during both day and night operations. As expected, the quantity and magnitude of the impacts were greater during high sea states and heavy weather when compared to low sea states and calm weather. However, the overall magnitude of the impacts were greater than expected, with some impacts exceeding 20 gs. Table 1 summarizes the environmental conditions and the corresponding impacts that occurred during each day's testing. Briefly, the average and maximum impact magnitudes during exposure days 1 and 2 (calm, cool day) were 4.6 and 20.81 gs; during exposure day 3 (flat, warm day) were 3.87 and 10.89 gs; during exposure day 4 (rough, stormy night) were 5.18 and 27.28 gs; during exposure day 5 (varied, warm night) were 4.68 and 17.77 gs; and during exposure day 6 (varied, rainy, warm night) were 4.12 gs and 15.86 gs. Distributions of shocks by frequency and magnitude for the six days of testing are presented in Appendixes B through G. The raw test data are available upon request.*

*Call Richard Roach, Code 2310, Coastal Systems Station, (904) 235-5281.

DISCUSSION

Results from testing suggest that NSW HSB operations are potentially harmful for operator/passenger members. These operations expose HSB's operator/passenger to repetitive impacts of considerable magnitude. Impact magnitudes in excess of 25 gs were recorded during testing. The scope of this study was not to ascertain the medical severity of these exposures but to quantify their magnitude. Factors that determine human tolerance to repetitive impacts (e.g., fatigue, protection, experience, orientation to the direction of shock) can be found in the literature. The National Aeronautical and Space Administration (NASA) has limits of shock exposure (e.g., ± 15 gs in the vertical direction) but this appears to be a one time vice a repeated exposure, and requires that personnel be secured in the vehicle and optimally located relative to the direction of the impact.² The U.S. Coast Guard (USCG) has a limit of exposure of 1.5 gs for short-duration repetitive impacts and 1.0 g for exposures over 4 hr, but these limits appear to be created to protect operators from sea-sickness and fatigue rather than from injury.⁴ The Army has instrumented tanks for repeated impact analyses but has not yet collected sufficient data on operators/passengers.³ The Navy has documented the effects of shock and vibration on man.⁵ However, specific exposure effects of high magnitude repetitive impacts on humans is not documented. NSW is conducting a parallel study on this subject.

Test data indicates that NSW HSB operators will experience impacts greater than 15 gs even in moderate sea states at normal operating speeds. Routine operating/training exposures generate hundreds of impacts greater than 2 gs regardless of sea state. These exposures exceed limits set and accepted by NASA and USCG. The quantity of high-magnitude impacts (greater than 10 gs) seems to be a direct function of boat speed, sea state, direction of the seas and boat heading, and weather (visibility). Figure 2 presents a sample comparison of HSB speed versus impact magnitude. As expected, the faster the boat travels, the greater the impact magnitudes experienced by the operator/passenger. During testing and actual NSW HSB operations, there were three types of impact dynamics that seemed to be most harmful to the operators. These dynamics are operator-boat decoupling, rapid-consecutive impacts and flat-bottom impacts.

- **Operator-Boat Decoupling:** This is the dynamic in which operators are tossed in the air and lose their footing and grip as a consequence of an impact. Becoming decoupled is life threatening, especially if a high-magnitude impact occurs before the operators recouple.
- **Rapid-Consecutive Impacts:** This is the dynamic in which the boat hits and launches off one wave and immediately hits another wave. During this dynamic, the operators do not have sufficient time to prepare for the second impact and are at risk.
- **Flat-Bottom Impacts:** This is the dynamic in which the boat's stern lands on the flat part of the hull under the engines. During this dynamic, the boat does not displace sufficient water to transfer the impact energy. Consequently, most of the impact energy is absorbed by the boat structure and operators.

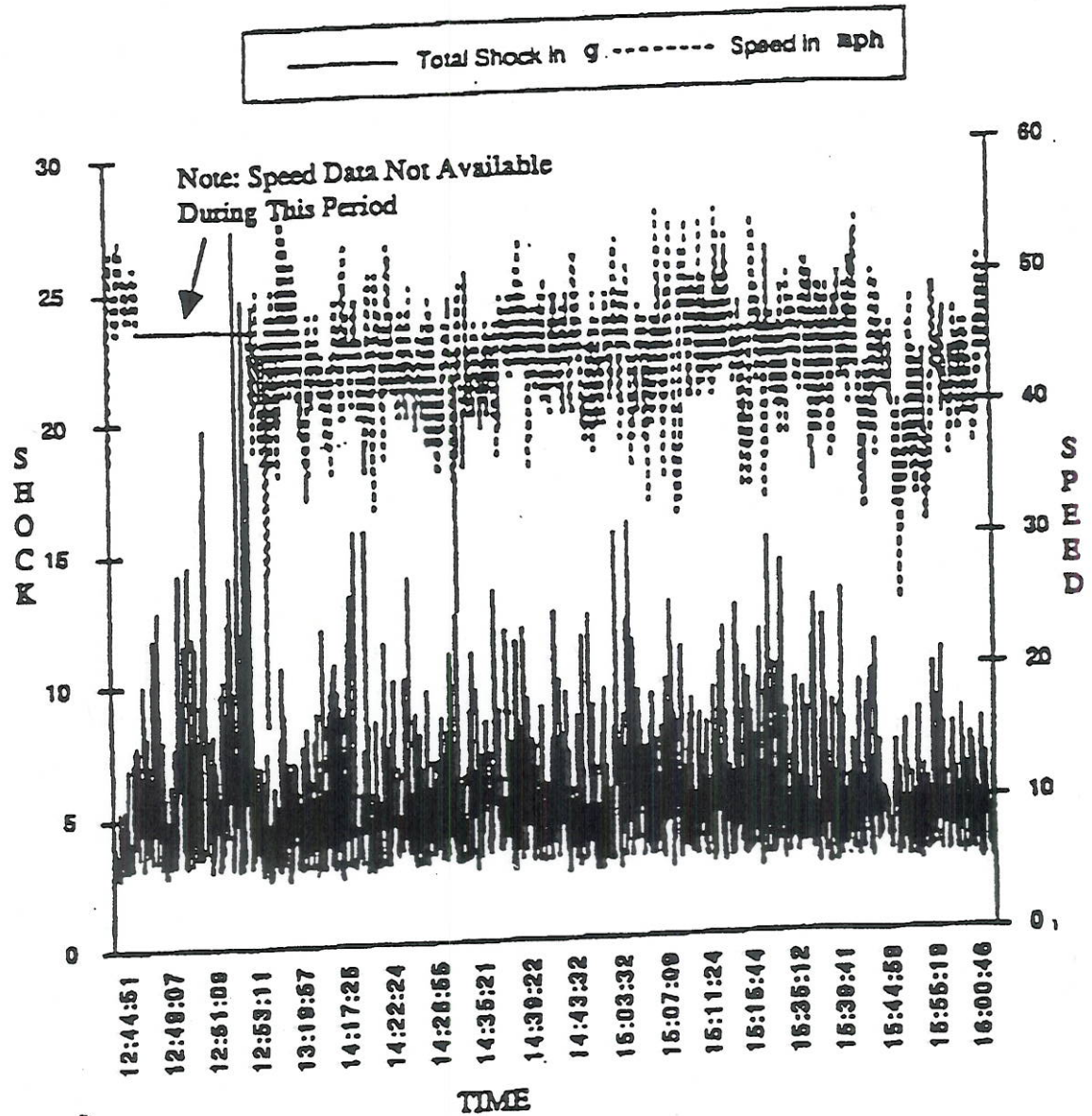


FIGURE 2. SAMPLE SHOCK VS. SPEED COMPARISON FOR NSW HSBS FROM EXPOSURE

RECOMMENDATIONS

The following recommendations are presented concerning the impacts incurred during HSB operations.

- Use the present methodology and baseline data to evaluate future HSB designs.
- Refine the techniques developed in this study to further develop a baseline database of impact data relative to HSB operations. Incorporate lessons learned to mitigate lost time and effort.
- Extend the study to include other NSW platforms such as the 10-m rigid inflatable boat (RIB), the I-rigid inflatable boat (IRIB), and the 24-ft RIB.
- Instrument the new NSW HSB to determine if recent changes to the craft's design have reduced the size and frequency of sudden impacts and/or increased the operators/passengers capability to tolerate exposures.

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3. Village, Judy, Development of a Standard for the Health Hazard Assessment of Mechanical Shock and Repeated Impacts in Army Vehicles, British Columbia Corporation, Applied Physics Division, Project # 6-07-409, 1992.
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**APPENDIX A
INSTRUMENTATION**

Peak Acceleration Logger (PALs): PALs from Dallas Instruments are self-contained, battery-powered, microprocessor-controlled data loggers with internal memory. They are housed in an aluminum container (10.25 by 5.875 by 3.5 in.) and weigh 5.2 lb. They receive data from three internal accelerometers (one on each axis, X, Y, and Z) 2000 times/sec. PALs are programmable for an impact magnitude range of 1 to 200 gs; for frequency ranges 1 to 25, 1 to 50, 1 to 100, and 1 to 200 Hz; and for logging intervals of 1 sec, 1 min, 5 min, and 15 min. During testing, the PALs were set to record shock magnitudes greater than 2 gs, lasting more than 40 msec every second.

Trimbal "TrimPack" Global Positioning System (GPS) Receiver and Antenna: The TrimPack is a battery-powered course acquisition (CA) code receiver with approximately 25-m accuracy. It works with an external antenna for GPS reception between 1.565 and 1.585 GHz. This setup was used to receive and fix GPS data during testing.

Compaq LTE 386 Personal Computer (PC): LTE 386 PC is a battery-powered computer with a 386 microprocessor; two serial and one parallel port; and 110 Mbytes of random access memory (RAM) and an 80 Mbyte hard drive for storing memory. Its dimensions are 12 by 8 by 3 in. and weighs approximately 7 lb. It was used for two functions: (1) to program the PALs for test settings and (2) to read and record GPS data during testing. The computer's hard drive was locked during testing to prevent damage. Data were recorded on a RAM disk and later transferred to the hard drive.

Instrumentation Mounting: During testing, all instruments were mounted inside ammunition canisters to prevent water damage, and because there were existing brackets in Naval Special Warfare high-speed boat (HSB) for ammunition canisters. The two aft ammunition canisters were placed in pre-existing HSB racks where they were secured using 2-in. wide ratcheting nylon straps. The forward center mounted ammunition canister with PAL was strapped down to the deck immediately behind the operator's/passenger's position.

APPENDIX B
DATA TEST EXPOSURE 1

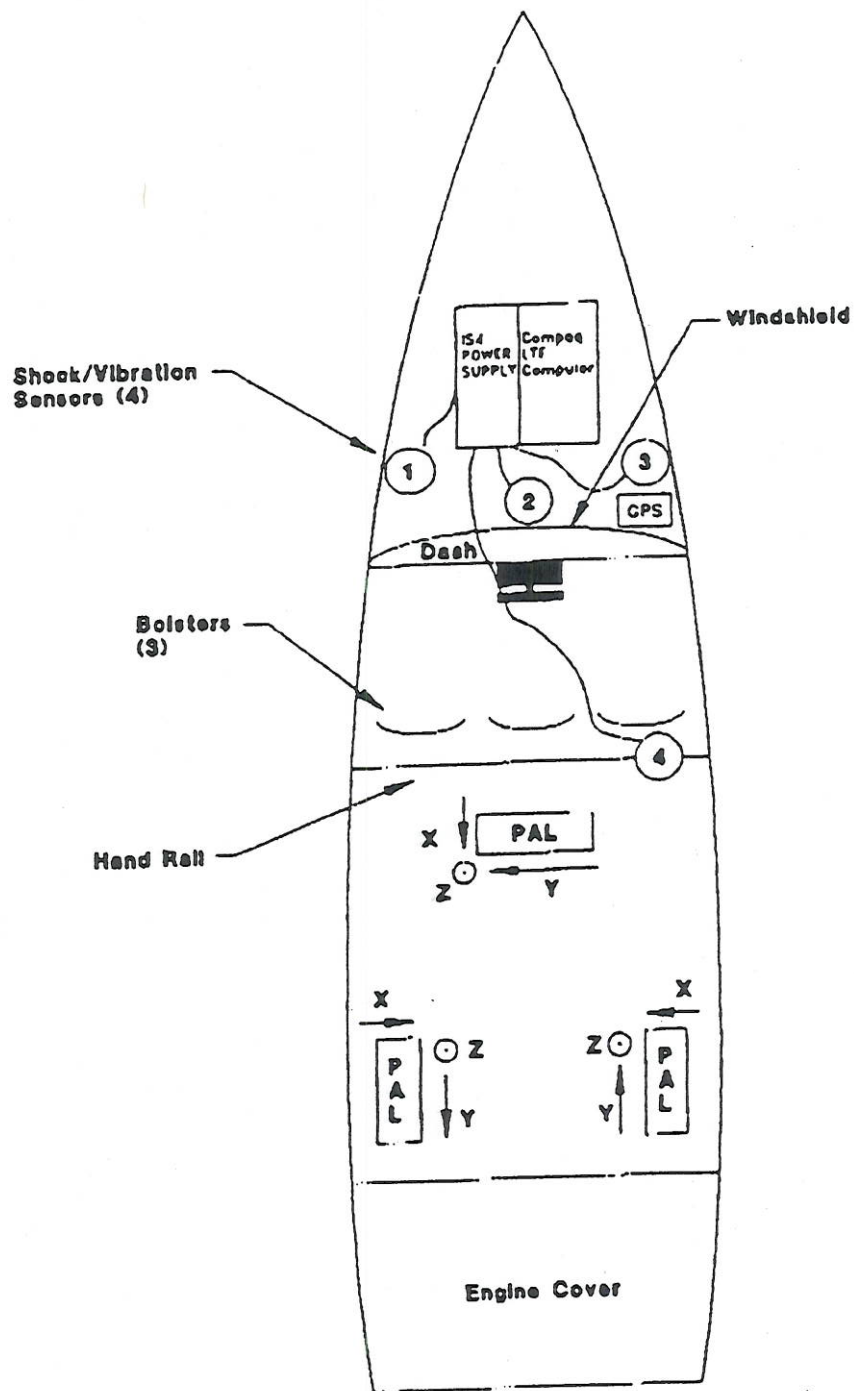


FIGURE B-1. SOC INSTRUMENTATION FOR EXPOSURE 1

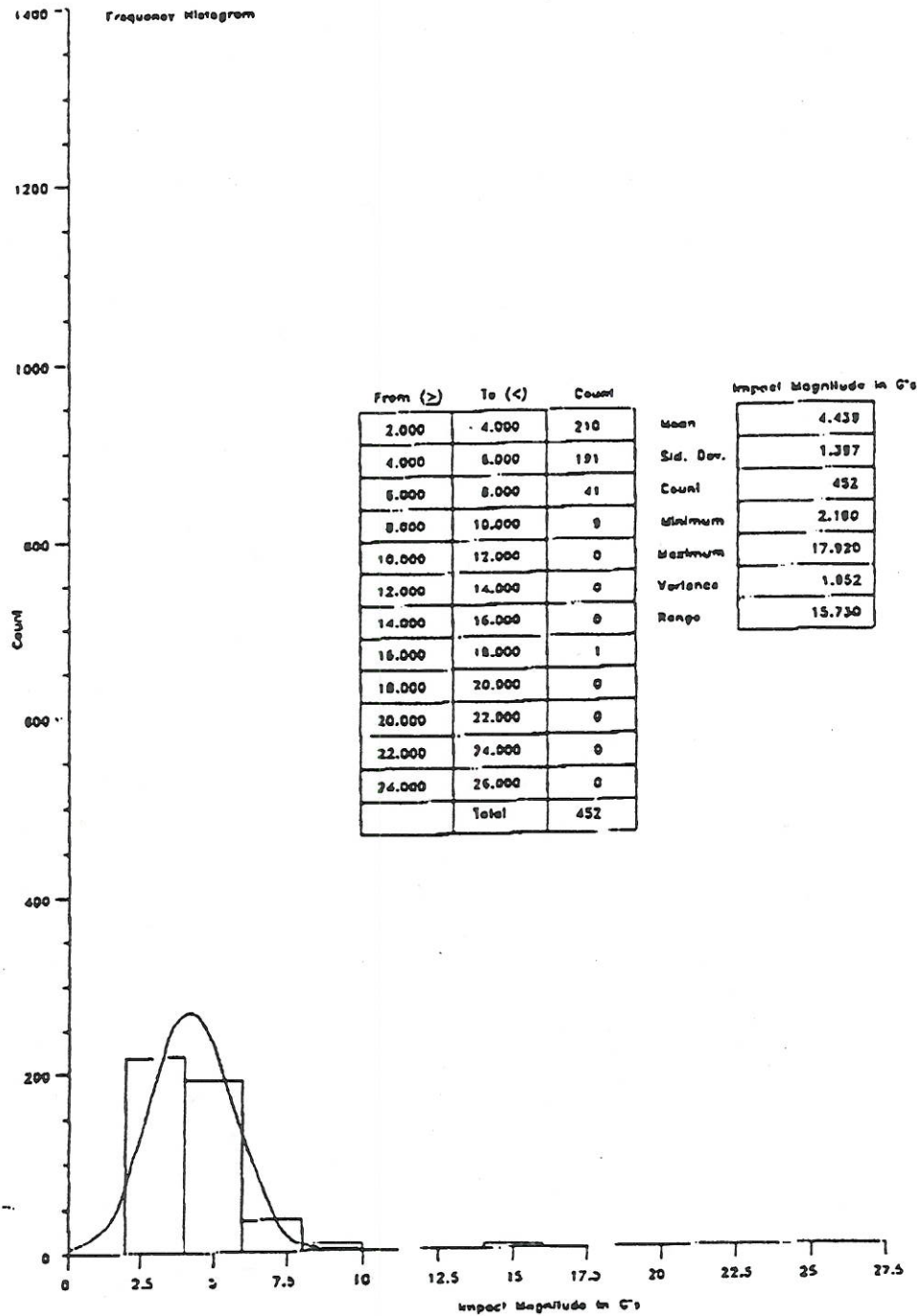


FIGURE B-2. DISTRIBUTION OF SHOCKS BY FREQUENCY AND MAGNITUDE DURING EXPOSURE 1

APPENDIX C
DATA TEST EXPOSURE 2

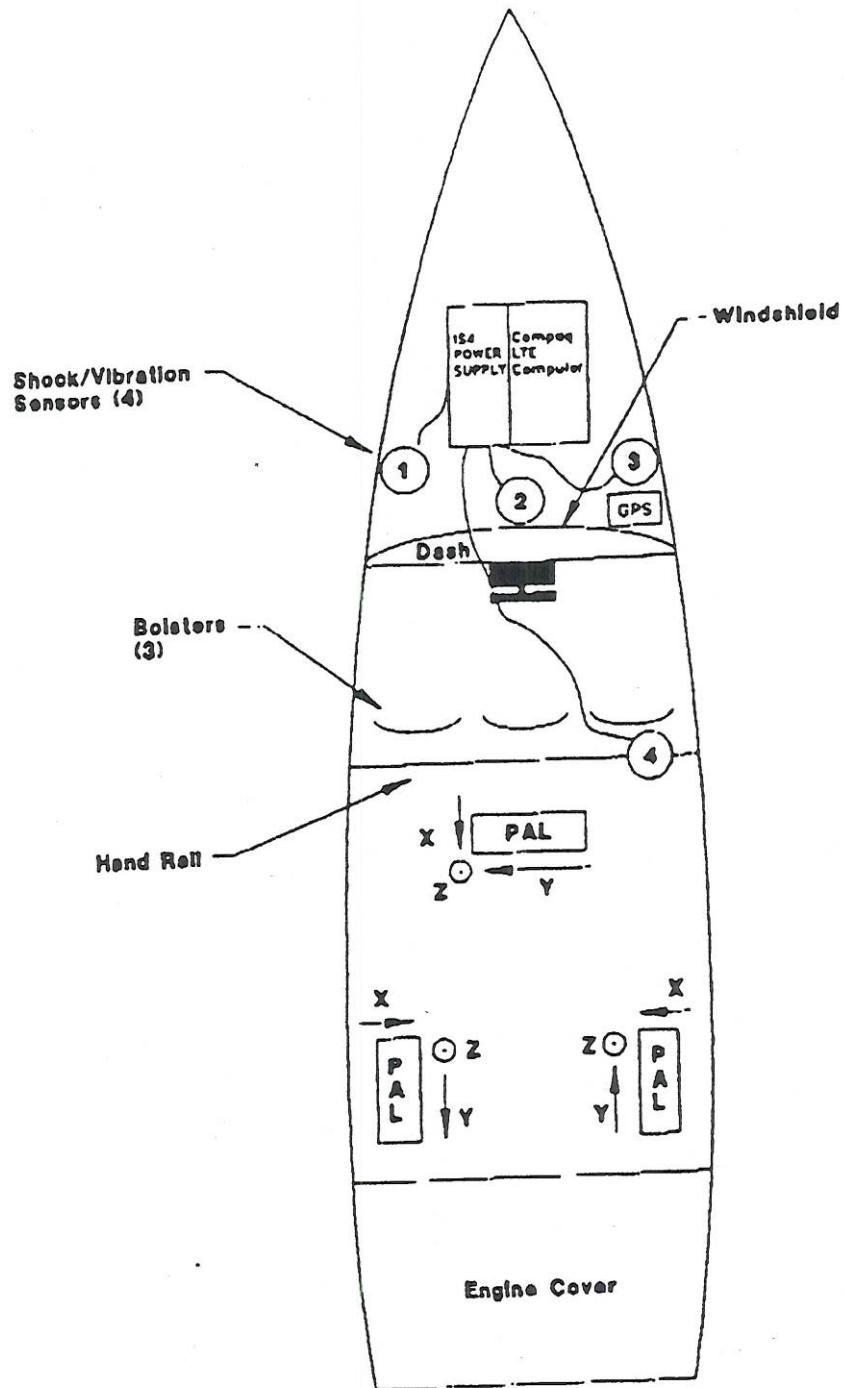


FIGURE C-1. SOC INSTRUMENTATION FOR EXPOSURE 2

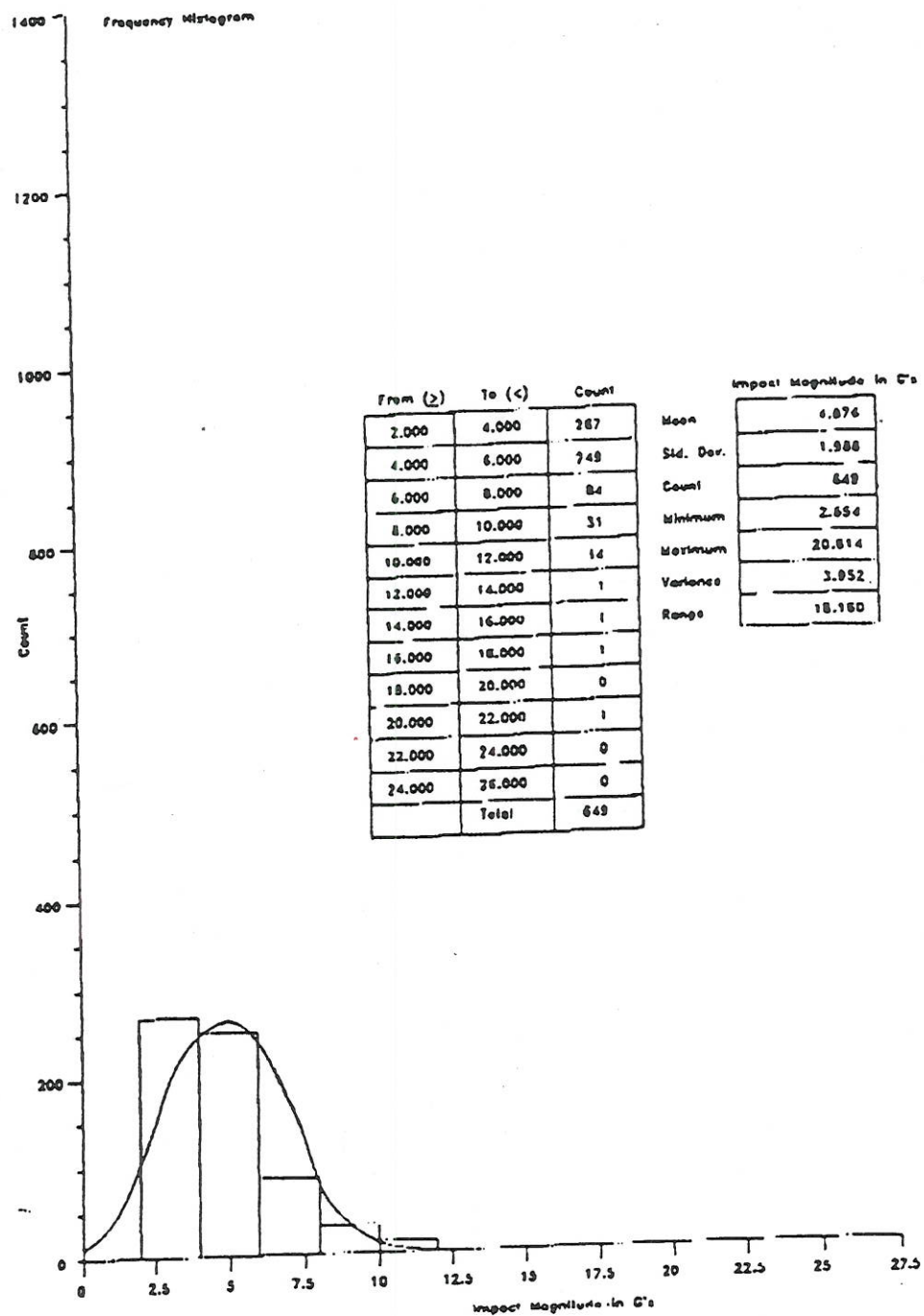


FIGURE C-2. DISTRIBUTION OF SHOCKS BY FREQUENCY AND MAGNITUDE DURING EXPOSURE 2

APPENDIX D
DATA TEST EXPOSURE 3

D-1/D-2

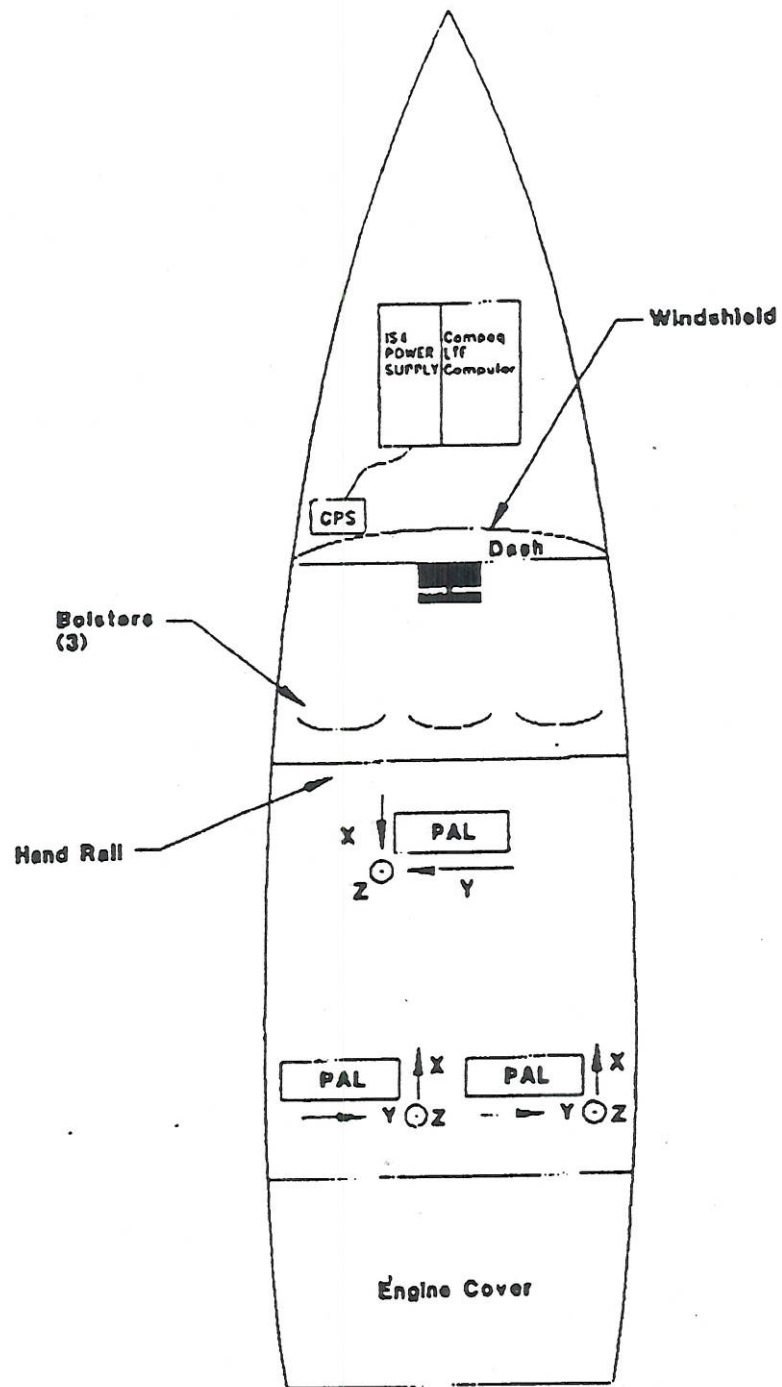


FIGURE D-1. SAC INSTRUMENTATION FOR EXPOSURE 3

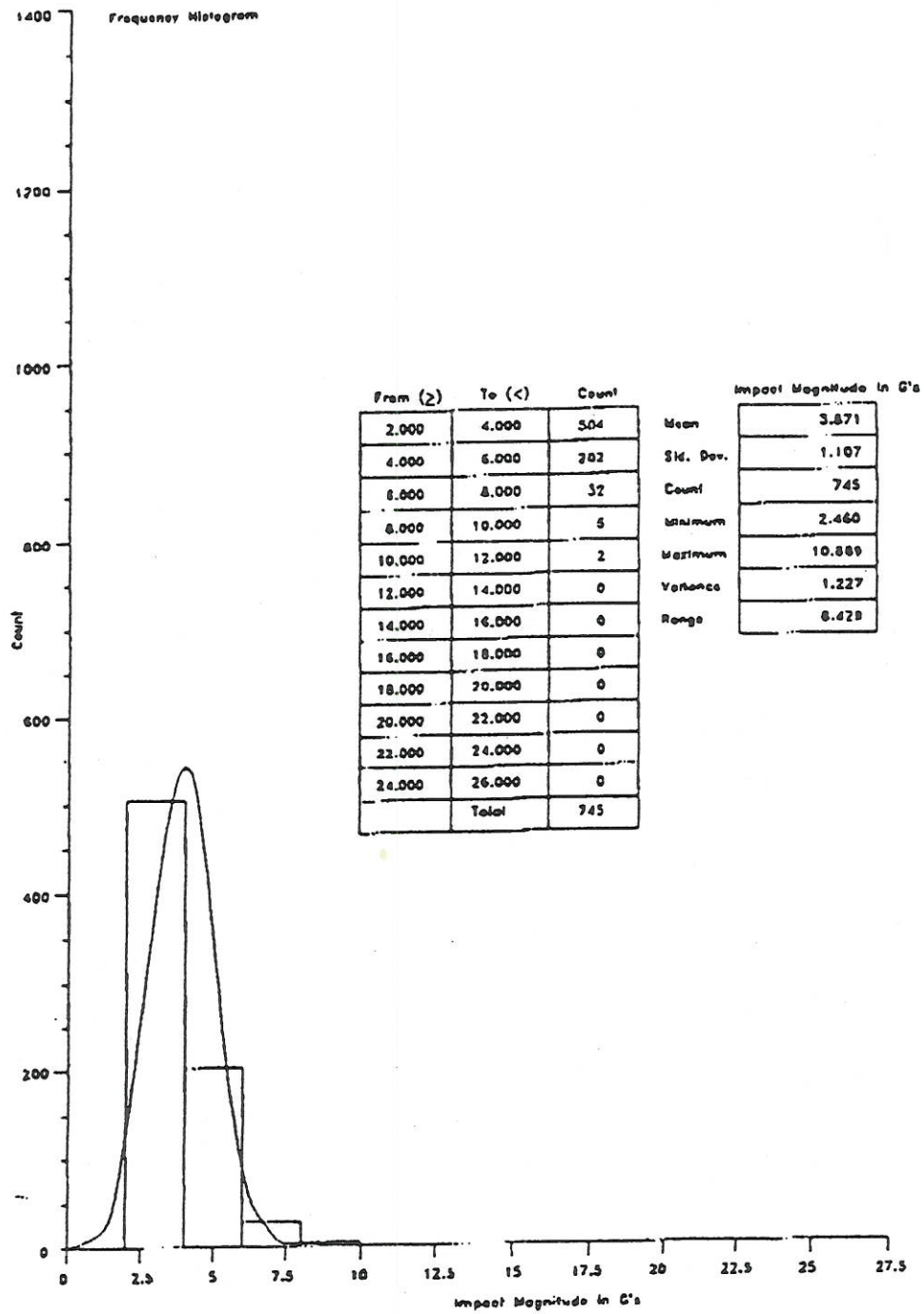


FIGURE D-2. DISTRIBUTION OF SHOCKS BY FREQUENCY AND MAGNITUDE DURING EXPOSURE 3

APPENDIX E
DATA TEST EXPOSURE 4

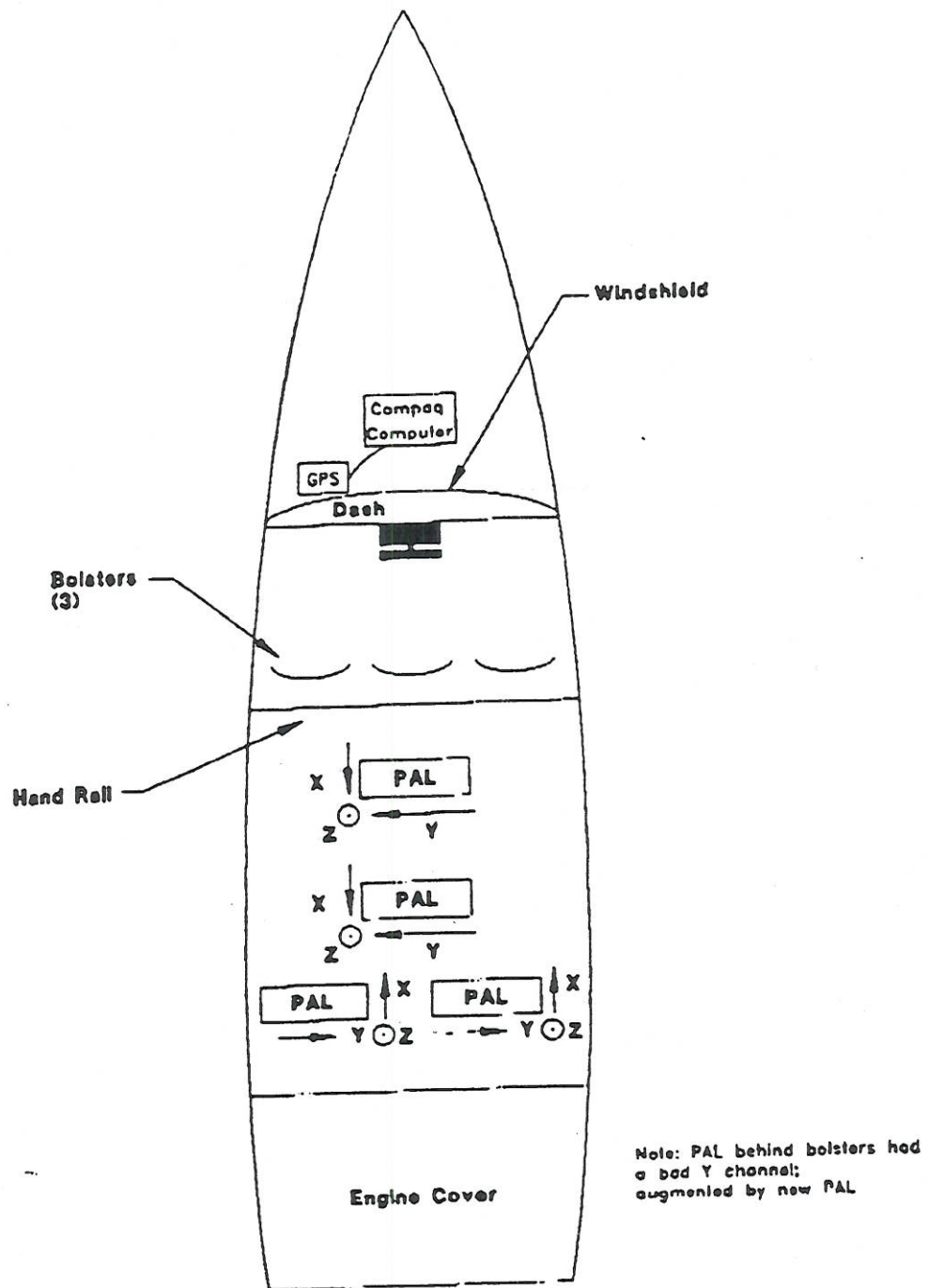


FIGURE E-1. SAC INSTRUMENTATION FOR EXPOSURE 4

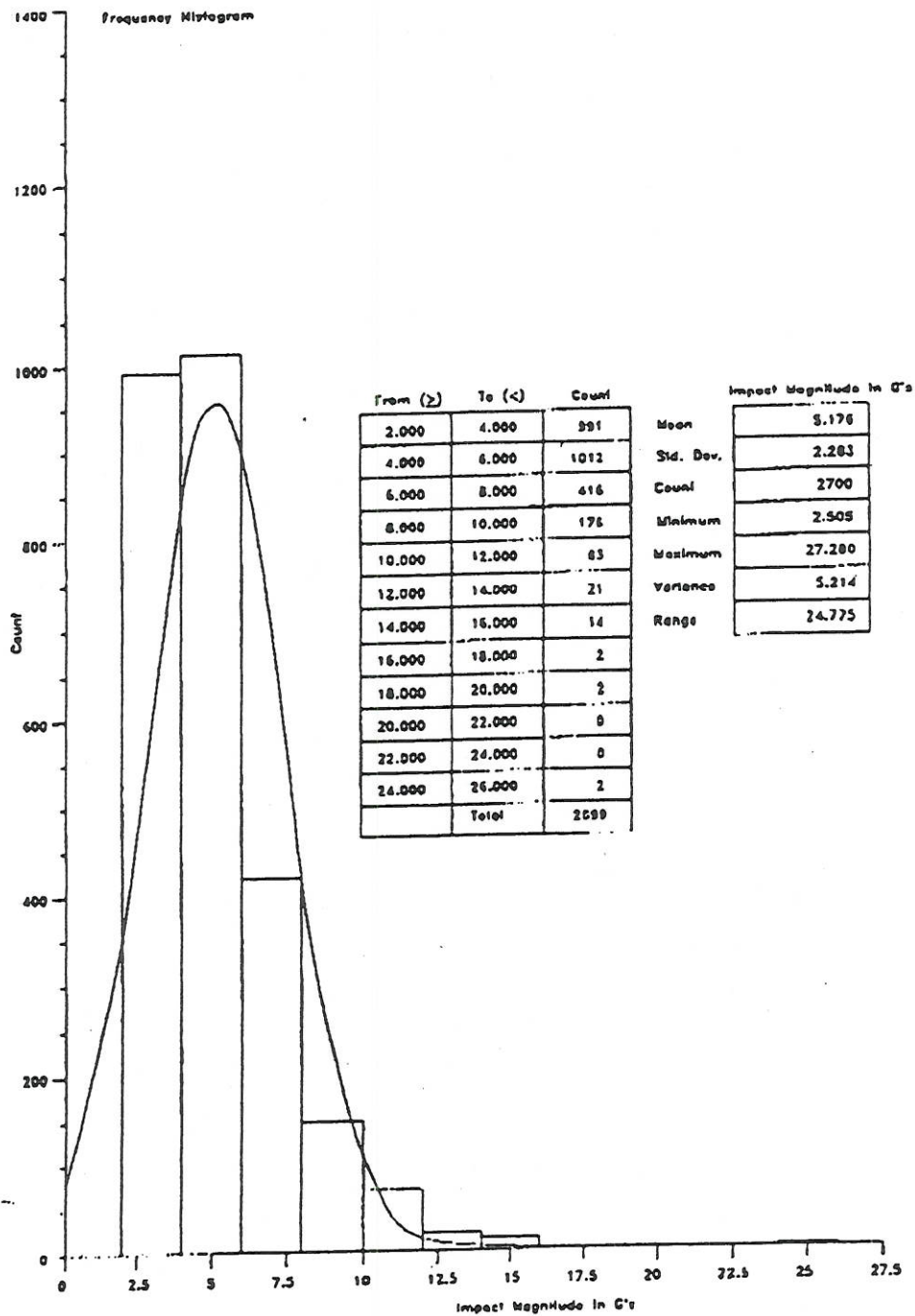


FIGURE E-2. DISTRIBUTION OF SHOCKS BY FREQUENCY AND MAGNITUDE DURING EXPOSURE 4

**APPENDIX F
DATA TEST EXPOSURE 5**

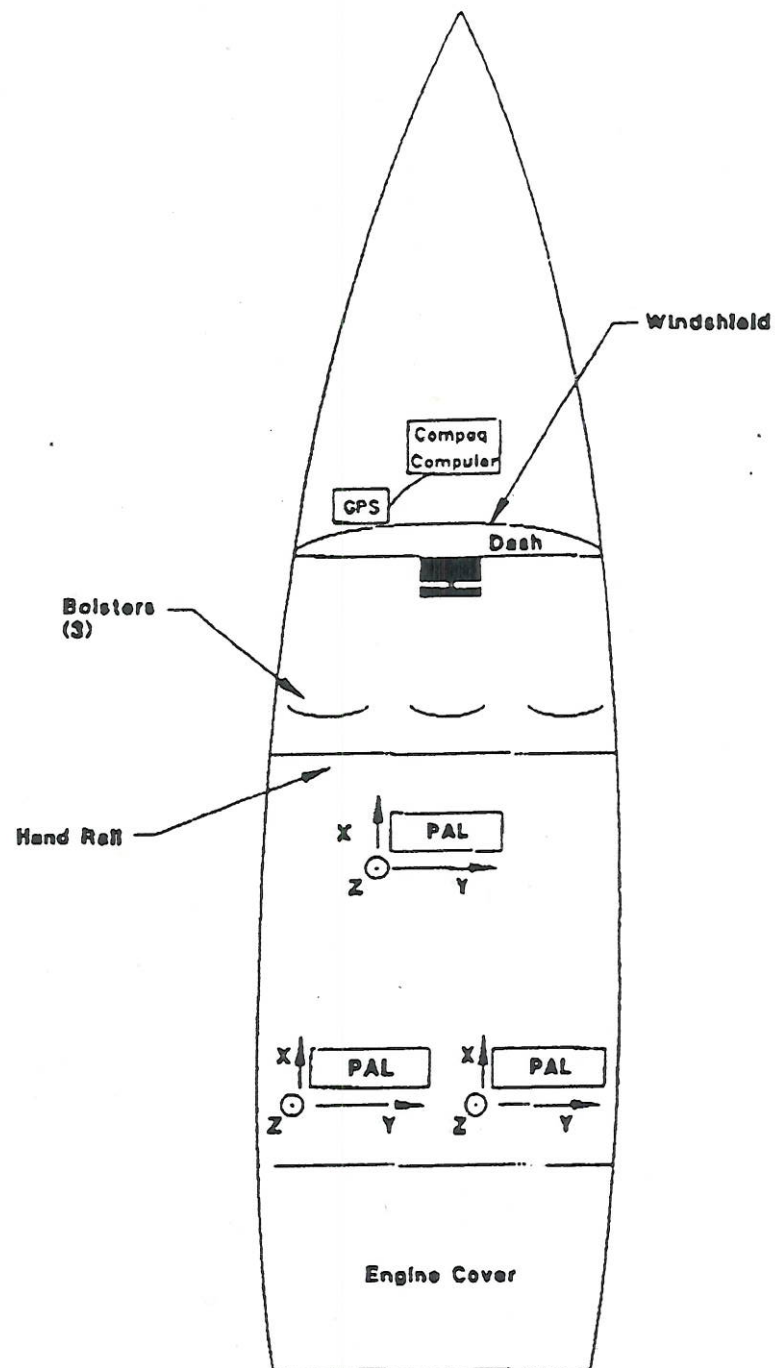


FIGURE F-1. SAC INSTRUMENTATION FOR EXPOSURE 5

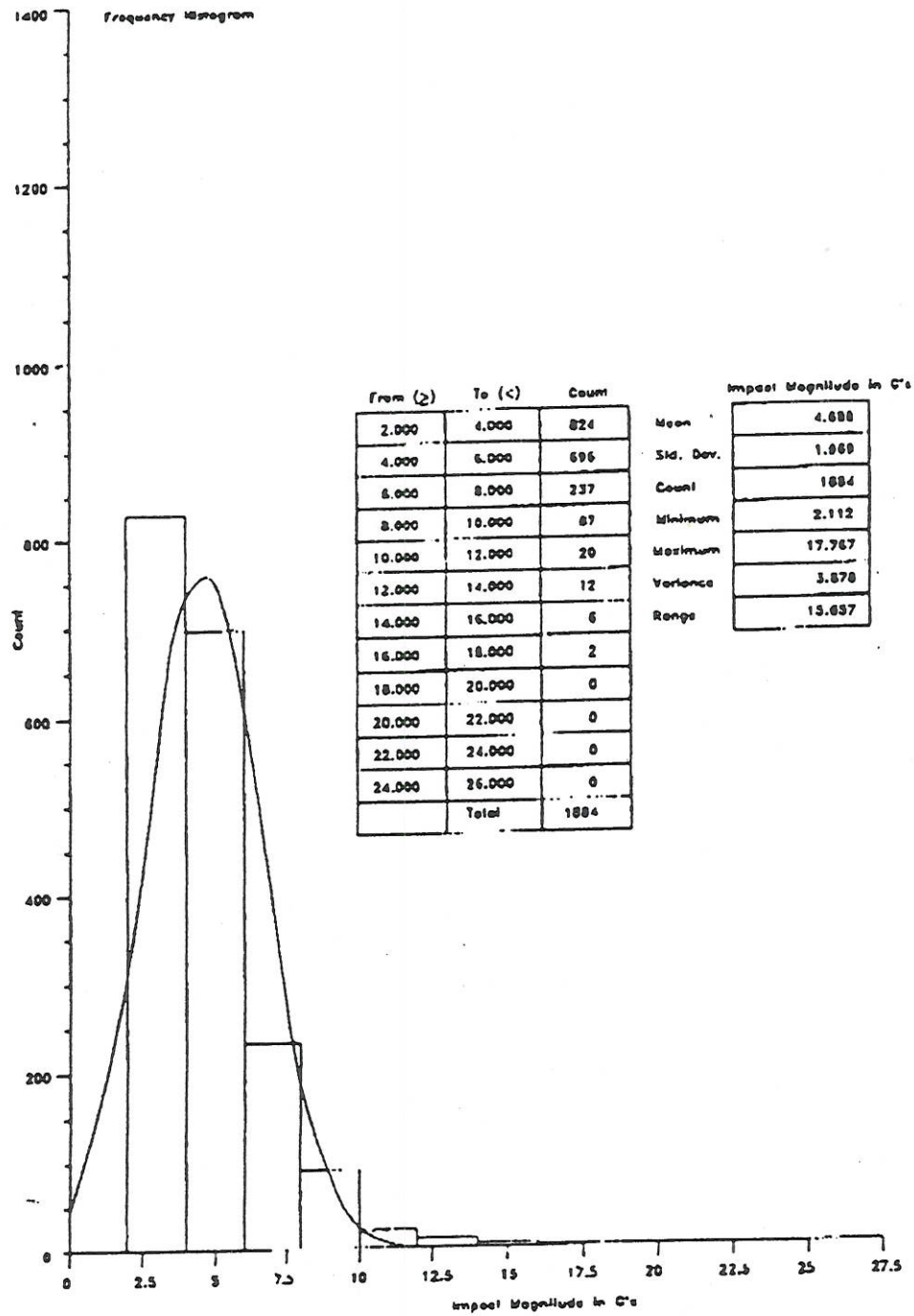


FIGURE F-2. DISTRIBUTION OF SHOCKS BY FREQUENCY AND MAGNITUDE DURING EXPOSURE 5

APPENDIX G
DATA TEST EXPOSURE 6

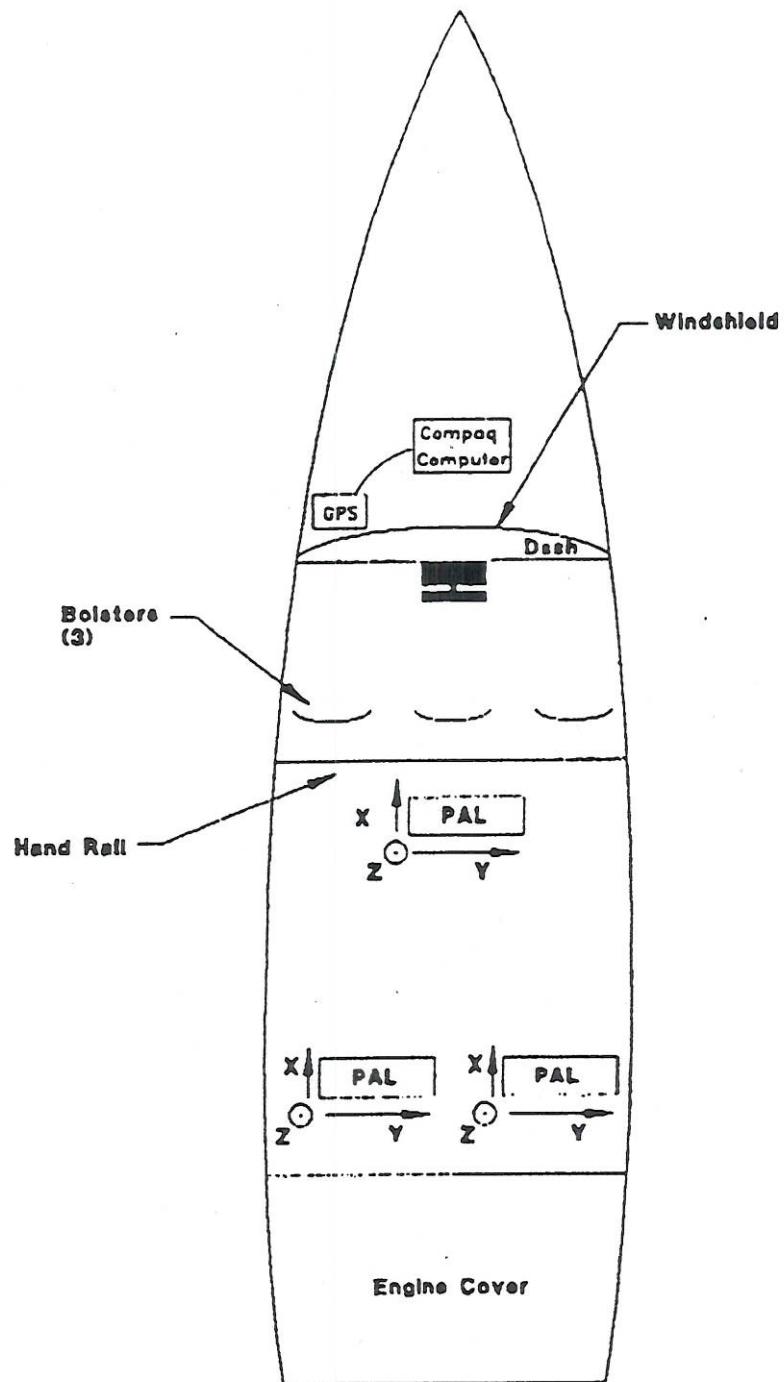


FIGURE G-1. SAC INSTRUMENTATION FOR EXPOSURE 6

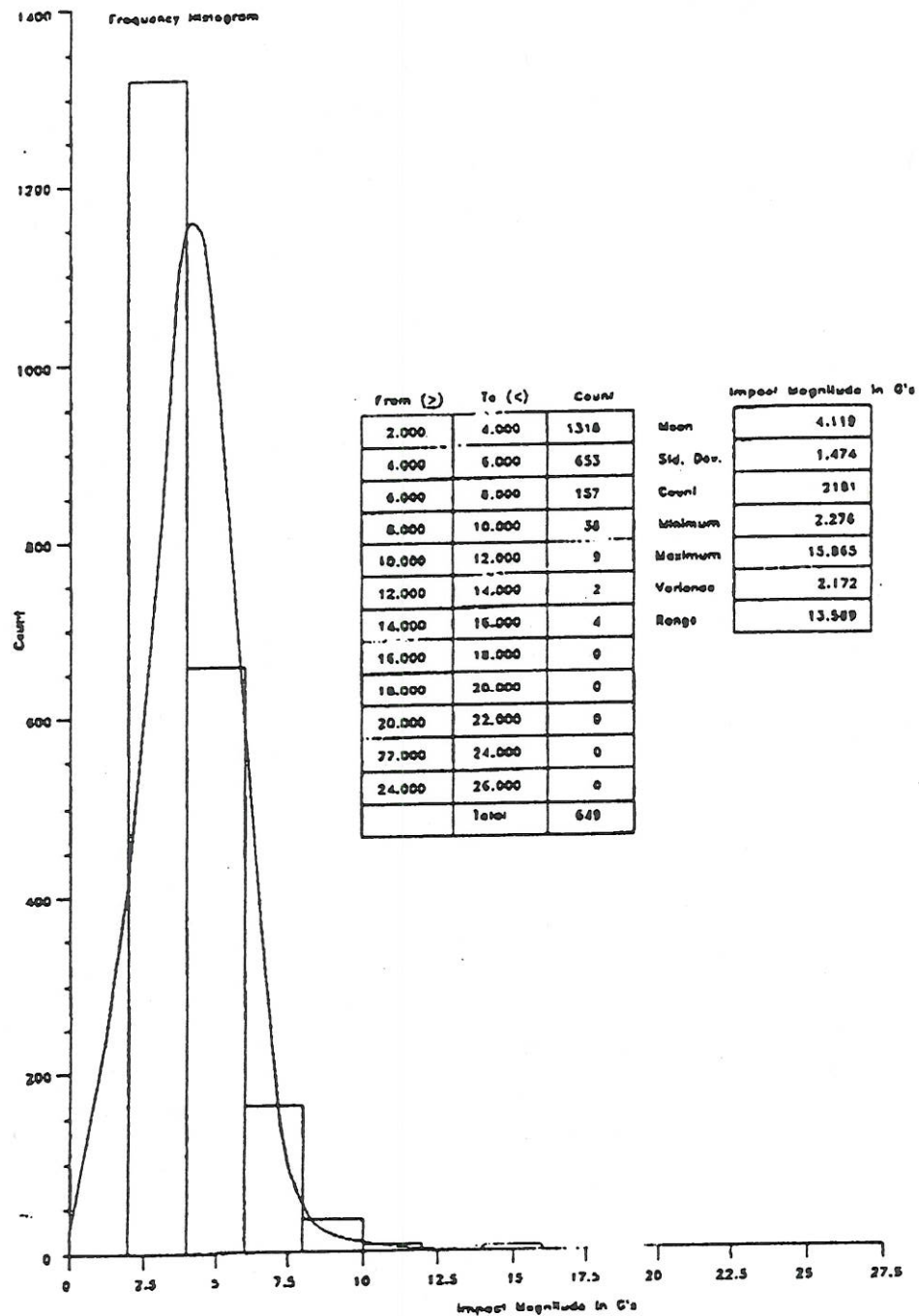


FIGURE G-2. DISTRIBUTION OF SHOCKS BY FREQUENCY AND MAGNITUDE DURING EXPOSURE 6

**APPENDIX H
LESSONS LEARNED**

H-1/H-2

The following anecdotes, observations, and comments are gleaned from authors' notes taken during the conduct of the study.

Comments From Tests

We did record subjects' appraisals of shocks and the time they occurred and compared that subjective data with the objective record of the Peak Acceleration Logger (PAL). We found that subjective ranking of shocks did appear to correlate positively and highly with objective ranking.

Launching and landing of the boat do not always injure the operators/passengers. The throttleman and helm can make a launch and landing look spectacular but be relatively smooth. Experienced operators/passengers learn how to prepare for an oncoming landing. It does hurt when the boat hits a large wave at speed and does not launch, and all of the energy (of the shock) is absorbed by the boat and operator/passenger instead of being dissipated by a lifting of the boat. A related event occurs when the boat launches off a wave and hits another wave that is rising as the boat is falling. Another potentially harmful event is a stern landing on the flat part of the hull under the engines. Of course, any landing that is not anticipated can cause injuries.

Naval Special Warfare high-speed boat operators and passengers label the phenomenon of being tossed in the air and losing their footing and grip as "decoupling." Becoming decoupled from the boat is very threatening to operators/passengers and can be lethal, especially if another impact occurs before "recoupling."

At the end of a boat ride, an adrenalin high may exist and seem to override the fatigue. We do not know the effects of repeated shock on boat operators/passengers 3 hr past exposure, the next day, the next month, or a year later.

Problems in Field Test

The Global Positioning System (GPS) had a momentary power interruption that locked up the software and caused all data being recorded by the LTE 386 PC to be lost (for that exposure).

To gather data on the computer interactive tests at remote sites, we placed an uninterrupted power source (UPS) between the gas-powered generator and the computers. This UPS was a battery bank that was charged by the generator and in turn powered the computers through power interrupters. This setup was necessary to protect the computers from power spikes that are common with generators. We turned on the system in anticipation of the operator's/passenger's arrival only to find the entire system dead when data collection began. After much investigation, we removed the UPS from the circuit and ran the computers directly off the generator. Later we learned that the batteries in the UPS were dead. Evidently the electrical power from the generator had so many spikes that the UPS interrupted the power from the generator. The computers ran for the short time off the batteries in the UPS until they were drained.

The alkaline batteries of the wave height meter (which worked fine) were replaced by "better" LIOH batteries. The LIOH batteries were damaged during shipment so the wave height meter did not turn on. Batteries were replaced again. The wave height meter mast was originally made of aluminum; it cracked on the first day. A steel mast with a short section of aluminum was used the second day; it broke at the steel-to-aluminum threads. A steel mast was finally used.

The motherboard of the Compaq LTE computer failed. When it was repaired, the math coprocessor that was necessary for data collection was left out of the computer. Later, a math coprocessor was installed.

After the preliminary testing, it was decided to return all of the testing equipment via Federal Express. The Federal Express airplane crashed into salt water, which wiped out the equipment. Furthermore the Navy ships items "self-insured," which meant that the equipment was not insured and that the Program Office had to pay for the replacement of the test equipment.

Systematic calibration of sensors is required. In one instance, three sensors needed calibration. One was calibrated twice and one was not calibrated at all. Finally all of them were calibrated.

Software written in the laboratory can be negatively affected by field conditions. The GPS data collection software required a physical connection and input from the GPS to the computer. This condition was necessary to end data collection and save the data. In the laboratory, data input was always available. In the field, it was necessary to disconnect the computer from the GPS before saving the data; the program precluded saving the data unless the GPS was connected. Therefore data could not be saved within the program. An additional software problem occurred when satellite link was lost within a certain loop. In this case, the program would lock up.

An existing screw on one of the HSBs was just long enough to bottom out inside an accelerometer and destroy it during testing.

The Oak Ridge National Laboratory (ORNL) tape recorder would operate on 12, 28, or 110V power. The 28V was selected because it was the most reliable. At the dock, the system worked fine; however, the recorder shut down on low voltage after getting underway. The cause was installation of a unique silver zinc battery in the power supply that did not recharge from ship alternators. This battery required a special charge in the ship and had to be replaced at a cost of \$30,000.