SSC-210

ANALYSIS OF SLAMMING DATA FROM THE S.S. WOLVERINE STATE

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1970

Dear Sir:

Among the contentious subjects in ship design has been the degree of influence of slamming stresses on the ship's hull girder. To determine the effect more precisely, the Ship Structure Committee initiated a project to add pressure transducers to the bottom plating of a partially instrumented ship.

The results of this collection of service data and the relationship between the slamming process and the hull and local plating response to concurrent wave conditions, ship speeds, and wave-induced bending moments are described in this report.

Sincerely,

W. F. Rea, III
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

SSC-210

Final Report
on
Project SR-172, "Slamming Studies"
to the
Ship Structure Committee

ANALYSIS OF SLAMMING DATA FROM THE *S.S. Wolverine State*

by

J. W. Wheaton, C. H. Kano, P. T. Diamant
and F. C. Bailey

under

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U.S. Coast Guard Headquarters
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1970

ABSTRACT

The stress recording system aboard the *S.S. Wolverine State* was expanded to include pressure transducers and accelerometers. Stress, pressure, and acceleration signals were recorded on magnetic tape over a period of three years, and data on hundreds of slams were recorded.

Slamming occurred only at Beaufort numbers above 5, and under relative headings within about 30 degrees of head seas. Reduction of speed did not appear to reduce the frequency of slamming, but the forward draft was a significant factor. Ochi's predictions of the statistical distribution of slamming occurences were confirmed, as were his model data relating pressure and relative velocity at impact. The bow acceleration was found to be a sensitive indicator of slamming phenomena, and relationships between acceleration, velocity, and pressure were established. Slamming pressure levels were consistent with ship model test results, but were less than other full-scale and drop-test data reported in the literature.

TABLE OF CONTENTS

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I. INTRODUCTION

As one of the generators of hull girder stress and of localized structural damage, slamming deserves the attention of those responsible for the design, fabrication, and operation of ships.

It is the intent of this report to present the results of pressure, acceleration, and midship stress measurements associated with slams, and to discuss the extent to which these data provide the desired information. The instrumentation system and method of data reduction and presentation are discussed, and conclusions and recommendations are presented. Stress data from the SS WOLVERINE STATE are reported in Reference 1, and background information on other theoretical and experimental studies are summarized in Reference 2.

II. VESSEL INSTRUMENTATION AND DATA COLLECTION

A. General

Detailed descriptive information on the SS WOLVERINE STATE is contained in Table A-III. The vessel is a C4-S-B5 general cargo carrier, machinery aft, built in 1945. Basic particulars are: Length Overall, 520 feet; Beam, 71 1/2 feet; Depth, 54 feet; and a capacity of 15,348 dwt.

B. Instrumentation

The vessel was instrumented with 20 pressure transducers along the keel in the forefoot region between Frame #5 and Frame #55. (See Appendix A for a detailed description of the instrumentation system). In the vicinity of Frame #30 and Frame #40, pressure gages were placed in a plane transverse to the keel extending to the turn of the bilge. The purpose of this array of transducer locations was to provide measurements of the longitudinal and transverse pressure profile in the region of previously recorded bottom plate damage. Accelerometers were placed at the extreme ends of the cargo space and provided measurements of slam-induced accelerations of the bow and stern of the ship. These accelerometers and the existing midship stress gages provided verification of the occurrence of a slam as discussed below in more detail. Not all of the transducers were recorded on the F-M magnetic tape recorder at one time, since only 12 channels were available for data. The scheme used for the duration of this study is described in Table A-I, and consisted of stress, acceleration, and seven selected pressure measurements. Once suitable data had been obtained on the selected array of pressure gages (see Figure A-3), it was planned to switch the system to record the output of another array.

C. Data Collection

The period of data collection covered by this report started in March, 1966 and ended in April, 1969. The period between March, 1966 and February, 1968 (Voyages 261 to 282) was occupied with voyages on the North Atlantic, from the east coast of the United States to northern Europe. Voyages 283 through 286 (November, 1968) were from the east or west coast of the United States to the far east. The last instrumented voyage, 288, was from Baltimore to southern Europe, and ended April 4, 1969.

As noted in Appendix A, the basic recording scheme consisted of an automatically programmed acquisition of one-half hour of data each four hours, unless certain overriding conditions--such as high stresses--triggered the recording cycle.

Using techniques to be discussed in the following section, it was established that significant slamming occurred during only three voyages for which data were available: 263, which terminated in June of 1966, 277 in April of 1967, and 288 in April of 1969.

The trans-Pacific runs were disappointing from the point of view of slamming. This is not totally surprising, however, when one considers the fact that the vessel on most westbound crossings was loaded to a deep draft. Under these circumstances, slamming was less likely to occur.

III. REDUCTION AND PRESENTATION OF DATA

A. General

Slamming data are presented in this report as tabulated measurements of accelerations, pressures, and stresses for a large number of slams which occurred during Voyage 288, and also as detailed measurements on expanded records of six slams which occurred during Voyage 277. The following parts of this section describe the general data reduction procedures, the equipment used, some of the important characteristics of both the transducers and the recording system, and present the specific data. Detailed discussions of the results of analysis and interpretation of the data appear in Section VI.

B. Selection of Intervals and Criteria for Slamming

Experience with stress recordings obtained from the WOLVERINE STATE in the years prior to the installation of the slamming instrumentation indicated that slamming rarely occurred when the Beaufort wind scale number was below 6. Slams were detected by expanding the normal "quick-look" record so that first-mode transient vibrations in the stress record could be seen. Because of the normal quick-look time compression (one-half hour of real time presented in about two inches of record), neither these stress transients nor pressure pulses can be detected without expansion.

After the pressure transducers were installed and some data were acquired, the search for slams was undertaken by inspecting, as the first step, entries in the logbooks kept by the vessel's crew for the investigators. Of particular interest, besides any direct observation of slamming, was Beaufort wind scale, wave height, and heading. Those intervals having reported Beaufort numbers greater than 5 or other indications of probable slamming were then expanded and inspected for transients. Once valid slamming signals were identified, detailed expanded records were prepared for analysis. In this way the study was narrowed down to 6 intervals in Voyage 263 containing approximately 196 slams, 4 intervals in Voyage 277 (about 163 slams), and 3 intervals in Voyage 288 (about 1142 slams). All intervals contained four hours of continuous data. In all three cases slamming occurred on the westbound portion of the voyage. Appendix B contains reproductions of the pertinent logbook sheets from Voyages 263, 277, and 288. As noted in "A" above, the data analyzed in this report were obtained from the two most recent voyages. The high concentration of slams in Voyage 288 and limitations on time and funding led to the decision to by-pass temporarily Voyage 263.

A large number of first-mode bending stress transients appeared to have been induced without the forefoot of the vessel leaving the water. However, for the purposes of this study a slam must involve the emergence of the forefoot and its subsequent reentry, as demonstrated by a flat portion on the low pressure transducer at the forefoot as it senses atmospheric pressure. This flat portion is followed by the transient pressure increase upon bow reentry and then by decay to the low frequency pressures associated with the pitching of the vessel. The characteristic appearance described above is illustrated in Figure 1.

C. Data Reduction System

The equipment used to reduce the slamming data was essentially the same as that used routinely to process the stress data from the ships instrumented under Project SR-153. In order to be able to see the short-duration slams, however, the laboratory tape recorder speed was reduced to 1-7/8 inches per second, a 6.25:1 speedup from real (ship) time. In addition, the oscillograph paper was run at speeds up to 25 inches per second in order to provide detailed information on individual slams.

Because the slamming instrumentation aboard ship was based on use of the Honeywell LAR 7468 tape recorder running at 0.3 inches per second (see Appendix A for a detailed description), the frequency content of the reproduced signals was necessarily limited to below 50 Hz. Thus, higher frequencies which may be considered to contribute to the short rise-time and narrow width of a slamming pressure would not appear in the reproduced signal. With this knowledge, an attempt was made early in the program to record slamming data with a wide-band recording system by making a manned voyage. The characteristics of the pressure transducers and their associated signal-conditioning electronics are such that slamming pressure signals having frequency components up to 2,000 Hz could have been recorded using oscillograph galvanometers. Unfortunately, the voyage selected for manning was quite calm, and slamming conditions were not encountered.

In order to assess the degree to which the 0-50 Hz bandwidth would distort triangular pressure pulses of short duration, an experiment was performed in the laboratory using a signal generator, a filter, and an oscilloscope. A triangular pulse with a base width of 100 milliseconds was generated, filtered, and compared with the unfiltered signal. This pulse width is similar to those found on the high-pressure transducer at Location 2.

The results are shown in Figure 2. With an equivalent signal frequency of 10 Hz and a low-pass filter cutoff of 30 Hz, there is only a small amount of distortion of the pulse, and its amplitude is attenuated by only a few percent, as indicated by direct comparison of the filtered and unfiltered waveforms.

This laboratory experiment indicates that the 50 Hz bandwidth limitations of the recording system will probably not cause significant distortion of measured pressure pulses down to about 50 or 60 milliseconds duration. However, for shorter pulses there would be increasing attenuation and distortion. For example, a reproduced pressure pulse which shows a base width of only 25 milliseconds is probably the distorted result of a real pulse approximately twice as short and twice the apparent amplitude.

A characteristic of the frequency-modulation (FM) system of tape recording is the inability of the reproduction system to distinguish between real frequency variations (data) recorded at constant tape velocity and variations in tape velocity with a constant recorded frequency. Thus, mechanical noise and vibrations which cause any variations in tape speed past the head are to be avoided. Compensation for such mechanically-induced electrical noise is possible through the assignment of one track from each head to record a constant frequency. The reproduced signal from this "compensation" track contains only the noise which is common to all tracks, and

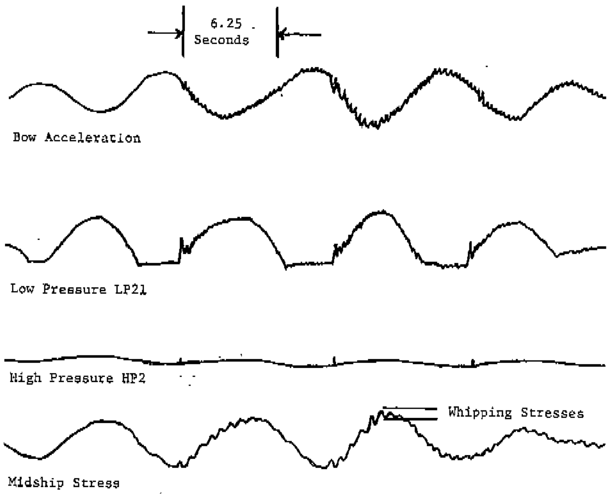
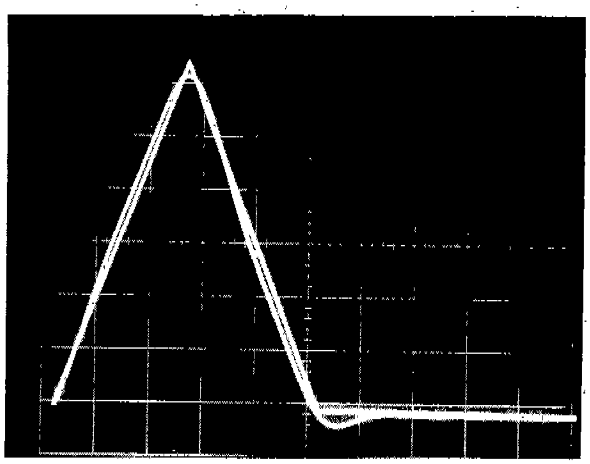


Fig. 1. Tracing of Typical Acceleration, Pressure, and Stress Signals During Slamming. Interval 57, Voyage 288W3



Fundamental Frequency: 10 Hz

Base Width: 100 milliseconds

Filter: 30 Hz cut-off, low pass

Fig. 2. Result of Low-Pass Filtering of a Triangular Wavefore Representing a Typical Pressure Pulse

can be used either to control the motor speed of the reproduction tape machine, or to provide a noise signal for electrical subtraction from the data-plus-noise signals on the other tracks.

The reproduction tape machine currently in use in the investigator's laboratory is an Ampex FR-1260. This machine uses the motor control, or "servo" method of compensation, which is excellent for removing the normal self-generated "wow" and "flutter" noise inherent in any tape recorder. However, it was found in the course of examining the data from the slamming voyages that this servo system was not able to remove satisfactorily the transient noise resulting from the shock to the tape recorder as a result of the slam itself. This noise, moreover, was about the same amplitude as the majority of the slamming pressure signals from the high-pressure transducers.

Considerable effort was expended, therefore, in attempts to remove this noise so that reliable pressure measurements could be reported. Eventually, these efforts were successful. They involved an adaptation of the noise subtraction technique to the reproduction tape machine, but this technique could be applied only to a maximum of two of the twelve data tracks (one odd and one even) at the same time, an unfortunate limitation requiring considerable duplication of the data reduction efforts.

In summary, the data presented here are based on relatively noise-free signals. Their amplitudes have been measured with reasonable accuracy. However, interpretation of the data must be made with knowledge of the characteristics of the individual transducers, and with the realization that frequency components over 50 Hz are attenuated.

D. Pressure Transducers

Two types of pressure transducers were used on the WOLVERINE STATE, and are described in detail in Appendix A. The high-pressure units were installed to measure the dynamic pressure on the hull induced by slamming. These units had flush diaphragms mounted at the hull surface in order to present a reliable picture of the pressures to which the hull was subjected. The low-pressure transducers were installed to indicate forefoot emergence and, possibly, to provide data from which relative velocities between hull and water surface could be calculated.

The sensing heads of these low-pressure units were connected to the hull-water interface by means of approximately four feet of Monel tubing. See Figures A-6 and A-8. Since this tubing probably contained a mixture of air and water when the vessel was slamming, the pressure measured by these transducers includes some indeterminate dynamic effect in addition to the gross pressure existing on the plate. Assuming insignificant attenuation due to the limitation of frequency response and damping, the measured transient slamming pressures from the low-pressure transducers can be as much as two times the real external transient pressures, as estimated from equivalent mass-spring considerations. However, no distortion would be expected after the initial slam transient.

E. Measurements from Voyage 288

Toward the end of Voyage 288 the WOLVERINE STATE encountered a storm which resulted in reported Beaufort numbers of 7, 8, and 9, with winds of 45 knots and wave heights of 20 feet. The logbook sheets covering this part of the voyage are reproduced in Appendix B, and the entries corresponding to recorded Intervals 56, 57, and 58 are indicated. The vessel was lightly loaded, with a forward draft of only 16.5 feet. The result was almost continuous slamming for the twelve hours covered by these three intervals. For example, the first twenty minutes of Interval 57 contain 47 slams, or almost one slam for every three pitching cycles.

Because of the high concentration of slams these three intervals were selected for detailed measurements of accelerations, pressures, and stresses. The data are presented in Table I. The measurements were made by making an oscillograph record of the Bow Acceleration, the pressures sensed by transducers at Location 21 (low-pressure) and Location 2 (high-pressure), and by the Midship Stress transducer, which was a half-bridge on the starboard side.

In the case of the Acceleration and Stress records, measurements of both the wave-induced signal and the transient slam response were made. For the low-pressure transducer at Location 21 (LP21), the total "static" pressure change from atmospheric to peak, the initial pulse height from atmospheric, the pulse height from a tangent to the pressure-time curve, and the time duration at atmospheric pressure were all measured and reported in Table I (see Figures 7 and 8). Pressures indicated by the high-pressure transducer at Location 2 (HP2) are also reported. In each case the scale factor is derived from the calibration signal at the beginning of the interval.

Figure 1 shows a typical segment of this record, during Interval 57.

F. Measurements from Voyage 277

A large number of slams was also recorded during the westbound portion of Voyage 277. For Interval 5 of Tape 2 (recorded March 24, 1967) Beaufort 9 was reported, with a wind speed of 35 knots, average wave height of 8 feet, an average swell height of 15 feet, and forward draft of 18.5 feet, as shown in Appendix B, pp. B-3 and B-4.

Table I-A.
Slamming Data From Voyage 288 Reel 3 Interval 56 (First 20 Minutes)
Relative Heading 19°; Beaufort 7, Fwd Draft 16 ½ feet

Time, Sec	Bow Acc., g's		Pitch Freq. Hz	Low-Pressure 21, psi*			LP21 Time at Atm., Sec.	High-Pressure 2 Slam, psi	Midship Stress, psi	
	p-to-p	Slam		atm-to peak (static)	Slam I	Slam II			Whip	Wave
61.7	0.66	0.096	0.139	11.1	5.84	3.34	2.19	<12**	1152	4320
68.7	0.54	0.060	0.139	12.5	5.28	2.5	1.88	<12	1730	2880
198.0	0.60	0.096	0.133	12.5	5.56	2.78	1.88	<12	1440	3170
215.0	0.60	0.072	0.145	11.1	5.56	2.5	2.19	<12	864	2160
222.5	0.66	0.096	0.133	13.9	5.84	4.26	2.19	<12	1152	5760
230.5	0.54	0.096	0.128	13.9	4.45	3.06	2.19	12	1440	5760
295.5	0.42	0.042	0.160	9.7	6.4	2.78	1.88	<12	720	3600
416.0	0.72	0.12	0.123	11.1	5.0	2.78	2.50	<12	864	5050
424.0	0.54	0.096	0.133	13.9	5.56	2.78	2.50	<12	864	7200
504.0	0.54	0.096	0.114	11.1	5.56	2.78	2.19	<12	864	5760
632.5	0.48	0.060	0.145	11.1	4.26	3.06	1.56	<12	720	5050
640.0	0.30	0.084	0.123	12.5	5.0	2.22	1.56	<12	1152	5760
715.0	0.60	0.108	0.145	11.1	3.06	1.39	1.56	<12	720	2880
741.0	0.42	0.060	0.123	11.1	3.06	2.22	1.56	<12	720	5050
749.0	0.48	0.060	0.145	11.1	3.34	0.83	1.56	<12	720	5760
778.0	0.48	0.084	0.133	11.1	5.0	2.5	1.88	<12	720	2160
785.0	0.60	0.12	0.145	12.5	7.78	3.06	2.50	<12	1300	5050
793.0	0.54	0.144	0.139	13.9	6.12	3.06	2.19	<12	1152	5050
801.0	0.48	0.108	0.118	12.5	6.12	2.5	2.19	<12	864	5760
809.0	0.48	0.12	0.123	13.9	2.78	1.39	2.50	<12	720	4320
846.5	0.48	0.084	0.128	11.1	4.26	1.39	2.19	<12	720	6480
863,5	0.48	0.108	0.123	11.1	5.84	3.62	2.19	<12	2160	5050
871.0	0.36	0.060	0.128	13.9	3.34	1.39	1.25	<12	864	5760
897.0	0.36	0.072	0.114	11.1	6.12	3.34	1.88	<12	720	2880
907.5	0.48	0.096	0.114	11.1	6.4	3.34	2.19	<12	720	5050
915.0	0.54	0.060	0.128	13.9	5.56	2.78	2.19	<12	720	5760
1039.0	0.36	0.096	0.139	8.34	5.56	2.22	1.56	<12	720	4320
1140.0	0.42	0.060	0.145	11.1	5.0	2.78	1.56	<12	720	5760

*refer to Figure 7

**indicates pressures less than the limit of resolution of about 12 psi

Table I-B.
Slamming Data From Voyage 288 Reel 3 Interval 57 (First 20 Minutes)
Relative Heading 10°; Beaufort 8 Fwd Draft 16 ½ feet

Time, Sec.	Bow Acc., g's		Pitch Freq. Hz.	Low-Pressure 21, psi*			LP21 Time at Atm., Sec.	High-Pressure 2 Slam, psi	Midship Stress, ps	
	p-to-p	Slam		atm.-to-peak (static)	Slam I	Slam II			Whip	Wave
17.8	0.55	0.11	0.133	9.7	8.3	5.6	2.2	<12**	1700	5230
25.5	0.55	0.11	0.133	13.9	5.6	2.8	2.5	<12	655	7850
34.4	0.44	0.055	0.100	12.5	2.8	1.4	1.56	<12	<655	5230
107.0	0.55	0.11	0.128	13.9	8.3	4.2	2.5	<12	655	4580
123.1	0.44	0.055	0.123	13.9	7.0	3.5	1.88	<12	655	3920
148.2	0.50	0.088	0.119	13.9	5.6	2.8	2.5	<12	920	3920
168.8	0.50	0.055	0.123	13.9	7.0	5.0	2.81	<12	<655	3920
177.0	0.61	0.088	0.128	13.9	8.3	5.6	2.81	<12	655	5230
205.0	0.66	0.11	0.128	16.7	11.1	5.6	2.81	28	1570	6550
241.5	0.44	0.055	0.123	13.9	5.6	2.8	2.2	<12	655	3920
321.7	0.61	0.055	0.123	11.1	6.1	3.3	2.5	<12	785	5230
330.0	0.61	0.066	0.128	16.7	6.1	2.8	2.81	23.3	655	7850
347.5	0.72	0.33	0.133	13.9	9.0	4.2	2.81	46.6	1960	7850
354.5	0.55	0.088	0.123	15.3	5.6	2.8	2.5	<12	1310	7850
363.5	0.44	0.088	0.114	15.3	7.0	2.8	2.5	<12	1310	5890
379.5	0.44	0.088	0.133	12.5	2.8	1.4	1.88	<12	655	5500
388.0	0.44	0.055	0.119	13.9	5.6	3.3	2.5	<12	655	5230
444.0	0.50	0.11	0.123	13.9	8.3	3.1	2.5	<12	920	6550
454.0	0.61	0.11	0.107	15.3	9.7	5.6	3.13	12	655	7200
462.0	0.77	0.088	0.114	19.5	11.7	5.6	3.13	<12	1570	9200
486.0	0.61	0.11	0.114	12.5	5.6	2.2	2.2	<12	1310	4580
536.0	0.50	<.055	0.123	12.5	3.3	1.4	2.2	<12	655	2620
546.0	0.61	0.055	0.114	13.9	7.0	2.8	3.13	<12	1310	6550
643.0	0.44	0.055	0.123	12.5	2.8	1.4	2.2	<12	655	4580
653.0	0.44	0.055	0.123	12.5	5.6	2.8	2.2	<12	655	3920
705.0	0.72	0.088	0.123	13.9	5.6	2.8	3.13	<12	1310	6550

*refer to Figure 7
**indicates pressures less than the limit of resolution of about 12 psi

Table I-B
Slamming Data From Voyage 288 Reel 3 Interval 57 (First 20 Minutes)
Relative Heading 10°; Beaufort 8 Fwd Draft 16 ½ feet
(continued)

Time, Sec.	Bow Acc., g's		Pitch Freq. Hz.	Low-Pressure 21, psi*			LP21 Time at Atm., Sec.	High-Pressure 2 Slam, psi	Midship Stress, psi	
	p-to-p	Slam		atm.-to-peak	Slam I	Slam II			Whip	Wave
725.0	0.61	0.055	0.107	15.3	5.6	1.4	2.81	<12	655	5200
734.0	0.33	0.055	0.119	13.9	5.6	2.8	1.88	<12	655	5890
755.0	0.50	0.165	0.114	12.5	8.3	5.6	2.37	<12	1045	5200
765.0	0.55	0.099	0.110	13.9	5.6	3.1	2.5	<12	1310	6550
830.0	0.66	0.11	0.123	11.1	9.7	5.6	2.81	23.3	1310	6550
838.0	0.44	0.099	0.114	13.9	5.6	2.8	2.81	12	1310	7850
884.0	0.44	0.055	0.128	9.7	6.1	3.3	1.88	<12	< 655	5890
913.0	0.55	0.055	0.123	12.5	6.1	3.3	2.81	<12	920	3920
990.0	0.39	0.055	0.110	13.9	3.3	1.4	2.5	<12	655	3920
1017.0	0.66	0.33	0.114	11.1	8.3	3.3	2.81	58.25	1960	6550
1028.0	0.61	0.11	0.107	15.3	8.3	5.6	2.5	12	1310	9200
1045.0	0.44	0.088	0.114	11.1	5.6	2.2	2.2	<12	655	3920
1122.0	0.77	0.33	0.139	11.1	8.3	4.4	2.5	23.3	2350	7850
1131.0	0.66	0.132	0.123	15.3	6.4	5.3	2.81	16	1310	9200
1140.0	0.66	0.088	0.119	13.9	8.3	5.0	2.81	12	1960	7850
1148.0	0.66	0.11	0.114	13.9	11.1	5.0	3.13	23.3	1310	7200
1156.0	0.66	0.055	0.110	15.3	4.2	1.4	2.2	<12	655	6550
1168.0	0.66	0.055	0.103	11.1	5.6	3.1	2.81	<12	< 655	7850
1175.0	0.72	0.22	0.123	16.7	9.7	3.3	3.13	23.3	1700	7850
1197.0	0.44	0.055	0.139	9.7	4.2	1.9	1.88	<12	655	6550
1206.0	0.44	0.055	0.119	12.5	5.6	2.5	2.5	<12	655	5890

Table I-C
Slamming Data From Voyage 288 Reel 3 Interval 58 (First 20 Minutes)
Relative Heading 15°; Beaufort 9, Fwd Draft 16 ½ feet

Time, Sec.	Bow Acc., g's		Pitch Freq. Hz.	Low-Pressure 21, psi*			LP21 Time at Atm., Sec.	High-Pressure 2 Slam, psi	Midship Stress, psi	
	p-to-p	Slam		atm.-to-peak (static)	Slam I	Slam II			Whip	Wave
75.6	0.42	0.06	0.107	12.5	2.78	0.55	2.19	<11.6**	655	6550
87.0	0.78	0.24	0.110	12.5	5.28	2.78	3.12	35.0	1960	6550
95.0	0.6	0.12	0.110	13.9	6.12	3.34	2.81	<11.6	1960	9200
134.1	0.78	0.25	0.123	11.1	11.12	5.56	3.12	46.6	2620	6550
163.0	0.6	0.096	0.123	13.9	5.56	2.78	2.50	11.6	655	5890
171.2	0.36	0.084	0.118	13.9	3.34	0.83	1.87	<11.6	655	7200
213.1	0.48	0.084	0.128	11.1	4.17	1.39	1.87	<11.6	655	5240
254.5	0.72	0.13	0.094	11.1	6.12	3.34	3.12	16.3	1310	5240
264.0	0.48	0.096	0.107	15.3	3.34	0.55	2.81	18.6	1310	7850
219.5	0.48	0.060	0.16	9.7	5.56	2.22	1.25	<11.6	655	6550
310.0	0.72	0.06	0.145	11.1	4.45	1.39	2.50	<11.6	655	5240
330.0	0.60	0.096	0.133	11.1	5.56	2.78	1.87	<11.6	1040	3920
346.0	0.36	0.096	0.123	12.5	6.12	3.06	1.87	<11.6	785	4580
382.0	0.60	0.084	0.123	12.5	4.17	2.50	2.19	<11.6	655	4580
389.5	0.60	0.12	0.114	11.1	5.28	2.78	2.50	<11.6	655	5240
397.5	0.42	0.096	0.133	11.1	6.12	2.78	1.87	<11.6	920	3270
422.5	0.42	0.13	0.118	11.1	5.84	2.78	2.19	<11.6	655	7850
489.0	0.54	0.06	0.133	12.5	4.17	1.39	2.19	11.6	1310	3920
510.0	0.78	0.072	0.145	11.1	6.12	2.22	2.19	<11.6	655	7850
572.0	0.54	0.13	0.139	13.9	8.35	2.22	1.87	11.6	1410	4580
617.5	0.84	0.36	0.128	13.9	8.35	5.56	3.12	49.0	2620	6550

*refer to Figure 7

**indicates pressures less than the limit of resolution of about 12 psi

Table I-C.
Slamming Data From Voyage 288 Reel 3 Interval 58 (First 20 Minutes)
Relative Heading 15°; Beaufort 9, Fwd Draft 16 ½ feet
(continued)

Time, Sec.	Bow Acct., g's		Pitch Freq. Hz.	Low-Pressure 21, psi*			LP21 Time at Atm., Sec	High-Pressure 2 Slam, psi	Midship Stress, psi	
	p-to-p	Slam		atm.-to-peak	Slam I	Slam II			Whip	Wave
626.0	0.72	0.216	0.128	16.7	5.56	5.56	2.81	18.6	1310	7850
634.0	0.32	0.072	0.107	11.1	5.01	2.22	1.87	<11.6	1310	7200
642.5	0.48	0.072	0.145	13.9	4.17	4.17	1.87	<11.6	1040	6550
770.0	0.66	0.12	0.1140	13.9	6.95	2.22	3.44	<11.6	1310	5240
785.0	0.72	0.108	0.097	13.9	4.17	0.834	2.81	<11.6	655	5240
875.0	0.84	0.204	0.118	11.1	5.56	2.50	2.19	30.3	2360	5240
882.5	0.72	0.108	0.128	13.9	5.56	5.56	2.50	11.6	655	5890
914.0	0.66	0.096	0.107	12.5	5.56	5.56	2.81	11.6	655	3270
922.5	0.60	0.12	0.118	13.9	6.95	2.78	2.50	18.6	1570	5240
1002.0	0.96	0.24	0.139	12.5	5.56	1.67	2.50	35.0	1960	9200
1053.0	0.72	0.12	0.110	11.1	5.84	3.62	2.81	11.6	1310	3270
1062.0	0.54	0.216	0.118	16.7	6.95	2.78	2.81	30.3	785	7850
1070.0	0.60	0.072	0.139	13.9	5.84	2.78	2.19	<11.6	920	7200
1078.0	0.48	0.084	0.145	11.1	4.17	1.39	1.56	<11.6	920	6550
1098.0	0.60	0.060	0.1	11.1	3.06	3.06	2.50	<11.6	655	3920
1105.0	0.36	0.060	0.123	13.9	3.62	1.67	2.19	<11.6	785	3270
1160.0	0.72	0.216	0.1	11.1	5.56	2.78	2.81	16.3	1570	4580
1170.0	0.60	0.12	0.110	13.9	6.67	2.78	2.81	16.3	1960	7850
1184.0	0.60	0.132	0.139	12.5	7.23	2.22	2.19	<11.6	1040	5240
1191.0	0.60	0.12	0.145	11.1	5.56	2.50	1.87	<11.6	1040	5240
1200.0	0.60	0.132	0.114	12.5	8.35	2.78	2.81	11.6	655	5240
1210.0	0.66	0.108	0.110	13.9	5.56	1.39	2.81	<11.6	655	3920

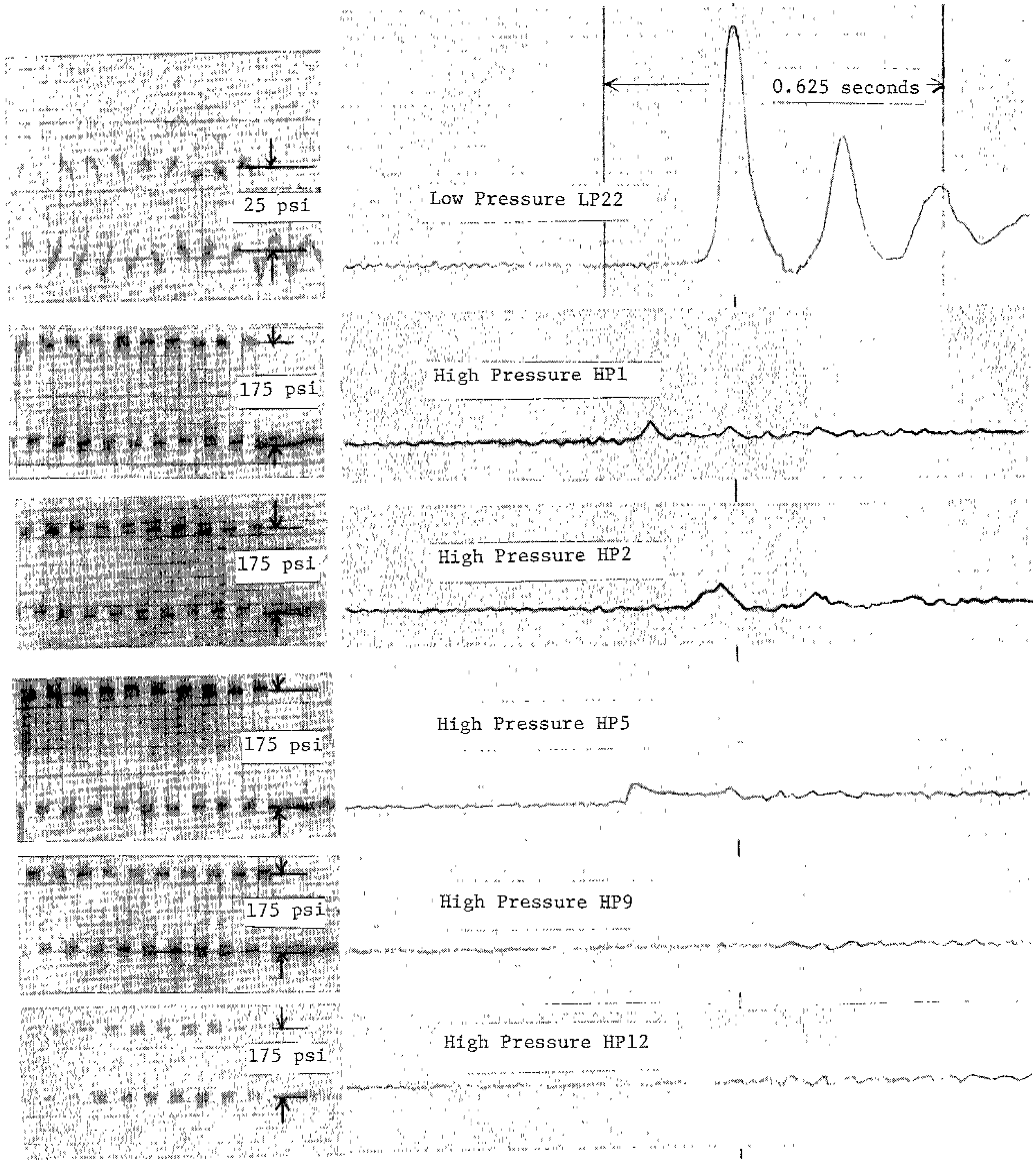


Fig. 3A. Slam 16, 277W2, Interval 5 with Calibration Signals

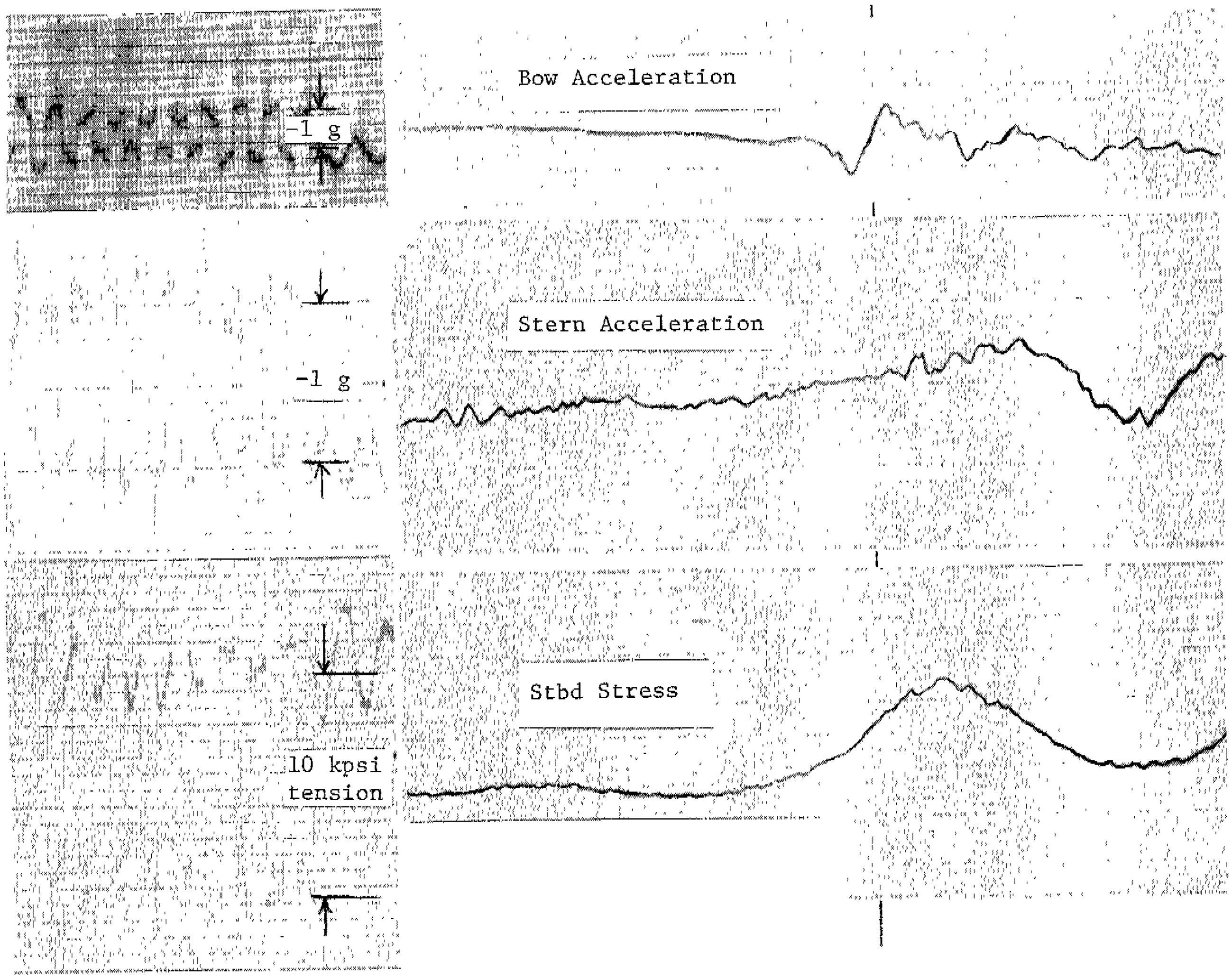


Fig. 3A. Slam 16, 277W2, Interval 5 with Calibration Signals (continued)

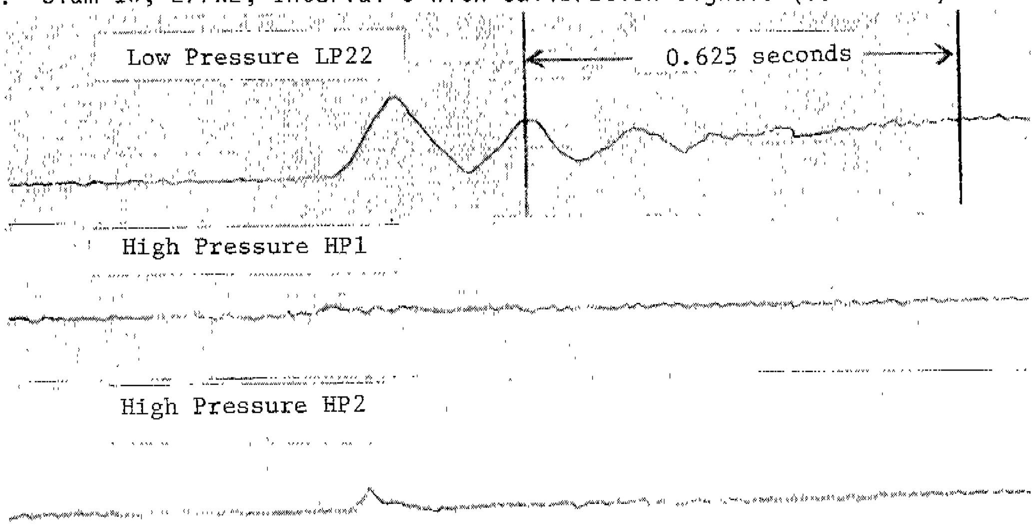


Fig. 3B. Slam 15, 277W2, Interval 5

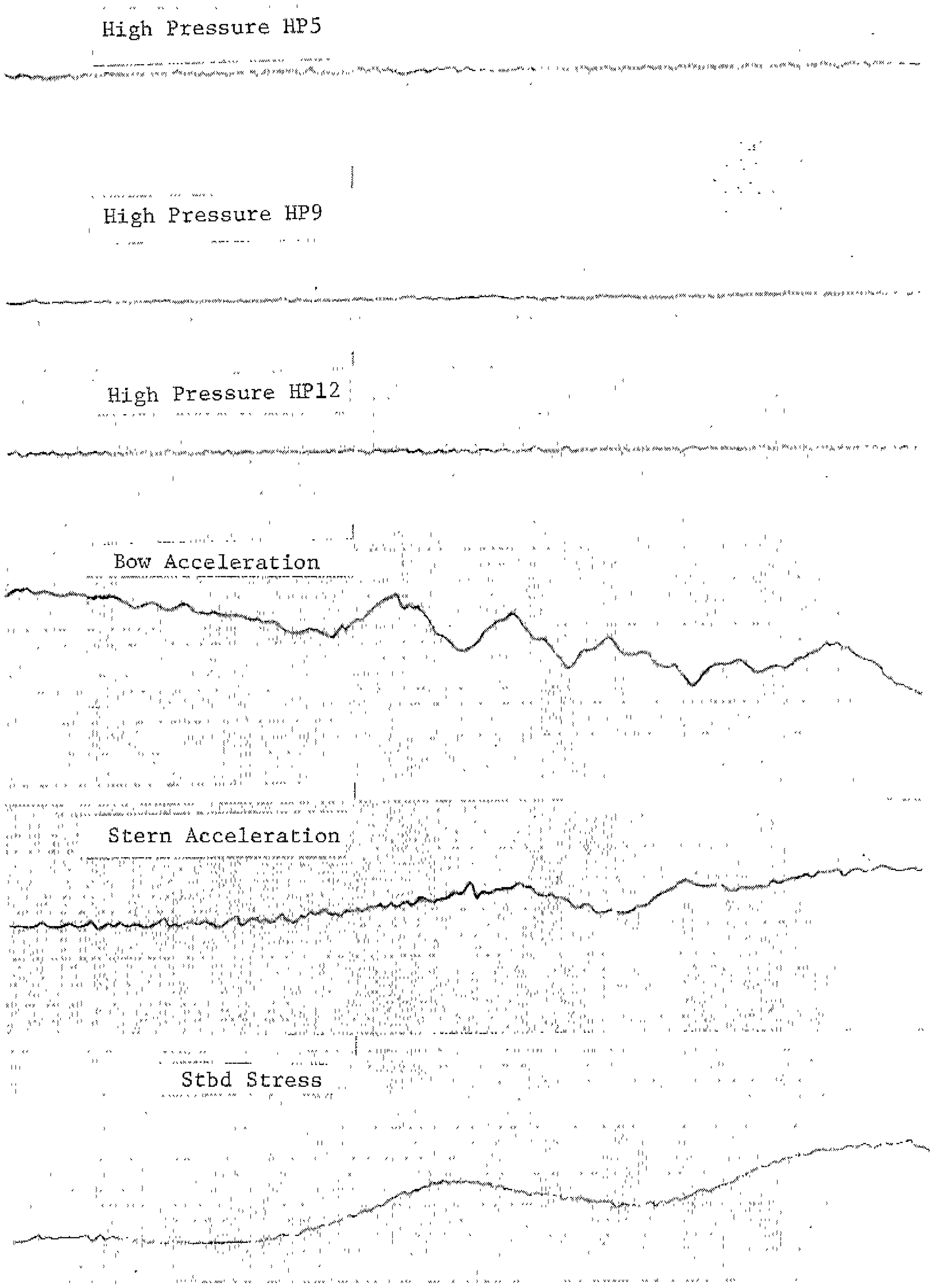


Fig. 3B. Slam 15, 277W2, Interval 5 (continued)

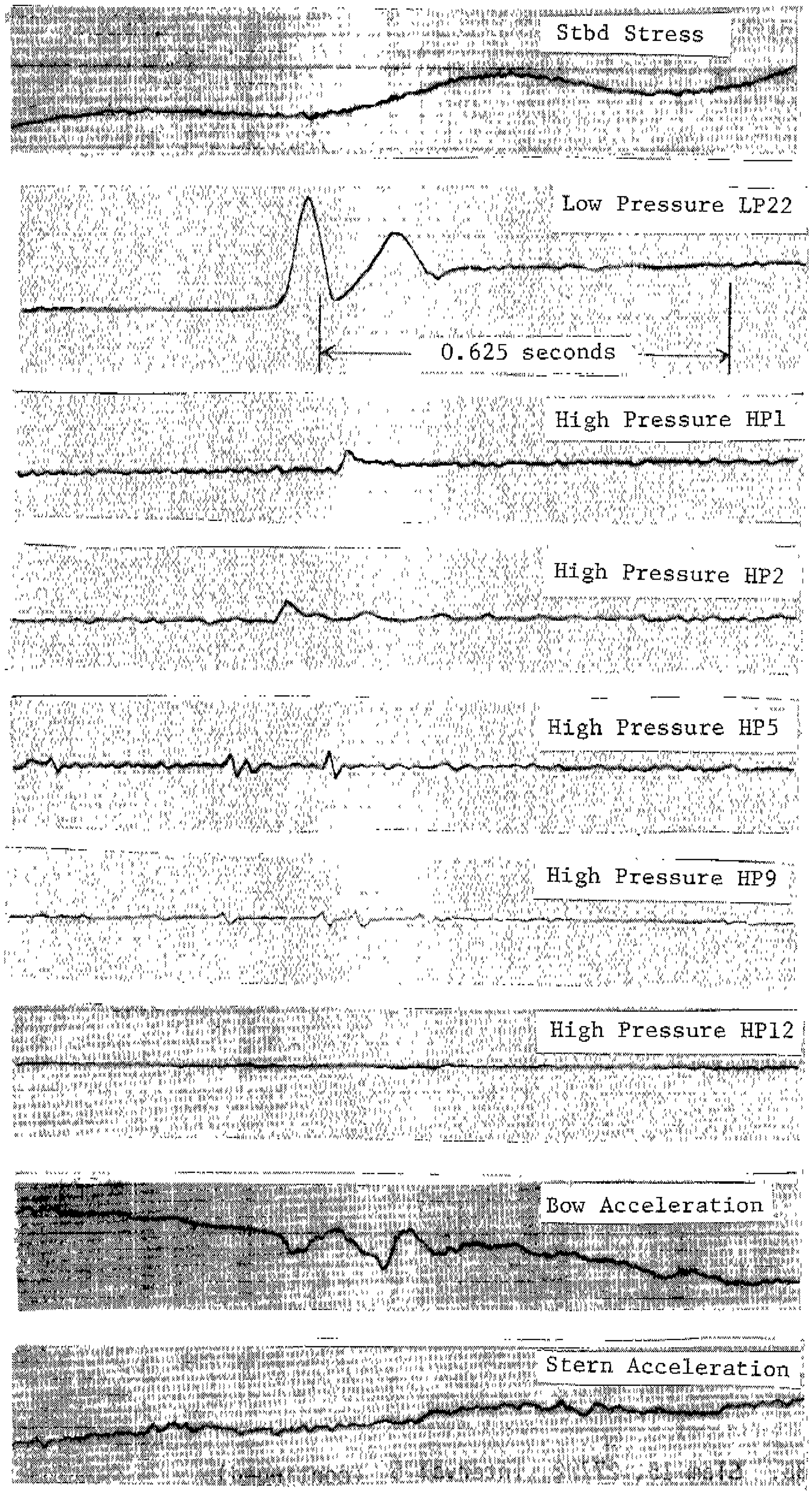


Fig. 3C. Slam A, 277W2, Interval 5

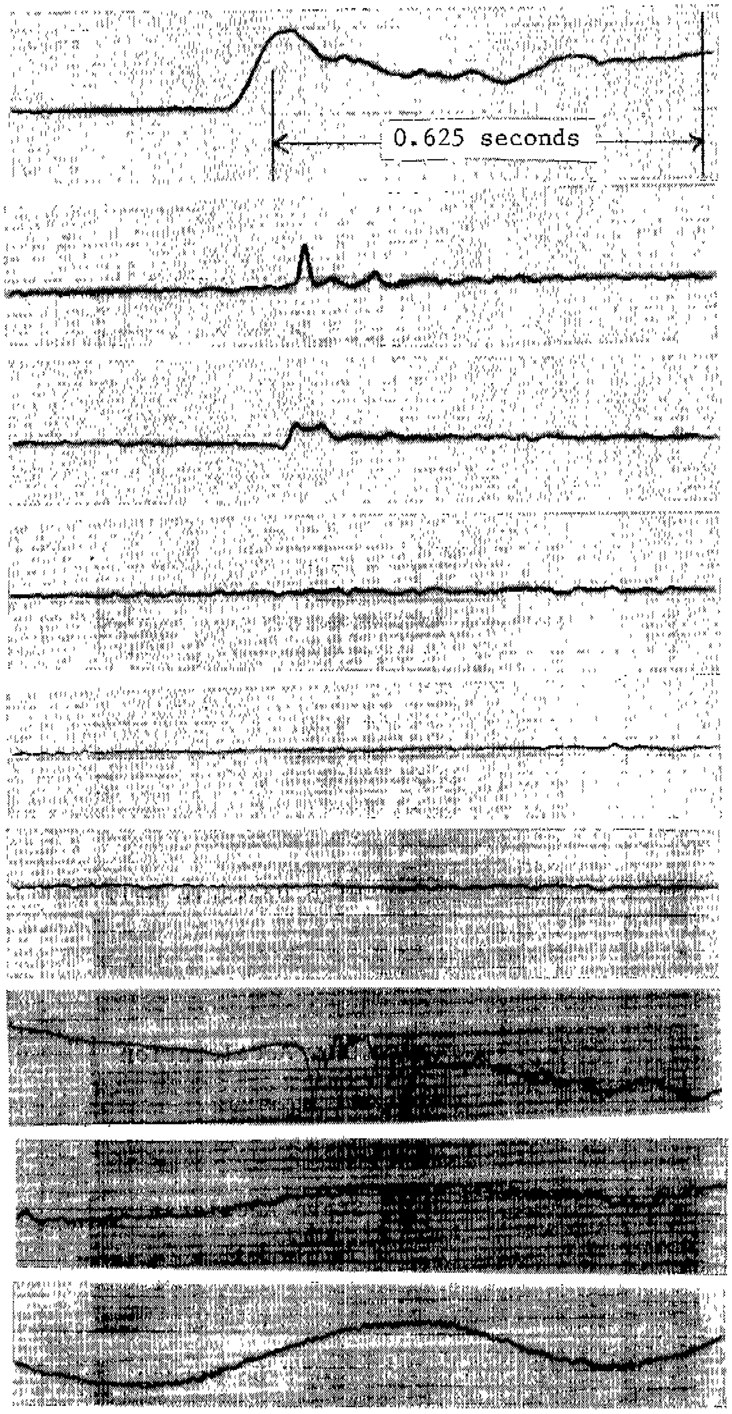


Fig. 3D. Slam B, 2772, Interval 5

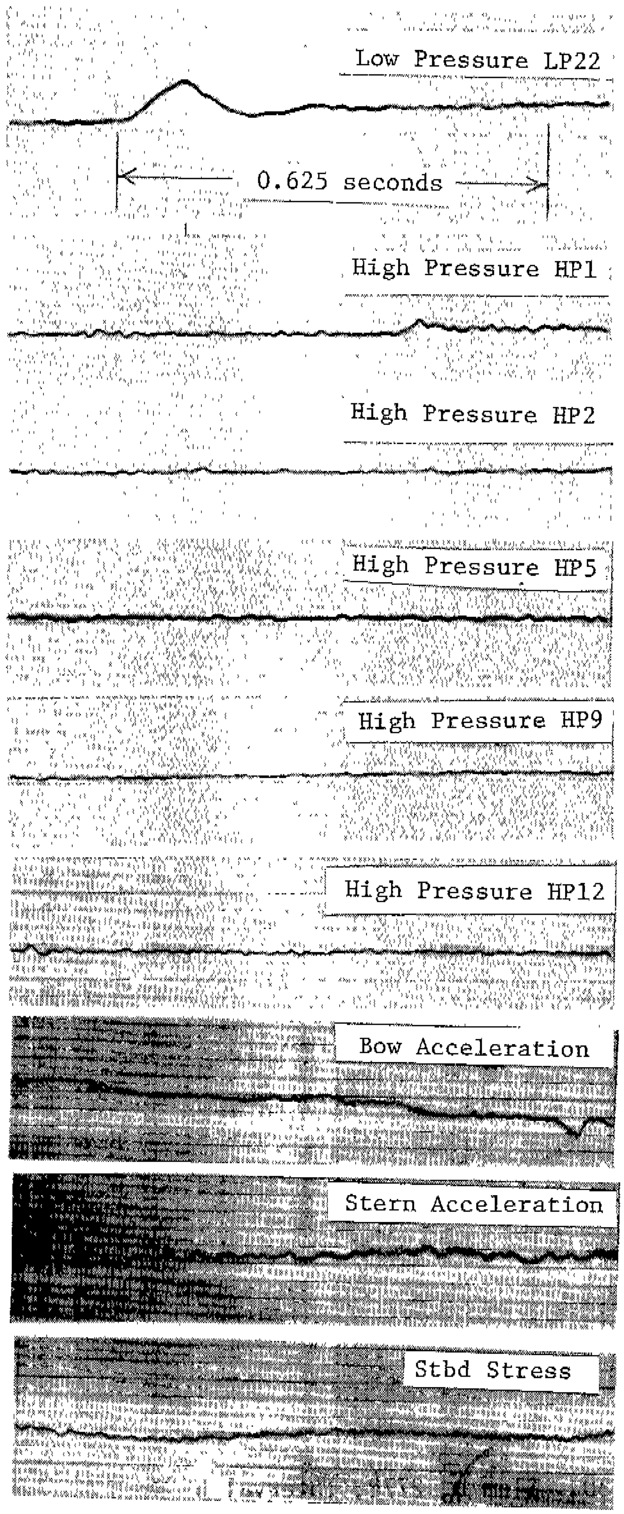


Fig. C, 277W2, Interval 5

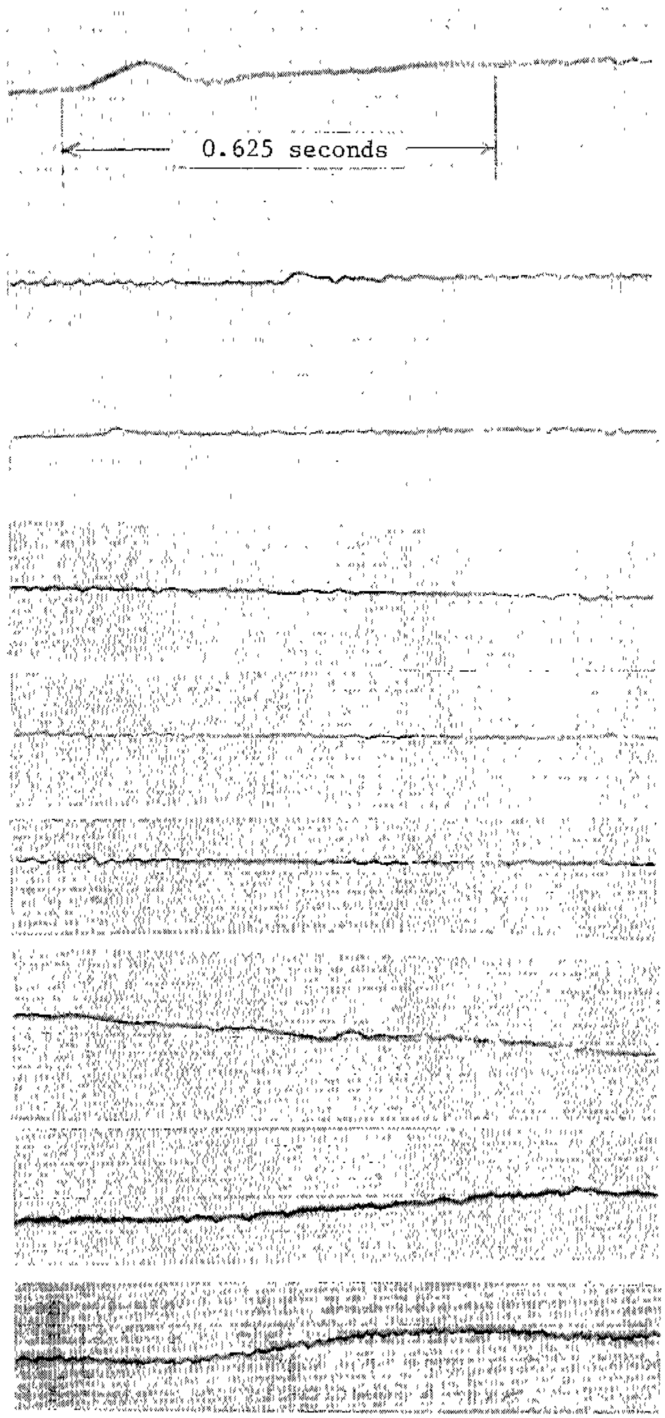


Fig. 3F. Slam D, 277W2, Interval 5

Six slams from Interval 5 were selected for detailed examination and calculations. The slams are identified as numbers 16, 15, A, B, C, and D, and are shown in Figures 3-A through 3-F.

Figures 3-A through 3-F are greatly expanded records of the events immediately preceding and following the reentry of the forefoot into the water for each of the six slams. The transient acceleration at the bow was used as a common signal for time synchronization of all of the tape recorded data. The calibration signals for each data channel are shown.

From the information in Figures 3A through 3F, measurements of signal amplitudes, durations, and time separations from the peak pressure on LP22* were made and are presented in Table II. These data were used to derive the velocity of reentry and the time distribution of the slam, and to establish the relationship between velocity and pressure. These calculations are discussed in Section IV.

*Note: The low pressure transducer at Location 22 was used during Voyage 277, whereas LP21 was used during Voyage 288.

IV. DISCUSSION

A. General

The initial decisions to operate with an unmanned instrumentation system with limited bandwidth, and those involved in the selection of transducers were based on a preliminary review of the literature covering theoretical, model, and full-scale studies of slamming. The investigators in the field were far from unanimous in their quantitative characterization of the phenomenon. The situation was reviewed again in depth after the project was underway, and this review is reported in Reference 2. As this critical review developed, and as the experimental program unfolded, it became apparent that matters of human judgment (manned vs. unmanned; selection of dynamic range of transducers; use of existing tape recorder) and conditions beyond the investigators' control (vessel routing; loading and speed; weather) had combined to limit the amount of data which could be collected, and made analysis and interpretation difficult.

Despite these difficulties, however, a considerable amount of useful information has been derived from the slamming data reported here. The following parts of this Discussion are concerned with specific areas where the data reveal the characteristics of slamming pressures and the response of the vessel to these pressures.

B. Frequency-of-Occurrence of Slamming

Ochi's work included a figure (Figure 13, p. 567, Ref. 3) prepared to verify that slamming is a sequence of events occurring in time following a Poisson process. This figure was based on measurements of times between successive slams in tests on a MARINER model.

Full-scale data from the WOLVERINE STATE (Table I) includes information from which a similar figure can be prepared. Using the 47 slams of Interval 57 which occurred over a period of 1206 seconds, the number of slams in successive twenty-second intervals was counted. Ochi's Equation 19 was evaluated for $\lambda = 0.77$, since there were 47 slams in 61 twenty-second intervals. The computations follow, and are plotted in Figure 4.

No. slams (r) per 20-sec. interval	0	1	2	3	4
No. of 20-sec. intervals	27	22	11	1	0
Percent	45.2	36.1	0.18	0.064	-

Theoretical: $P\ (X=r) = \frac{\lambda^r}{r!}\ e^{-\lambda}$ where λ = expected value = 47/61 = 0.77

Table II
Basic Data, Slams 16, 15, A, B, C, D
(Transient Data Only)
Voyage 277W2, Interval 5

Slam	Transducer	Peak Amplitude	Duration, ms	Separation from LP22 Peak, ms
16	HP1	35 psi	35	-157
	HP2	48 psi	93	-25
	LP22	69 psi	150	0
	HP5	29 psi	63	-193
	HP9	--	--	
	HP12	--	--	
	Bow Acc	1.55 g		
	Stern Acc	0.53 g		
	Stress	4560 psi		
15	HP1	14 psi	37	-168
	HP2	32 psi	100	-107
	LP22	20 psi	175	0
	HP5	--	--	--
	HP9	--	--	--
	HP12	--	--	--
	Bow Acc	0.26 g		
	Stern Acc	0.23 g		
	Stress	2150 psi		
A	HP1	37 psi	75	+60
	HP2	34 psi	100	-25
	LP22	27 psi	88	0
	HP5	18 psi	25	-430
	HP9	13 psi	25	-390
	HP12	--	--	--
	Bow Acc	0.20 g	--	
	Stern Acc	0.14 g	--	
	Stress	2140 psi	--	
B	HP1	54 psi	25	+37
	HP2	20 psi	62	+12
	LP22	19 psi	250	0
	HP5	--		
	HP9	--		
	HP12	--		
	Bow Acc	0.31 g		
	Stern Acc	0.18 g		
	Stress	2140 psi		
C	HP1	19 psi	50	+360
	HP2	--		
	LP22	10 psi	175	0
	HP5	--	--	--
	HP9		--	--
	HP12	--	--	--
	Bow Acc	0.12 g		
	Stern Acc	--		
	Stress	500 psi		
D	HP1	18 psi	50	+212
	HP2	12 psi	50	-50
	LP22	7 psi	175	0
	HP5	--	--	
	HP9	--	--	
	HP12	--	--	
	Bow Acc	.09 g		
	Stern Acc	--		
	Stress	650 psi		

--

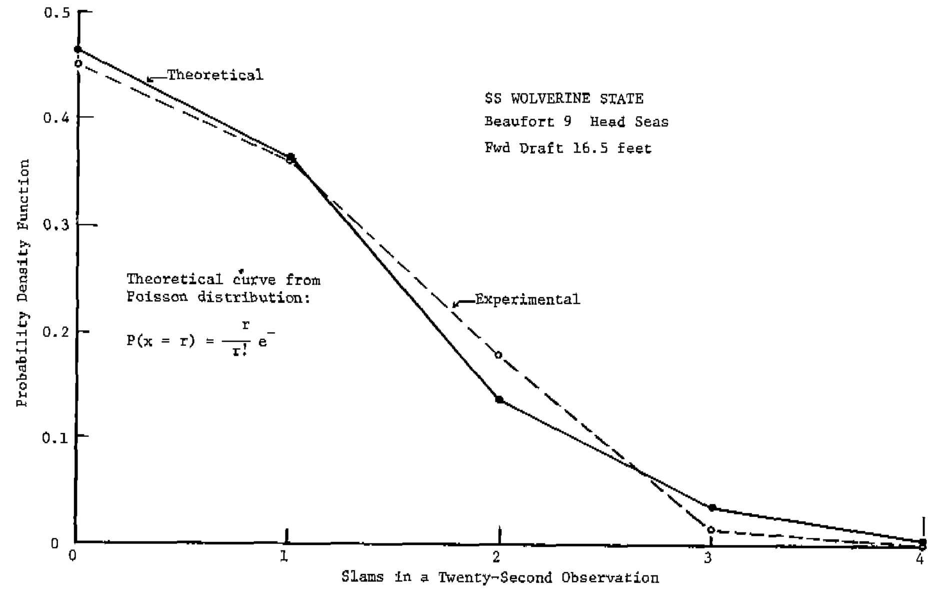


Fig. 4. Probability Density of Slams in a Twenty-Second Observation

r	r!	λ^r	P(X=r)
0	1	1	0.463
1	1	0.77	0.366
2	2	0.59	0.137
3	6	0.456	0.035
4	24	0.351	0.00676

The full-scale data appear to follow the Poisson process at least as well as the model data reported by Ochi.

Using the same set of basic data, Ochi's prediction that the time between successive slams follows a truncated probability density function (Ref. 3, p. 568, Eq. 20 and Fig. 14) can be evaluated. The natural pitching period of the WOLVERINE STATE was computed as 7.2 seconds, and the data for 118 slams show only five shorter intervals (7.0 seconds) between successive slams. A histogram of the time interval data was prepared for Interval 57, with truncation at 7 seconds and ten-second intervals. The theoretical values were obtained from Ochi's Equation 20:

$$f(t) = N_s e^{-N_s (t - t_*)} \qquad , \; t \geq t_*$$

where N_s = number of slams per unit time

t_* = minimum time interval between two successive slams (natural pitching period)

The full-scale data give a value of 0.0396 for $N_s \left(\frac{47}{1206-18}\right)$.

The histogram and the theoretical distribution are plotted in Figure 5. Again, there is good agreement between the theoretical and experimental data.

C. Effect of Heading and Loading Condition

Although a detailed analysis of the slams from Voyage 263 is not presented here, the number of slams which occurred during six successive four-hour recording intervals is included as part of Table III. This table presents basic logbook data from Voyages 263, 277, and 288 from which the effects of heading and loading condition on slamming may be assessed.

The relative heading information has been plotted in Figure 6 as a histogram of the number of occurrences of headings in ten-degree groups, where zero degrees is defined as head seas. Of the thirteen intervals, only one of them had a relative heading greater than 30 degrees. All of these intervals were recorded on the WOLVERINE STATE while she was westbound in the North Atlantic.

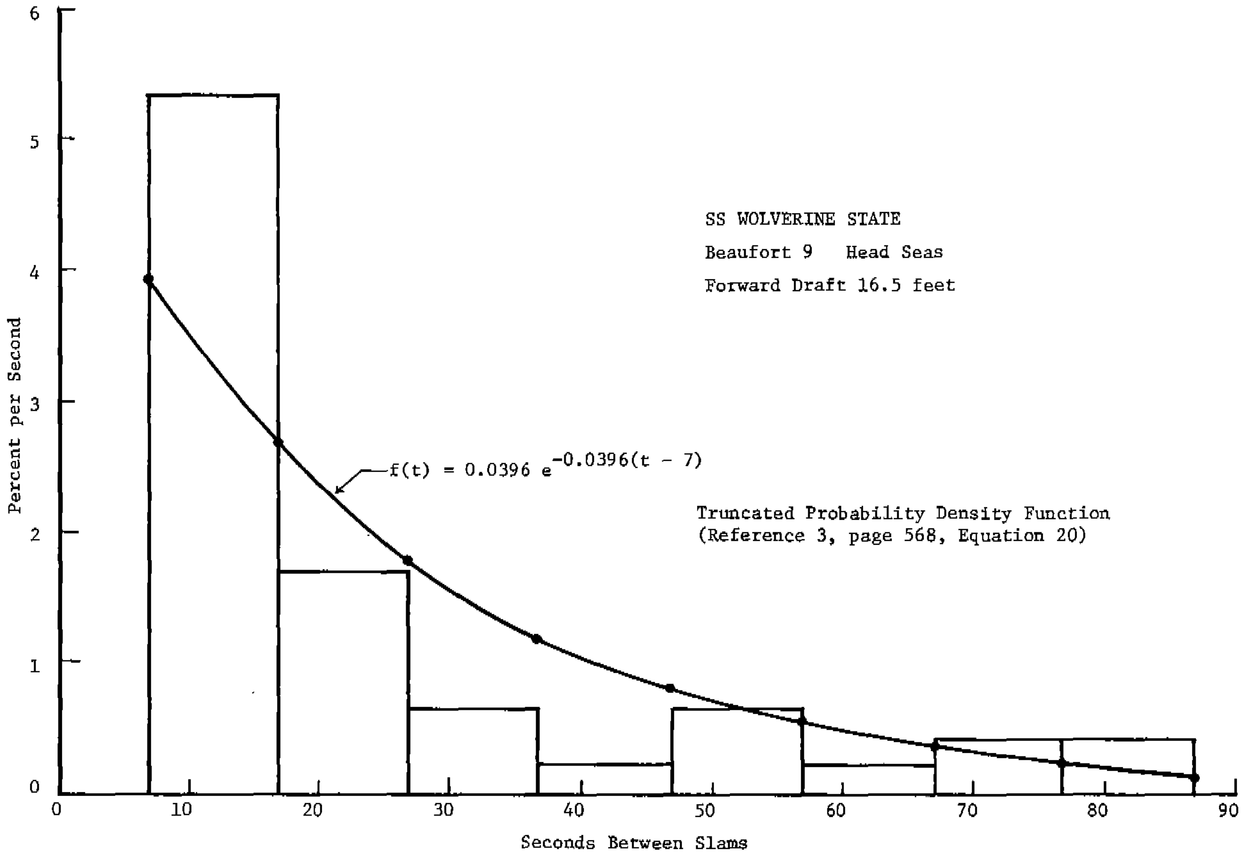


Fig. 5. Probability of Density of Time Between Slams

Table III
Summary of Logbook Data, Slamming Intervals

Voyage/Interval	Relative Heading, deg.	Fwd. Draft, ft.	Beaufort Number	Wind Velocity Knots	Avg. RPM	Slams per Hour*
263W2-9	32	17.5**	5	20	81.5	0.25
-10	22	17.5	6	25	77.8	4.5
-11	6	17.5	7	30	65.0	12.0
-12	6	17.5	6	30	62.1	14.75
-13	5	17.5	6	30	63.4	11.5
-14	16	17.5	5	10	68.8	5.75
277W2-2	1	18.5	7	35	72.8	14.25
-3	1	18.5	9	44	59.6	8.0
-4	1	18.5	9	35	45.0	10.75
-5	24	18.5	9	35	61.6	7.75
288W3-56	18	16.5	7	31	66.7	98
-57	10	16.5	8	40	46.8	110
-58	15	16.5	9	40	48.0	77.5

*Total number of slams in 4-hour intervals divided by 4.

**Estimated draft, Voyage 263

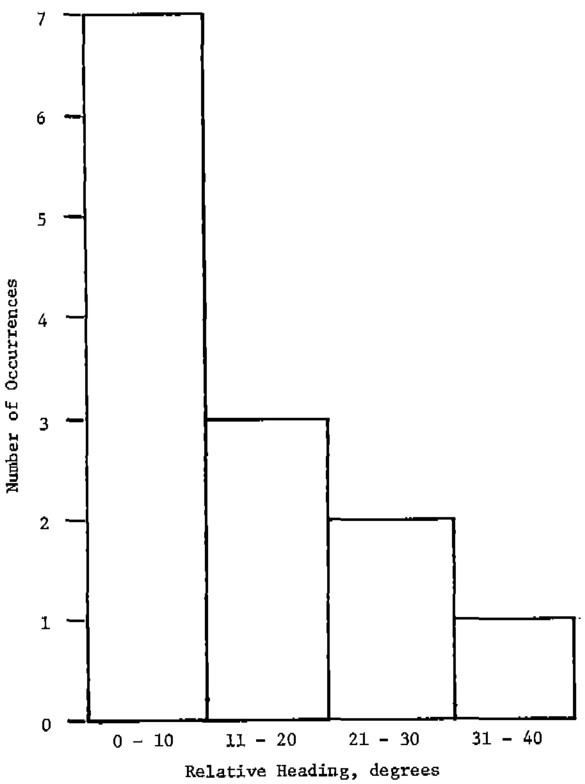


Fig. 6. Histogram of Relative Headings from Table III

Experience in analyzing stress data from the WOLVERINE STATE indicates that logbook data on Beaufort numbers, wave heights, and wave lengths must be handled with considerable tolerance. The vessel does not have an anemometer, and these observations are all based on human judgment. With regard to wave heights and lengths, for 288W3, Interval 57, p. B-7 (Appendix B) shows a wave height of 20 feet, a period of 5 seconds, and a wave length of 100 feet, with a swell (p. B-8) 20 feet high and 100 feet long. This observation was made at one o'clock in the morning (GMT), which, for Beaufort 8 at longitude 61° West early in April, means a dark and stormy night. Obviously, these logbook data cannot be treated on the same basis as laboratory data from model tests.

Probably the most significant information from Table III is the very large increase in the number of slams during Voyage 288, when the forward draft was extremely light (16.5 feet). Any differences in headings, Beaufort numbers, wind speeds, and engine RPM seem to be of little importance in comparison.

Draft data for the SS WOLVERINE STATE have been supplied by States Marine Line, as follows:

Year	Voyage Numbers	Voyages	Avg. Draft	Avg. Trim	Avg. Displ., LT
1961	148/149--170/171	12	19'-8 1/8"	3'-11"	12,340
1962	171--192/193	12	19'-1 1/4"	3'-11 1/8"	11,950
1963	194/195--217/218	12	18'-10"	5'-1 5/8"	11,750
1964	219/200--239/240	11	18'-10 3/4"	4'-11"	11,800
1965	241/242--255/256	8	19'-8 1/8"	4'-6 1/4"	12,340

For the 57 voyages from 148/149 to 259/260, the average draft was 19'-3". For the 5 voyages 249/250-259/260, the average draft was 20'- 2 1/2". The 16' - 6" draft during Voyage 288, therefore, is unusually light in comparison with these average figures.

In order to make quantitative comparisons of the observed full-scale slamming rates with predictions based on Ochi's work (Ref. 3, Table II) the continuous time records of both relative velocity and relative motion between the vessel's forefoot and the sea surface must be known. This information is not available from the recorded data.

D. Computation of Vertical Velocity at Impact

Due to the difficulty of determining analytically the vertical impact velocity at the slam because of unknown factors such as the vertical wave velocity at time of impact and because the added effective mass of water at time of impact is indeterminate, an approximate analytical approach will be adopted and later verified by actual experimental data.

The general equation for measured pressure is:

$$p = \rho gh + \frac{\rho v_r^2}{2} + f(m,t) \qquad (1)$$

where p = impact pressure

ρ = sea water mass density

g = acceleration of gravity

h = depth of immersion of pressure transducer below surface

v_r = impact velocity

m = mass

t = time

As noted earlier, the amplitude of the pressure transient on the low-pressure signal immediately after bow reentry has little real significance. However, the basic low-pressure waveform can be used in two ways to derive relative ship-wave surface velocity at impact. First, the rate of change of pressure due to immersion can be used to establish the velocity at immersion. This involves the first term of Equation (1). Second, the step change in pressure at immersion results from the stagnation effect and is given by the second term of the equation (see Figures 7 and 8).

Each term of Equation (1) will be considered separately in the following discussion.

The term "ρgh" is the pressure due to the static head of water at a point below the surface. However, this relationship is strictly true only for a still-water situation. When there is a wave pattern on the surface, the pressure contours below the surface are modified by the "Smith effect". The "h" component, then, is really the sum of two terms, "z", the depth below the still-water surface, and "g", the instantaneous increase or decrease in pressure relative to still water at any point due to the wave.

The first term will be used to derive the relative velocity, v_r, of the vessel and water at impact by considering "h" to be the integral of velocity with respect to time. Before proceeding with this analysis, the Smith effect will be evaluated numerically to determine if it may be neglected.

Following the example given on page 610 of Principles of Naval Architecture (Reference 4), the Smith effect was evaluated for the conditions reported in the logbook for Tape 277W2, Interval 5 (see Appendix B, pages B-3 and B-4). Wave height was reported as 8 feet, with a 15-foot swell 150 feet long. Based on the swell only, and the draft of 18.5 feet, the evaluation results in a pressure 84.5 percent of the pressure which would result from the static superposition of a 7.5-foot swell amplitude on an 18.5-foot draft. Of course, the numbers reported are "effective", and there is no practical way of knowing what the actual wave or swell height and length was for the actual slams measured.

The determination of relative velocity depends upon a measurement of the slope of the pressure-time curve at the moment of impact. The Smith effect is most significant at the maxima and minima of the wave, and the percentage change is relatively small (15 percent) for the case considered. Therefore, since the process of drawing a tangent to the curve (see Figure 7) is not an exact one to begin with, it is concluded that the calculated change in peak pressure amplitude will not significantly affect the tangent and the resulting velocity. In the following development of the velocity relationship, the value of "h" will be assumed to be the total depth below the instantaneous surface, and the measured pressures will be used in the evaluation.

$$p = \rho g h$$

$$p = \rho g \int v_r dt$$

or,

$$\Delta p = \rho g v_r \Delta t$$

Solving for v_r,

$$v_r = \frac{\Delta p}{\Delta t} \frac{1}{\rho g} \quad (2)$$

From the low-pressure transducer installed for the purpose of velocity estimates (and also for indications of bow emergence), the slope $\Delta p/\Delta t$ of the pressure-time behavior at impact can be determined. A curve drawn through the average pressure signal and extended through the transient to the beginning of the slam will intersect the sharply-rising pressure pulse at the instant of impact (see Figure 7). A tangent to the newly-formed curve drawn at the intersection point will yield the desired $\Delta p/\Delta t$ slope. The value of Δp can be determined from the pressure transducer calibration, and Δt (real time) can be determined from knowledge of tape recording speeds and playback procedures.

Using slopes $\Delta p/\Delta t$ measured from slams 16, 15, A, B, C, and D, relative velocities were calculated from equation (2). These values are shown in Table IV.

Verification of these relative velocities can now be obtained using the second term of Equation (1)

$$p = \frac{\rho v_r^2}{2}$$

which is the velocity-induced stagnation pressure at the transducer.

The pressure amplitude was measured experimentally as the vertical distance between the zero-pressure base line (transducer out of water) and the intersection of the previously-described tangent and the first pressure impulse. See Figure 7.

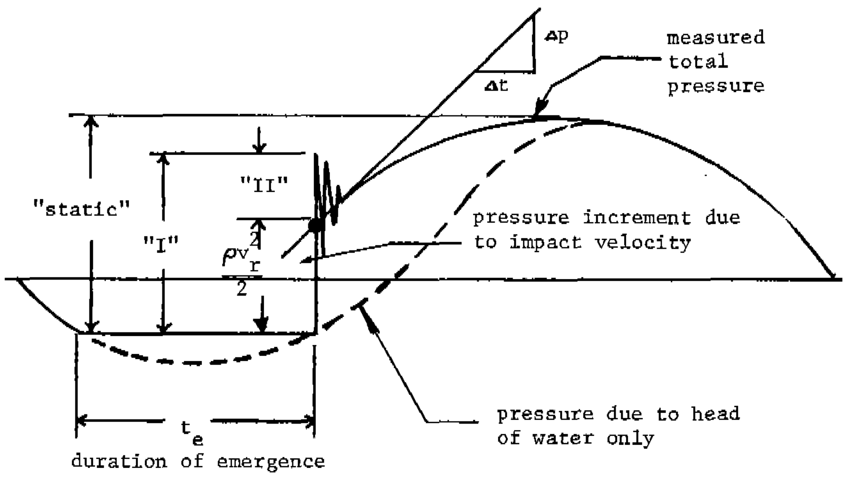


Fig. 7. Details of Low-Pressure Transducer Slam Response

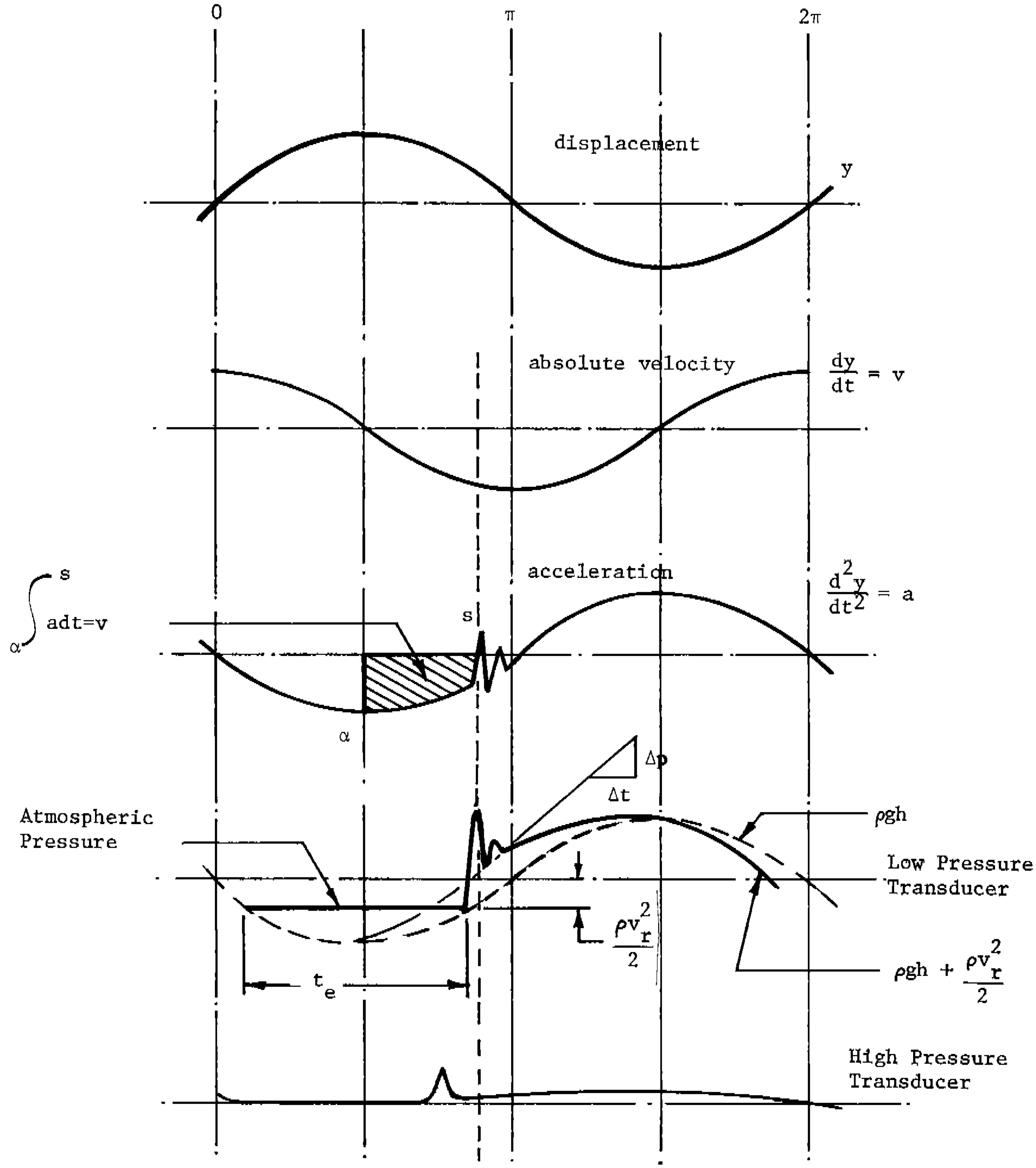


Fig. 8. Schematic of Pressure and Acceleration Relationships During Slamming

Table V shows the correlation between the analytically-determined pressure increments using the velocities from the static head calculation (as shown in Table IV) as compared to the pressure increments obtained by measurements from the experimental data.

Table IV
Impact Velocity from Pressure-Time Slopes
Voyage 277W2, Interval 5

Slam	Δp, psi	Δt, seconds	$\frac{\Delta p}{\Delta t}$	Relative v, fps
16	40	3.5	11.2	25.2
15	22	2.5	8.8	19.8
A	23	2.5	9.2	20.7
B	22.5	2.5	9.0	20.2
C	20.8	2.5	8.4	18.7
D	14.2	2.5	5.7	12.8

Table V
Comparison of the Analytical and
Experimental Values for the Velocity-Induced
Pressure Increment

Slam	$p = \frac{\rho v_r^2}{2}$, psi	Pressure Measured From Oscillograph Record, psi
16	4.4	4.0
15	2.7	3.0
A	3.0	6.2
B	3.0	5.0
C	2.4	2.1
D	1.1	1.2

From the good correlation obtained it is justified to use for velocity determination, as a first approximation, the first term (right-hand side) of equation (1), i.e., the extension of the static pressure curve and its tangent at the point of impact. This, of course, is not the general solution to the problem, but merely a first- and second-order attempt to solve analytically a very complex physical phenomenon.

As a matter of interest, the relative velocities obtained were compared with integrated acceleration-time measurements taken simultaneously with the pressure measurements. For example, Figure 8 shows a typical acceleration-time record associated with a slam. By integration (shaded area, Figure 8) the absolute bow velocity at impact is obtained. Table VI shows the relative velocity values previously obtained from pressure-time slope measurements as compared with the absolute velocities derived from the independent acceleration measurement.

Table VI
Comparison of Impact Velocities Derived from Slope Measurements and from Acceleration Measurements, Including Associated Pressures from HP2

Slam	Slope Velocity (Table IV), fps	Velocity from Acceleration, fps	HP2 Pressures (Table II)
16	25.2	20.0	48
15	19.8	14.0	32
A	20.7	21.0	34
B	20.2	22.2	20
C	18.7	18.3	-
D	12.8	10.3	12

From the results shown in Table VI it can be seen that there is a very strong correlation between analytical and experimental data, and the fact that the experimental velocities are both above and below the analytical ones can be attributed to the effect of vertical wave velocities. These velocity differences are consistent with the maximum vertical velocities which can be computed from wave theory for various wave lengths. For example, the logbook for voyage 277W2 (Appendix B, page B-2) shows wave or swell lengths estimated to be as much as 250 feet (Interval 3, Index 74). Using the relationship

$$v = 0.355 \sqrt{\lambda}$$

derived from trochoidal wave theory for $\lambda/h = 20$, where v (feet/sec) is the maximum vertical wave velocity and λ is the wave length in feet, a maximum vertical velocity of 5.6 feet/sec is computed for a wave length of 250 feet. This is in good agreement with the average difference in velocities shown in Table VI.

Returning to Equation (1), the third term ($p = f(m,t)$) is a function of changing mass of water with time. There are no data available upon which to base an analysis of the magnitude of this third contributor to pressure, but since the other two terms predict pressures in reasonable agreement with the measurements, its effect must be relatively small. The first two terms of the right-hand side of Equation (1) may be considered as a special case of the general Bernoulli equation for the determination of pressure at the stagnation point.

The pressures measured by the high-pressure transducer at Location 2 (HP2, 0.1L aft of FP) have been added to Table VI for correlation with the velocity figures. Plotting the pressures as a function of velocity on log-log paper (Figure 9), a straight line having a slope of 2 was drawn through the highest slope-derived relative velocity. Of the available data, four of the five points lie quite close to this line. The data were treated in this manner for direct comparison with Ochi's tests on a MARINER model. He found (Reference 3, Figure 1, p. 549) that his experimental data indicated that pressure and relative velocity were related by the equation $p = 0.086v^2$ for a location 0.1L aft of FP, and that there was a threshold velocity of about 12 feet per second below which no pressures were measured. Ochi's curve has been added to Figure 9 for reference.

The experimental data from the WOLVERINE STATE reported here show similar results, although the number of slams for which velocities have been computed is small. The relationship, assuming that the exponent is 2, is $p = 0.077v^2$. In comparing these results, it must be remembered that the slope-derived velocities computed for the WOLVERINE STATE include the effect of wave vertical velocity, while the acceleration-derived velocities are the absolute bow vertical velocities and not necessarily the true impact velocities. The acceleration-derived velocities have been plotted as the solid dots on Figure 9, and show much more scatter than the slope-derived velocities.

Chuang (Reference 5, p. 17, Equation 9) reported data on flat-bottom drop tests, and derived the relationship between maximum pressure and impact velocity for the air-entrapped case as $p_{max} = 4.5v_o$. One of Chuang's data points and his curve have been added to Figure 9 for comparison with the MARINER model and WOLVERINE STATE full-scale data.

E. Pressure Statistics

The pressure measurements from Voyage 288W3, Intervals 56, 57, and 58 tabulated in Table I have been used to prepare a histogram showing the probability density for various pressure ranges. This histogram is shown in Figure 10. Because of the low values compared with the dynamic range of the pressure transducers and recording system, accurate measurements were difficult. Many of the slamming pressures from HP2 reported as being in the 0 - 10 psi range may have been, in fact, zero. Thus, the probability density of the first range of the histogram may be exaggerated. The pressures shown in Table I as being less than the resolution limit of about 12 psi have been included in the 0-10 psi category.

Computation of the theoretical function for the probability density of slamming pressures (per Ochi, Ref. 3, Eq. 15, p. 560) requires a knowledge of the variance of the relative velocity between the forefoot of the vessel and the water surface and therefore requires a continuous record of relative displacement or velocity. This information is not available from these full-scale tests, so no theoretical curve can be indicated for comparison.

The absolute values of pressures measured and reported here are low in comparison to those reported by other investigators. Ochi's model tests (Reference 3) found pressures close to 100 psi, and Greenspon (Reference 6) measured pressures over 200 psi in full-scale tests on the USCGC UNIMAK. Drop tests also result in substantially higher pressure levels, as noted in Figure 9 and References 2 and 5. It was on this basis that the dynamic range of the high-pressure transducers was selected as 0 - 350 psi. Since the recording bandwidth does not appear to be the limiting factor as discussed above, it is possible that such high pressures did not occur due to air entrapment under the relatively flat bottom of the WOLVERINE STATE during storm conditions.

F. Relationship of Pressure to Stress and Acceleration

As illustrated in Figures 1 and 3, the stress signal shows that the first-mode whipping vibration is induced by the slam. This vibration, at a frequency of about 1.5 Hz, persists for as long as 30 seconds after a severe slam. The vibration usually begins just after a maximum hog (tension) stress variation. A computation of the approximate first-mode vibration frequency by the Todd method results in a value of 1.64 Hz, in good agreement with the experimental results.

Figure 11 is a plot of the HP2 slamming pressures vs. the resulting whipping bending stresses and the wave-bending stress which existed coincident with the slam. The whipping stresses were measured by scaling the apparent maximum value for each slam from the expanded oscillograph record as shown in Figure 1. The existing data do not show a very strong correlation between pressure and bending stress.

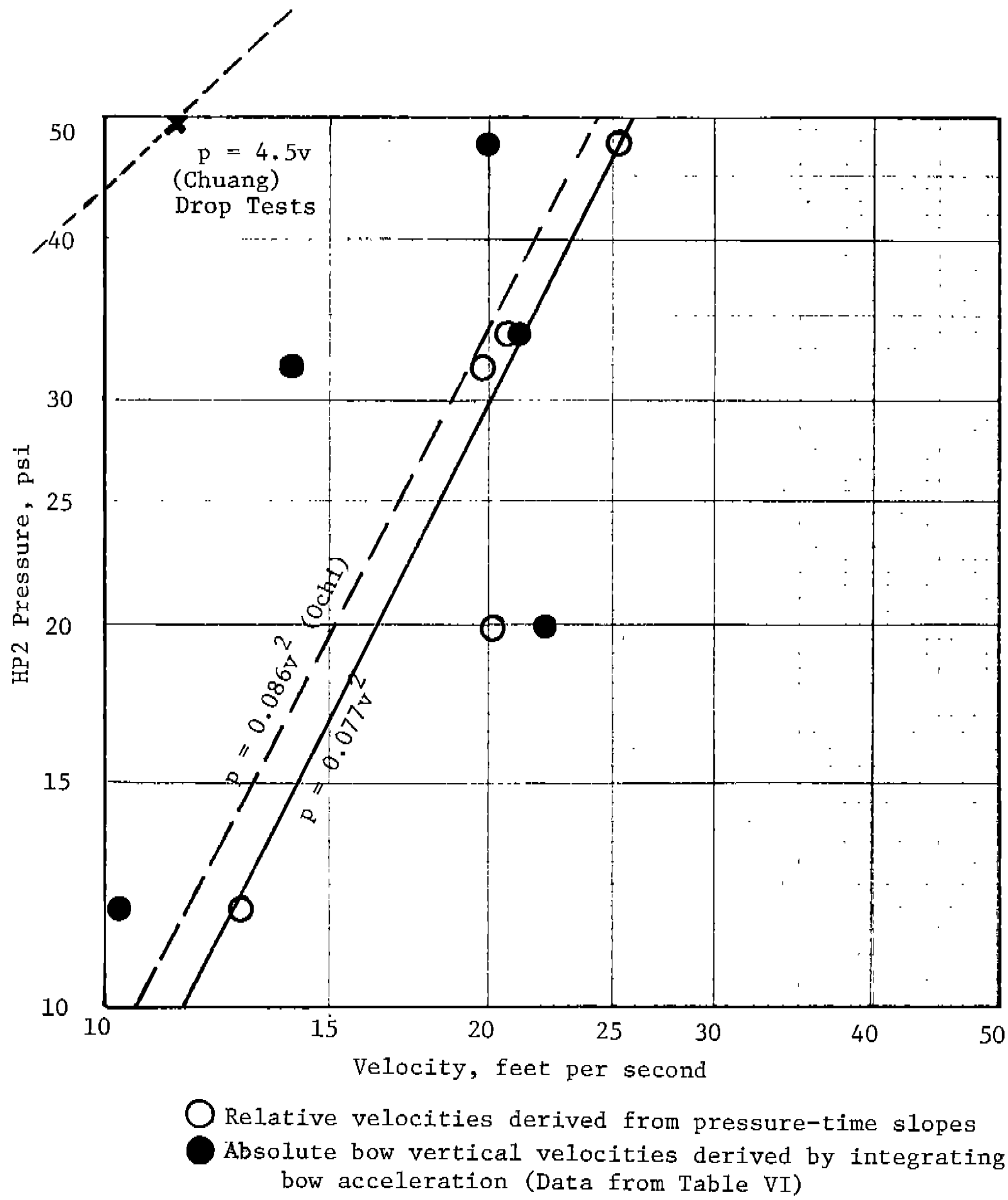


Fig. 9. Pressure (HP2) vs. Velocity

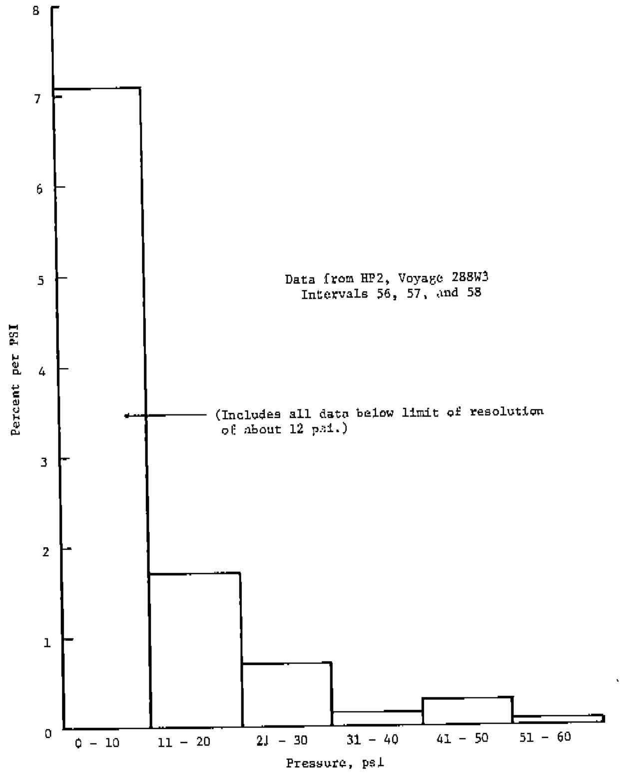


Fig. 10. Probability Density of Pressure Measurements

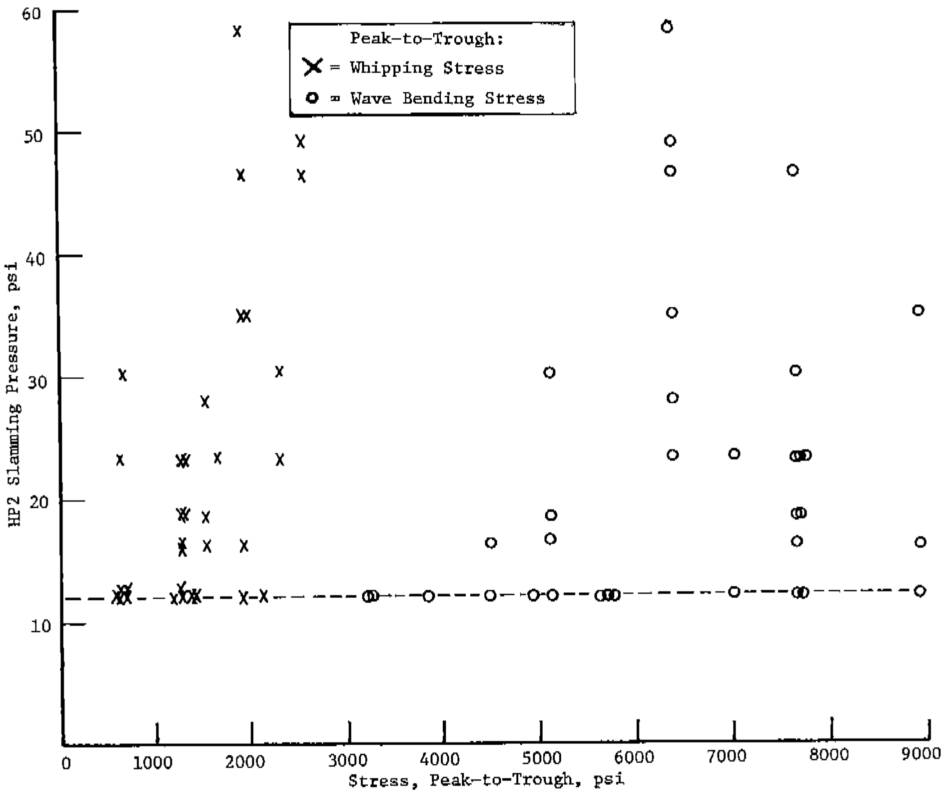


Fig. 11. HP2 Pressure vs. Stress

However, these pressures are measured at one location only, and the energy input causing large stresses may well have occurred at different places on the hull at different times.

The general characteristics of the bow acceleration signal are shown in Figure 1. When a slam occurs the accelerometers respond to the transient accelerations, which are superimposed on the general data. The accelerations measured at the bow are of particular interest. They indicate not only a sharp transient acceleration coincident with the first pressure peak on the low-pressure transducer, but also a series of smaller transients in rapid succession. This is particularly evident in Figure 3-A on both the acceleration and LP22 traces, but can be seen also in most of the other figures showing the details of the six slams. The stern accelerometer, however, does not show much indication that a slam has occurred.

A plot of LP21 transient slamming pressure vs. peak-to-trough low-frequency (wave-induced) bow acceleration is shown in Figure 12. Whereas the absolute magnitudes of pressure from the low-pressure transducer are questionable, there appear to be some limits on the envelope of data points both in absolute values and in slopes. There were no wave-induced peak-to-trough accelerations below about 0.3g accompanied by slams. In addition, the maximum values of pressure associated with accelerations appear to follow a well-defined straight line relationship.

There are fewer data points from the HP2 transducer above the minimum resolution level of about 12 psi, as shown in Figure 13. The pressures below 12 psi have been shown as arrows below that level. The same general type of relationship between pressure and acceleration can be deduced from this plot also, however. From the physical standpoint, of course, the pressure measured at either of these locations is a function of the local water surface angle and vertical velocity as well as of the bow acceleration, thus the large scatter in the data.

G. Time Distribution of Slamming Pressures

It is of specific interest to the designer to know whether or not slamming pressures are effective over large areas of plating at the same time. The time measurements from Figures 3-A through 3-F shown in Table II provide some information in this regard.

In Figures 3-A through 3-F the signal from the Bow Accelerometer was used as a common reference, and the signals from all transducers were aligned accordingly. Using the first peak signal from LP22 as an arbitrary zero time for each slam, the times of occurrence of the peak pressure signals from each transducer were measured in terms of milliseconds before (minus) or after (plus) that arbitrary zero time. In addition, the peak value of each pressure pulse and its base width in time were measured.

The results are plotted in Figure 14, in which each pressure pulse is represented by a triangle of the measured amplitude and duration. As an example, in the case of Slam 16, HP1 peak occurred about 160 milliseconds before LP22, but in Slam C HP1 peak occurred about 360 milliseconds after LP22. From this and other examples which could be cited it seems evident that slamming pressures are generally of short duration in comparison with the length of time the slam is observable at the various locations, and thus are not effective simultaneously over large areas. Pressures at LP22, HP2, and HP1 occasionally cluster together in time, but these transducers are located quite near to each other (see Figure A-3). The duration of measured pressures at LP22 may be exaggerated, also, because of the tubing which connects the pressure transducer to the hull plating.

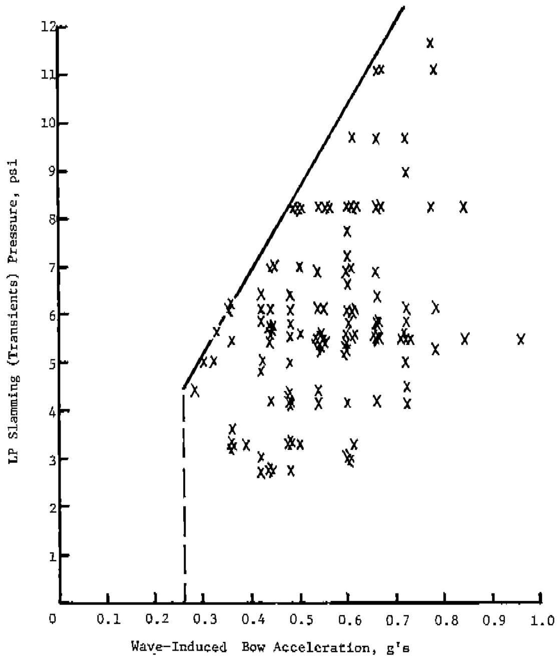
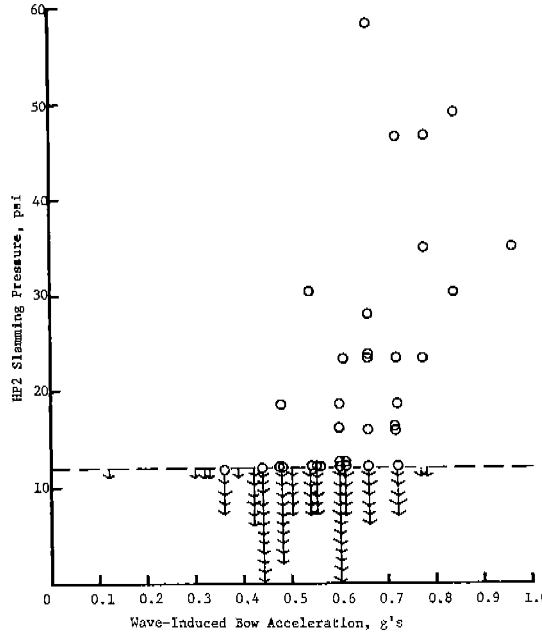


Fig. 12. LP21 Slamming Pressure vs. Wave-Induced Bow Acceleration



(Each arrowhead represents one data point <12 psi)

Fig. 13. HP2 Slamming Pressure vs. Wave-Induced Bow Acceleration

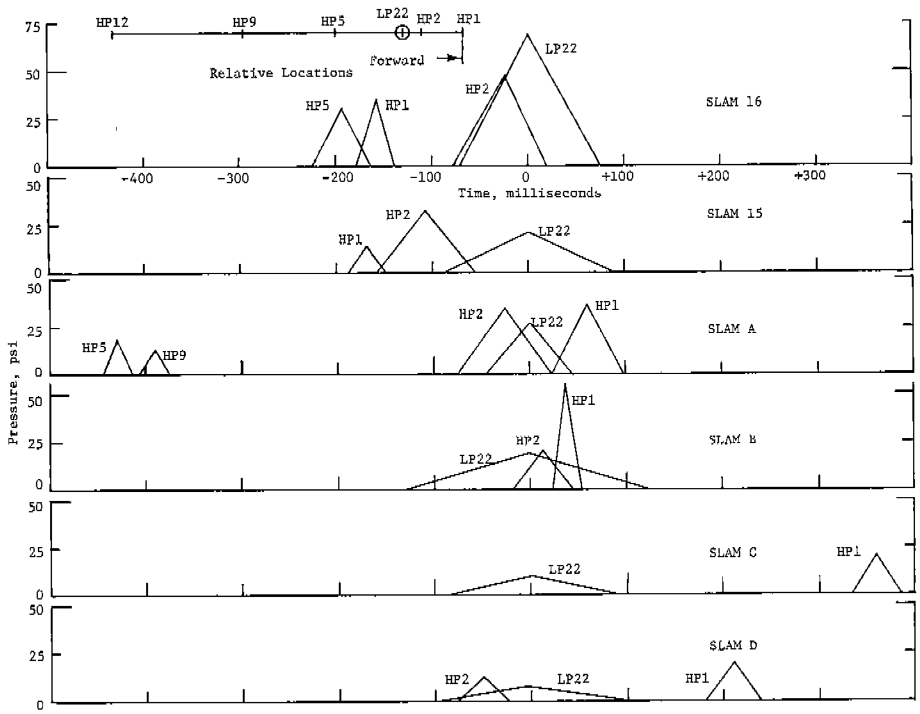


Fig. 14. Time Distribution of Slams, Data from Table II

H. Whipping Stress vs. Wave-Bending Stress During Slamming

The data reported in Table I provide some insight into the manner in which whipping stresses combine with wave-bending stresses when slamming occurs. For each of the slams reported in Table I, the whipping stress has been plotted as a function of the wave-bending stress occurring at the time of the slam (Figure 15).

In general, high wave-bending stresses and high whipping stresses appear to occur at the same time, but the data show that the maximum whipping stress does not necessarily occur coincident with the maximum wave-bending stress. It should also be noted in passing that other examinations of the records show that the maximum whipping stresses rarely occur exactly at the maximum point on a wave-induced cycle.

I. Impact Velocity as a Function of Bow Acceleration and Duration of Emergence

In "D" above the impact velocity was computed using the pressure-time slope, and was approximately verified by integrating the bow acceleration. Since the wave-induced acceleration records are somewhat simpler to work with, it was decided to investigate other means whereby peak-to-peak wave-induced acceleration measurements and related parameters could be used to predict impact velocities.

Figure 16 shows the derivation of velocity using the forward draft, the easily-established pitching period ($T = \frac{2\pi}{\omega}$), and either duration of bow emergence (Figure 16, Equation 1), or peak-to-peak bow acceleration (Figure 16, Equation 2). The data from the six slams for 277W2 were reduced in this way and the results are plotted in Figure 17 along with the relative velocity computed using the more acceptable pressure-time slope method, and the velocity computed directly from integration of the acceleration signal.

On the basis of the small amount of data shown, and assuming the slope data to be "acceptable", one must conclude that the integration of accelerometer data is at least as acceptable as the other two methods, which are considerably more difficult. Since only the slope and emergence methods include any effects of motion of the water surface, this conclusion leaves something to be desired. However, the correlations are strong enough to suggest that further exploration of the relationship between bottom slam pressure and relative velocity deduced from acceleration or emergence records is necessary before the use of these "secondary" data sources is rejected.

V. FINDINGS AND CONCLUSIONS

A. The additional instrumentation installed on the WOLVERINE STATE to gather data on slamming pressures, accelerations, and hull response performed well considering the limitations previously discussed. Hundreds of slams were recorded on magnetic tape under a variety of conditions.

B. Full-scale measurements and analysis have confirmed that the frequency of occurrence of slamming follows a Poisson distribution, and that the time interval between slams follows an exponential probability function truncated at the pitching period.

C. Although all instances of high Beaufort numbers were investigated, slamming was found only in those cases where the relative heading was within about 30 degrees

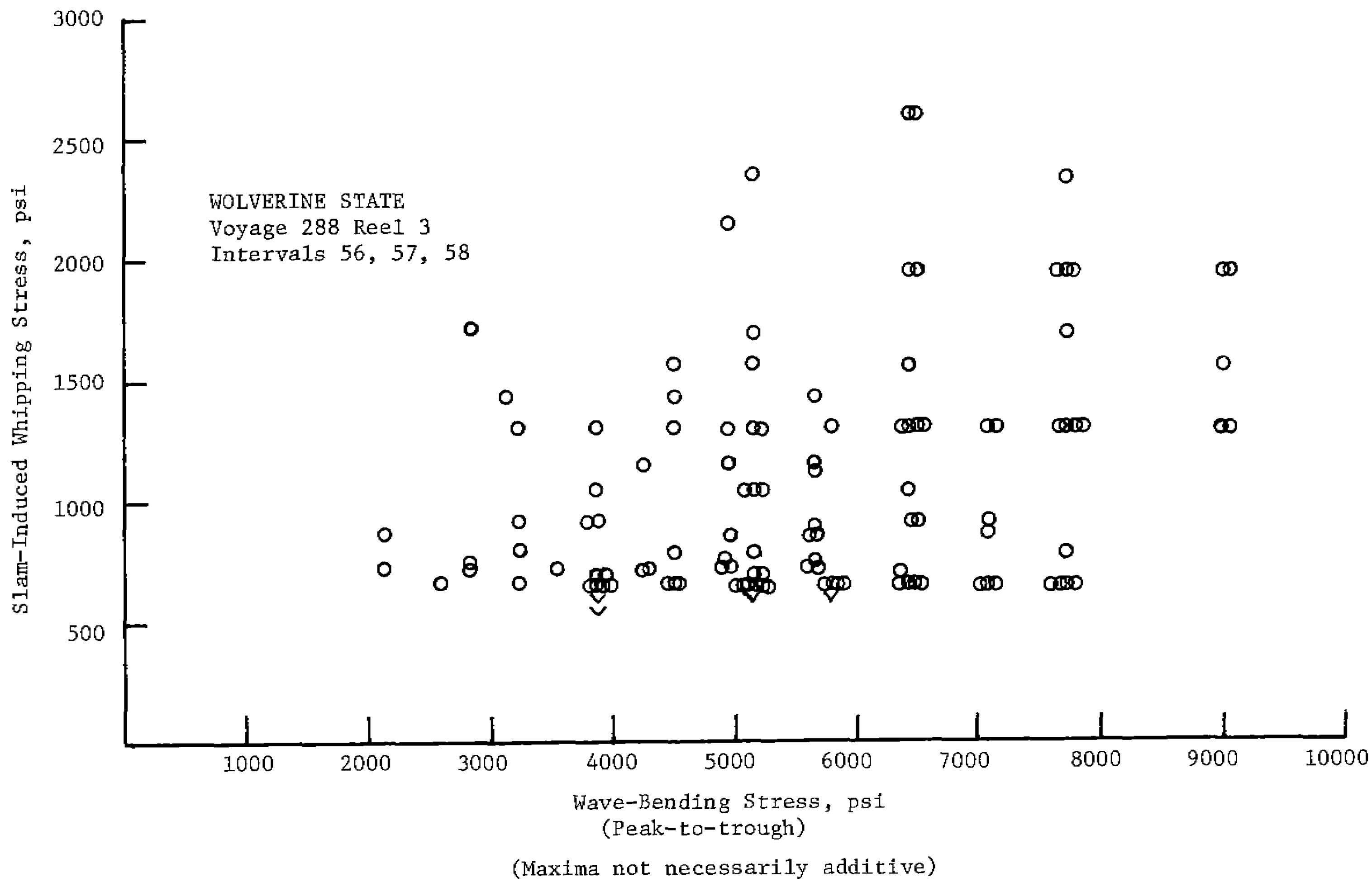
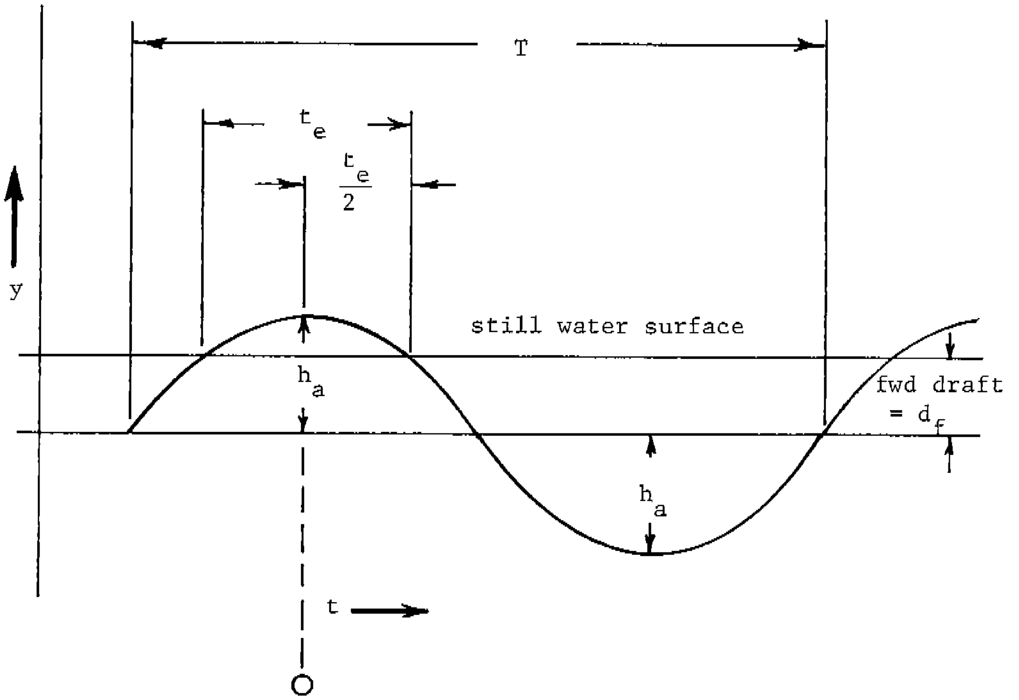


Fig. 15. Whipping Stress vs. Wave-Bending Stress



$y = h_a \cos \omega t$ = displacement

$\dot{y} = -h_a \omega \sin \omega t$ = velocity

$\ddot{y} = -h_a \omega^2 \cos \omega t$ = acceleration

v_i = velocity at immersion

a_a = amplitude of acceleration signal

t_e = duration of emergence

At immersion $y = d_f = h_a \cos \frac{\omega t_e}{2}$

$$\omega t_e = \cos^{-1} \frac{d_f}{h_a} = \frac{2\pi t_e}{2T}$$

$$v_i = h_a \omega \sin \frac{\omega t_e}{2} = h_a \omega \sin \frac{\pi t_e}{T}$$

Since $h_a = \dfrac{d_f}{\cos \frac{\omega t_e}{2}}$,

$$v_i = d_f \frac{1}{\cos \frac{\pi t_e}{T}} \frac{2\pi}{T} \sin \frac{\pi t_e}{T} \quad \ldots (1)$$

Or, since $a_a = h_a \omega^2$

$$v_i = \frac{a_a T}{2\pi} \sin\left[\cos^{-1} \frac{d_f 4\pi^2}{a_a T^2}\right] \quad \ldots\ldots (2)$$

Fig. 16. Derivation of Velocity and Acceleration Relationships

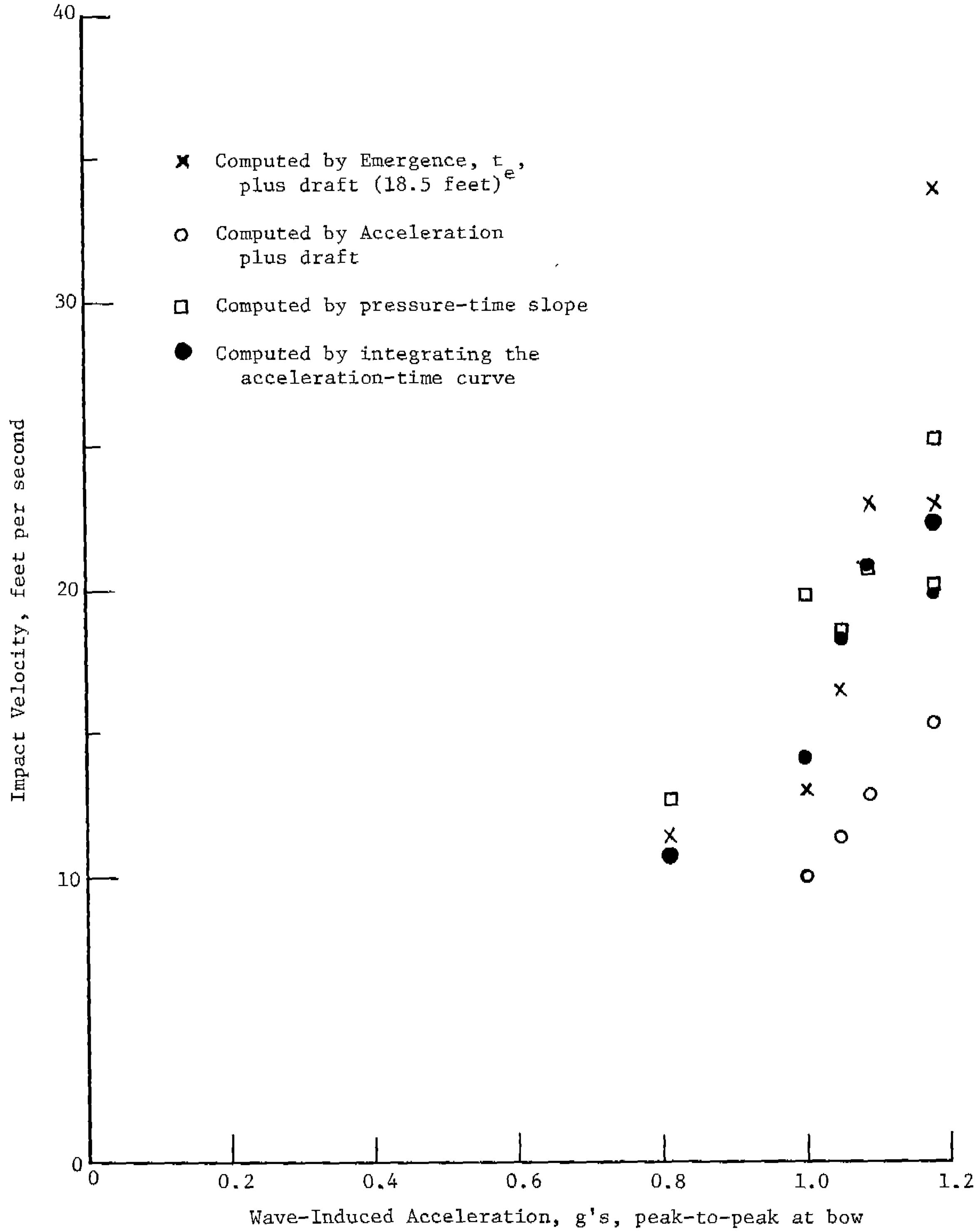


Fig. 17, Impact Velocity vs. Wave-Induced Acceleration Four Methods 277W2 Six Slams of head seas. Reduction in engine RPM to the point of being "hove to" did not appear to reduce the frequency of slamming. It is concluded that high Beaufort number alone is not sufficient to produce slamming. Also, slamming has never been observed in this study at low (i.e., below 5) Beaufort number.

D. The light forward draft (16.5 feet) on the westbound portion of Voyage 288 appeared to be the cause of a dramatic increase in the rate of slamming, as compared with cases of similar headings and Beaufort number, but with a draft of 18.5 feet.

E. As of the last drydocking of the WOLVERINE STATE, no plates had been replaced due to slamming damage over the past three years. It may be concluded, therefore, that the slams experienced on Voyage 277 were not harmful. Voyage 288 occurred after the last docking.

F. One of the objectives of the study was to measure impact velocity as related to slamming. Relative velocities ranging from 12.8 to 25.2 feet per second were computed for the six slams studied in detail. These values were confirmed in general by estimating the velocity by integrating the wave-induced bow acceleration, and by establishing relationships between velocity and peak-to-peak acceleration and duration of bow emergence.

G. Plotting the slope-derived velocities against pressure, the relationship $p = 0.077v^2$ was found to be a good fit to the data. Ochi determined the relationship to be $p = 0.086v^2$ from tests on a MARINER model.

H. The absolute values of slam pressure were found to be lower than those reported elsewhere for drop tests, but were consistent with Ochi's model test data, as noted above.

I. Slamming excites the first-mode vertical hull vibration at a frequency of about 1.5 Hz. These vibrations are superimposed on the wave-induced bending stress. The associated whipping stress was 20 percent of the highest measured wave-induced stress during slamming. However, there were several cases of lower wave-induced stress variations in which the associated whipping stresses were 40 percent of the wave-induced value. Maximum absolute whipping stresses observed did not coincide with maximum bending stresses.

J. The bow accelerometer is quite sensitive to slamming phenomena. It not only shows a transient acceleration at impact, but also indicates that the bow is experiencing a higher-mode vibrational response at about 5 Hz. Integration of the gross bow acceleration yields velocity values in general agreement with those computed by other methods.

K. Examination of the time distribution of slamming pressures for six slams leads to the tentative conclusion that the slamming pressures are short in comparison with the passage of the slam pressure along the bottom. However, since no damage was reported as a result of slams from this voyage (277), the nature of plate-deforming pressures is still unknown.

VI. ACKNOWLEDGEMENTS

This project was sponsored by the Ship Structure Committee, and has been conducted under the guidance of Advisory Group I of the Ship Research Committee of the National Academy of Sciences, National Research Council with Mr. J. F. Dalzell as coordinator.

The data reported here could not have been acquired without the continuous helpful contribution of States Marine Lines, in particular John Ritter, Philip Kimball, and Joseph Buchanan. Especial thanks are due the officers and men of the SS WOLVERINE STATE for their vital assistance in keeping the special logbooks and operating the instrumentation system.

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APPENDIX A

INSTALLATION OF THE SLAMMING DATA RECORDING SYSTEM ABOARD THE SS WOLVERINE STATE

(Edited Excerpts from Technical Report No. 929/122, Final Report on Contract NObs 94035, 15 June 1966)

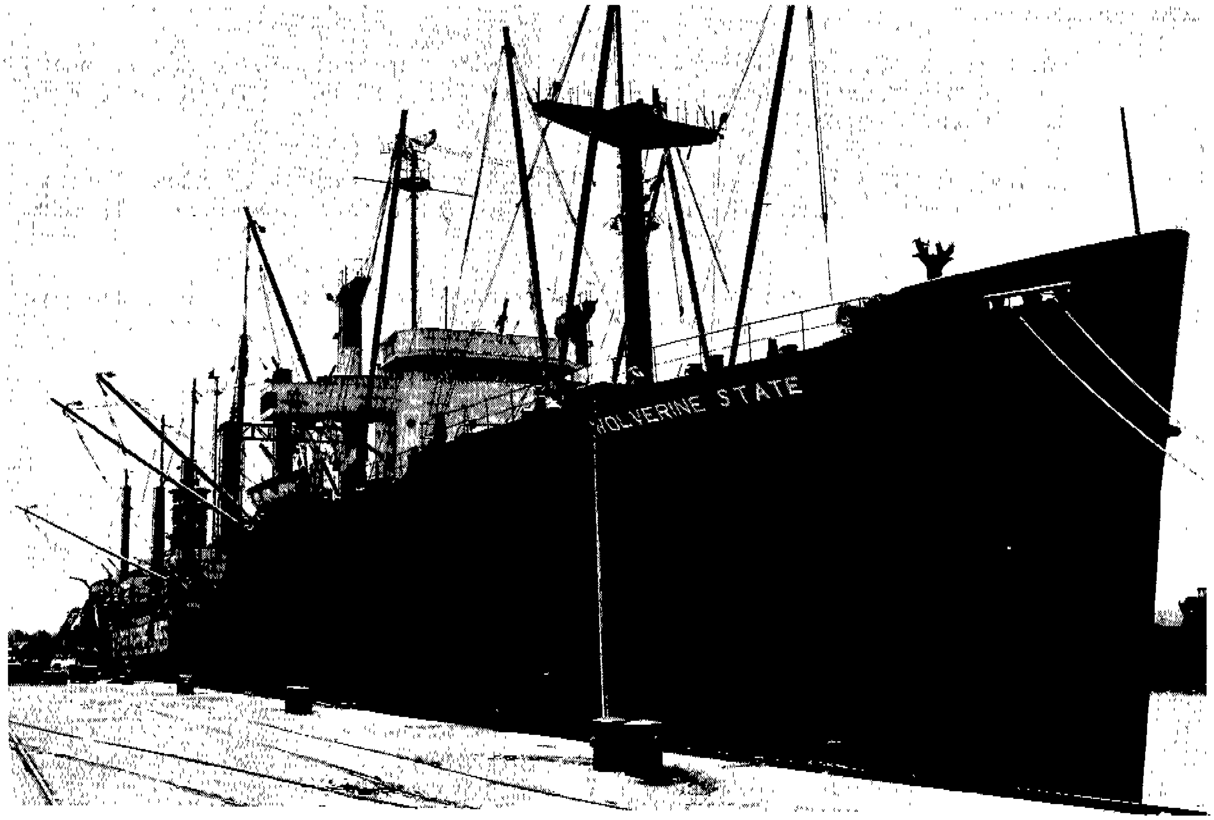

Fig. A-1. *S.S. Wolverine State*

I. INTRODUCTION

Since June 1959, Teledyne Materials Research has been actively engaged in the collection of data on wave-induced bending moment stresses under SSC Project SR-153. Data have been recorded on magnetic tape using semiautomatic instrumentation systems aboard four operating dry cargo vessels.[1, 2, 3, 4, 5*] The recorded data are subsequently reduced in the Teledyne laboratory, using a statistical probability analyzer, and reported to other investigators for analysis and interpretation.

Because of the similar nature of the data collection requirements for the slamming study, SSC Project SR-172, it was decided that the recording system aboard the SS WOLVERINE STATE, a C4-S-B5 machinery-aft dry cargo vessel, see Figure A-1, would be expanded by the addition of recording channels and the installation of the necessary transducers. It is the selection of components, and assembly and installation of the system which are described in this Appendix.

*See References at end of Appendix A.

II. INSTALLATION OF TRANSDUCERS AND RECORDING EQUIPMENT

A. General

In October 1965 the entire recording system consisting of the instrumentation tape recorder and motor-alternator set was removed from the SS WOLVERINE STATE. The tape recorder was reconditioned and modified for installation during January 1966 as a part of the new data gathering system aboard the SS CALIFORNIA BEAR, a West Coast Mariner operated by Pacific Far East Lines.[6] The motor-alternator set was reconditioned for return to use on the SS WOLVERINE STATE.

Components for the augmented system were selected on the basis of a review of the experience of other investigators. Certain equipment items, notably the tape recorder and programmer unit, were placed on order early in the summer of 1965 under an existing contract for equipment acquisition (U.S. Navy Contract NObs 92134). The remaining items of equipment were placed on order in mid-October 1965 at the completion of contracting arrangements for the slamming system installation. These items, the pressure cells and pressure cell signal conditioning equipment, were available for installation along with the remainder of the system during an anticipated mid-December drydocking. The drydocking was twice postponed because of ship operating schedule commitments until mid-March. During this period there was an opportunity to perform further laboratory checkout and operational checks on the complete system.

In late January 1966, during the return of the ship to the U.S. East Coast, a two-man team supervised the shipboard reinstallation of the reconditioned motor-alternator and the new tape recorder. At this time bow and stern vertical accelerometers were also installed in existing accelerometer locations and connected into the recorder using existing shipboard transducer cables.[3] This was all of the work which could be accomplished without access to the bottom of the ship in a drydock. This work was performed at this time to reduce the future workload to be performed while the ship spent a limited amount of time in the shipyard. It also provided an interim system capable of recording port and starboard midship bending stresses and bow and stern vertical accelerations.

During the mid-March drydocking, a four-man team supervised the location, installation, and cabling of the pressure transducers at the forward end of the ship, the installation of the pressure cell signal conditioning units in No. 2 Hold, and the installation of necessary additional shipboard wiring from the pressure cell locations to the recording equipment in the Instrument Room.

Following the completion of the installation, an overall systems operational checkout was performed aboard the ship during a coast-wise run from New York City to Norfolk, Virginia. During these tests the system operated satisfactorily except for a few minor malfunctions.

Immediately following the coastwise voyage, a manned roundtrip to Europe took place. The purpose of this attended operation was to observe system operation under severe sea conditions and to make direct high-frequency chart recordings of slamming pressures. Unfortunately, there was a minimal amount of severe weather.

B. Pressure Transducer System

A functional block diagram representation of the entire seaway data recording system installed aboard the SS WOLVERINE STATE is provided in Figure A-2. Table A-I presents a listing of the recording functions assigned to each of the fourteen available tape recorder channels. This section is concerned primarily with the pressure transducer portion of the system, its associated electronic circuitry, and interconnecting shipboard wiring. Specific details of the recording system, the transducers, and associated equipment components will be described in the next section.

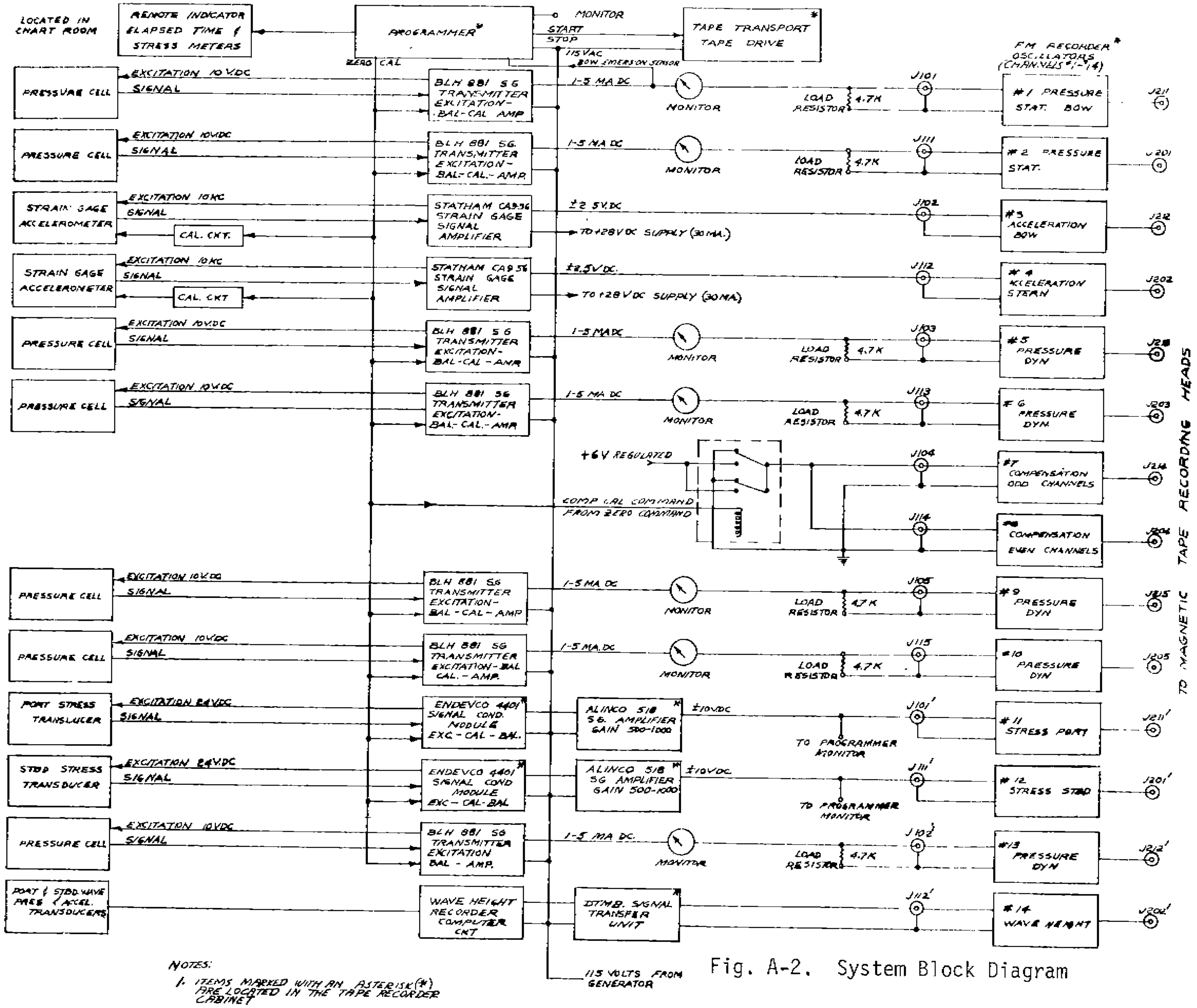

Fig. A-2. System Block Diagram

Table A-I.
Assignment of Tape Recorder Channels

Channel No.	Function	Linear Transducer Range	Calibration Level
1	Static Pressure	0 - 50 psig	25 psig
2	Static Pressure	0 - 50 psig	25 psig
3	Bow Acceleration	± 5 g	-1.0 g
4	Stern Acceleration	± 5 g	-1.0 g
5	Dynamic Pressure	0 - 350 psig	175 psig
6	Dynamic Pressure	0 - 350 psig	175 psig
7	Compensation (odd channels)	Reference Signal*	
8	Compensation (even channels)	Reference Signal*	
9	Dynamic Pressure	0 - 350 psig	175 psig
10	Dynamic Pressure	0 - 350 psig	175 psig
11	Port Stress	Elastic Range	10,000 psi
12	Starboard Stress	Elastic Range	10,000 psi
13	Dynamic Pressure	0 - 350 psig	175 psig
14	Wave Height	NIO Wavemeter	20 ft

* A constant frequency is recorded on tape channels 7 and 8. These reference signals are used during playback to compensate for flutter and wow; i.e., to improve the signal-to-noise ratio of the data by reducing any extraneous noise which may be introduced by mechanical effects in the tape transport.

Figure A-3 and Table A-II indicate the positions of the twenty-four pressure transducer mounting locations which were installed in the bottom plates in the forward portion of the vessel. A plot included in Figure A-3 summarizes the cumulative damage to the bottom plating experienced on three vessels of the same type, C4-S-B5, operated by States Marine Lines in North Atlantic service (WOLVERINE STATE, HOOSIER STATE, KEYSTONE STATE). Most of the slamming damage experienced by these ships is observed to occur between Frames 25 and 45, toward the forward end of the #2 Double Bottom Tanks. The majority of the pressure transducer mounting locations have been distributed over this area. Transducers were installed in twenty of the twenty-four available locations. The remaining four in the No. 1 Deep Tank were sealed with blank flanges.

Detailed descriptive information on the *S.S. Wolverine State* is contained in Table A-III.

Figure A-4 depicts the installation of the pressure transducer mounting assembly through the bottom plating of the ship. A suitable circular hole about 3 1/4 inches in diameter is flame cut and beveled to form a vee groove. The housing is then installed by an overhead welding operation and a fillet weld is made around the region in which the lower portion of the housing meets the inside surface of the bottom plate. A mock-up of this assembly was made by Teledyne Materials Research to develop the necessary welding techniques and to check for warping of the housing during

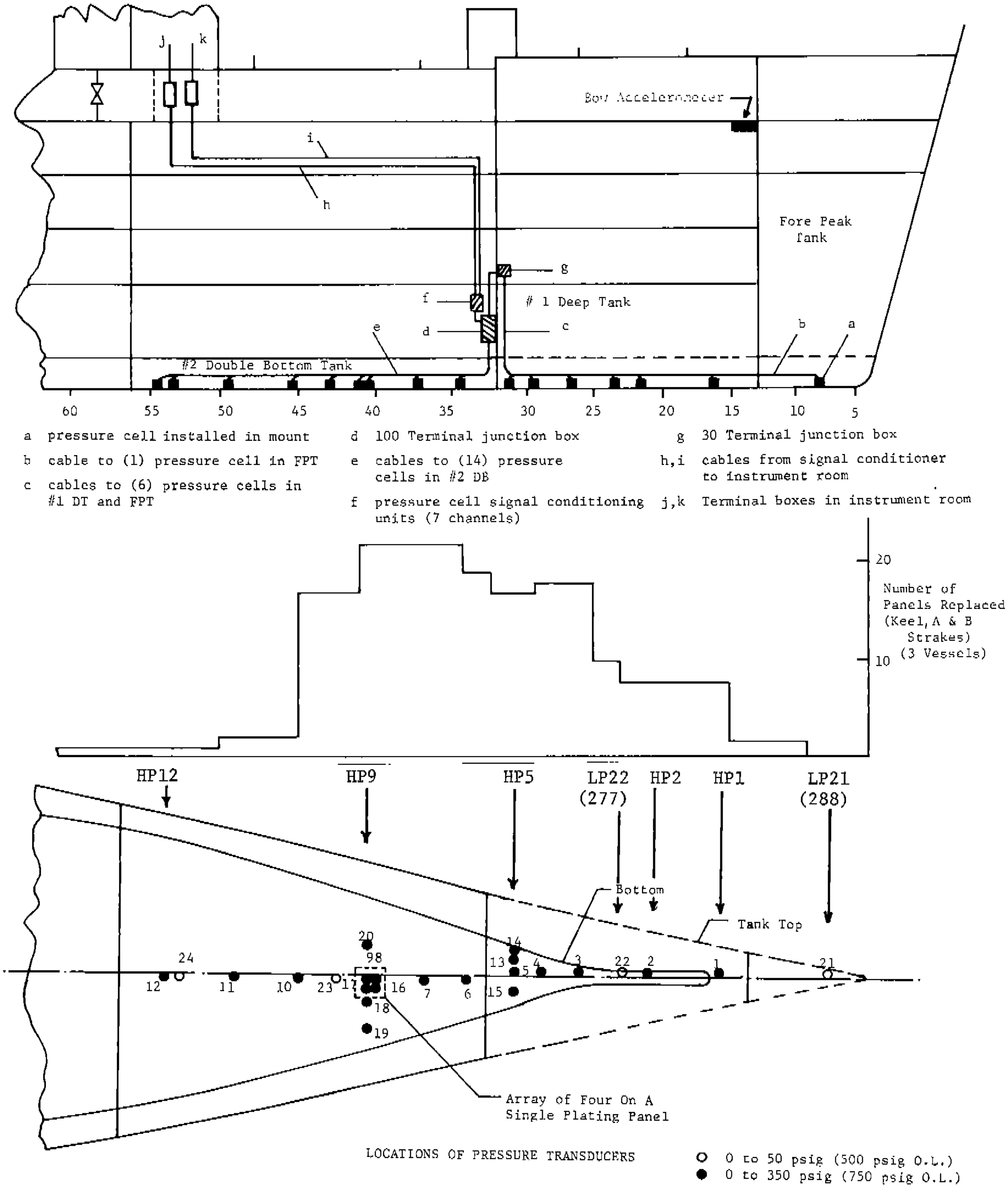

Fig. A-3. Location of Slamming Damage on *S.S. Wolverine State* and Two Sister Ships, Locations of Pressure Transducers, and Intercabling to Recording Instrumentation

Table A-II
Pressure Transducer Mounting Locations

Location Number	In Tank	In Bottom Plate	Between Frames	Distance Aft of Frame	Off Center Vertical Keel	Distance Aft from Bow
1	#1 D.T.	FK-1	16-17	11" aft FR.16	11" P	41' 5"
2	#1 D.T.	FK-1	21-22	11" aft FR.21	11" P	52' 8"
3	#1 D.T.	FK-2	26-27	11" aft FR.26	11" P	63'11"
4	#1 D.T.	FK-2	29-30	11" aft FR.29	11" P	70' 8"
5	#1 D.T.	FK-2	31-32	11" aft FR.31	11" P	75' 2"
6	#2 D.B.	FK-3	34-35	11" aft FR.34	9" S	82' 5"
7	#2 D.B.	FK-3	37-38	11" aft FR.37	11" S	89'11"
8	#2 D.B.	FK-3	40-41	6" aft FR.40	11" S	97' 0"
9	#2 D.B.	FK-3	40-41	24" aft FR.40	11" S	98' 6"
10	#2 D.B.	FK-4	45-46	11" aft FR.45	11" S	109'11"
11	#2 D.B.	FK-4	49-50	11" aft FR.49	9" S	119'11"
12	#2 D.B.	FK-4	54-55	11" aft FR.54	11" S	132' 5"
13	#1 D.T.	A-8	31-32	11" aft FR.31	41" P	75' 2"
14	#1 D.T.	A-8	31-32	11" aft FR.31	65" P	75' 2"
15	#1 D.T.	A-8	31-32	11" aft FR.31	41" S	75' 2"
16	#2 D.B.	A-9	40-41	6" aft FR.40	30" S	97' 0"
17	#2 D.B.	A-9	40-41	24" aft FR.40	30" S	98' 6"
18	#2 D.B.	A-9	40-41	24" aft FR.40	69" S	98' 6"
19	#2 D.B.	B-6	40-41	24" aft FR.40	105" S	98' 6"
20	#2 D.B.	A-9	40-41	24" aft FR.40	69" P	98' 6"
21	Forepeak	A-3	8-9	11" aft FR.8	11" P	24' 8"
22	#1 D.T.	FK-1	23-24	11" aft FR.23	11" P	57' 2"
23	#2 D.B.	FK-3	43-44	11" aft FR.43	11" S	104'11"
24	#2 D.B.	FK-4	53-54	11" aft FR.53	9" S	129'11"

Table A-III
Particulars of *S.S. Wolverine State* (C4-S-B5)

A. General

Original Name: MARINE RUNNER
Type: C4-S-B5 Machinery-Aft Dry Cargo Vessel
Builder: Sun Shipbuilding and Drydock Company
Chester, Pennsylvania
Date: September 1945
Hull Number: 359

Length Overall:	520'-0"
Length Between Perpendiculars:	496'-0"
Beam, Molded:	71'-6"
Depth, Molded:	54'-0"
Depth, Molded to Poop Deck:	52'-0"
Depth, Molded to Upper Deck:	42'-6"
Depth, Molded to Second Deck:	35'-0"
Depth, Molded to Third Deck:	26'-0"
Load Draft, Molded (Design):	30'-0"
Load Draft, Keel (Full Scantling):	32'-9 7/8"
Gross Tonnage:	10,747
Net Tonnage:	6,657
Official Number:	248,740

Block Coefficient:	0.654 (30' Molded Design Draft) 0.61 (18' Typical Present Operation)
Prismatic Coefficient:	0.664 (30' Molded Design Draft) 0.628 (18' Typical Present Operation)
Waterplane Coefficient:	0.752 30' 0.685 18'
Midship Section Modulus (with deck straps):	45,631 in.^{2} ft. (top top of Upper Deck)

B. Light Ship

Light Ship Weight:	6,746 L.T.
Center of Gravity:	30.40 ft. above keel 24.20 ft. aft of amidships
Light Ship Drafts:	3'-7" forward 19'-9 1/2" aft 11'-8 1/4" mean
Dead Weight at 32'-9 7/8" (Cargo Capacity):	15,348 L.T.

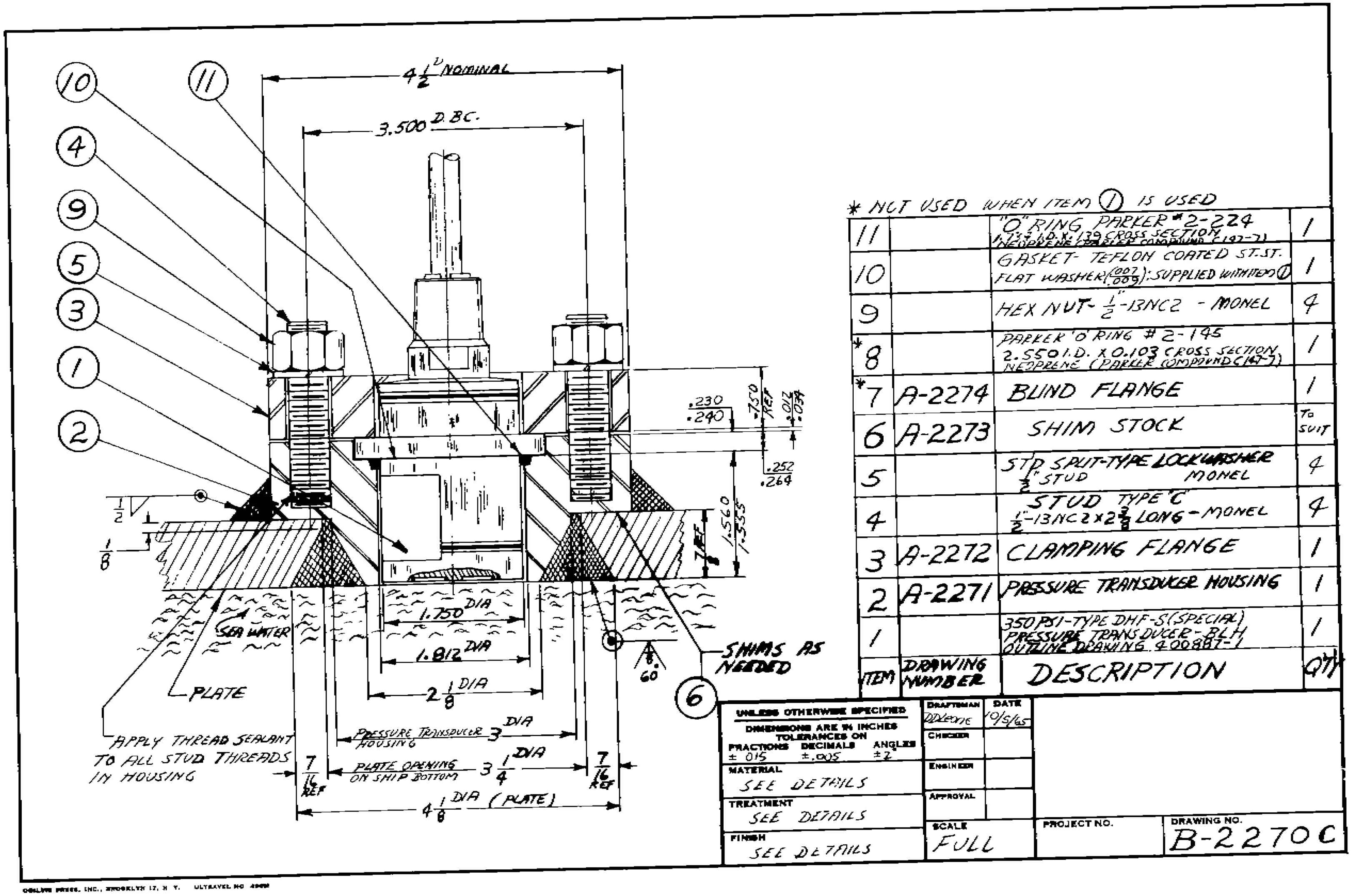

Fig. A-4. Pressure Transducer Installation Assembly Layout the welding process. This assembly withstood a hydraulic test pressure of 500 psi without leaking.

Two types of pressure cells are employed in the study. There are sixteen high pressure (dynamic) cells having a linear range of 350 psig which were used to record the slamming pressure pulses, and four low pressure (static) cells having a linear range of 50 psig which measure the slowly varying pressures resulting from the passage of ocean waves and the gross motions of the ship. The characteristics of the two types of cells will be discussed in the next section. The pressure transducer mounts were developed specifically for the high pressure, flush diaphragm pressure cells, but are equally suitable for the low pressure cells. During installation, prior to welding in place, shims were used if needed to recess the flush diaphragm of the high pressure cell approximately 1/32-inch back from the outer surface of the bottom plate. The combination of a teflon coated stainless steel gasket and "O" ring provided a very effective internal watertight seal between the pressure cell and the housing. In the case of the low pressure cell a blind flange with a small central hole replaces the clamping flange shown in Figure A-4. The low pressure cell is bracket-mounted to a nearby stiffener in the tank and the slowly varying pressure changes are conducted to it through a length of small diameter monel tubing. The use of the pressure transducer mounting assembly with each type of pressure cell is illustrated in Figure A-5 for the high pressure cell and in Figure A-6 for the low pressure cell. Figure A-7 shows a completed high pressure transducer assembly mounted in place on the inside of the bottom plating within one of the tanks. The entire assembly is painted over with a black waterproofing material which has the trade name Bitumastic Tank Solution (Koppers Company) to protect it when the tank is flooded. In Figure A-8 a low pressure cell is being mounted on its bracket next to a lightening hole in a stiffener in No. 1 Deep Tank.

Seven pressure cell signal conditioning units (transmitters) were installed on the forward bulkhead of No. 2 Hold above the No. 2 Double Bottom Tank top. The output signals from seven selected transducers are amplified by these transmitters and carried by newly-installed shipboard cables to the instrument room where they are recorded on the proper channels of the tape recorder. Figure A-9 shows four of the seven pressure cell transmitters mounted in position in No. 2 Hold. The remaining three units are mounted underneath the four but are obscured by a vertical batten support in the photograph. The top portion of Figure A-3 indicates the routing of the signal cables from the transducers, through the junction boxes to the transmitters, and thence to the instrument room and the tape recorder.

The four pressure transducer locations which remained unused were Nos. 4, 13, 14, and 15, all in the No. 1 Deep Tank.

C. Recording System

The characteristics of the component items of the data recording system are summarized in this section.

1. Tape Recording System

The Honeywell LAR 7468 Magnetic Tape Record/Reproduce System, shown in Figure A-10, records fourteen tracks of information on one-inch wide polyester tape one mil thick. Ten and one-half inch diameter reels contain 3,600 feet of tape and will record for forty hours of elapsed time at the normal recording speed of 0.3 inch per second (ips). The frequency bandwidth using this F-M recording technique is 0 (d-c) to 50 Hz.

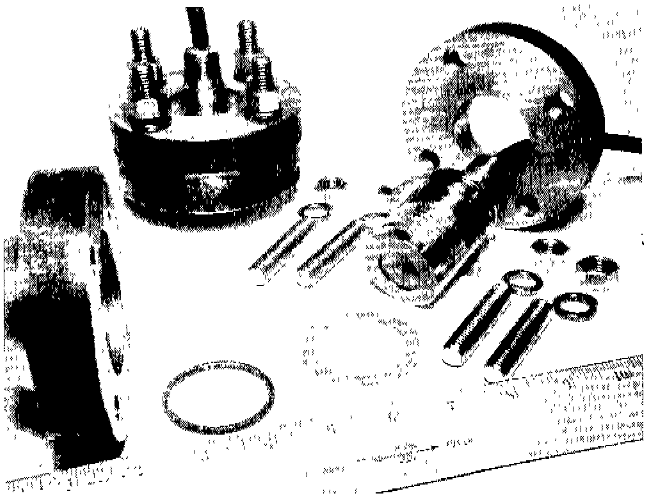

Fig. A-5. Transducer Mounting for High Pressure Cell

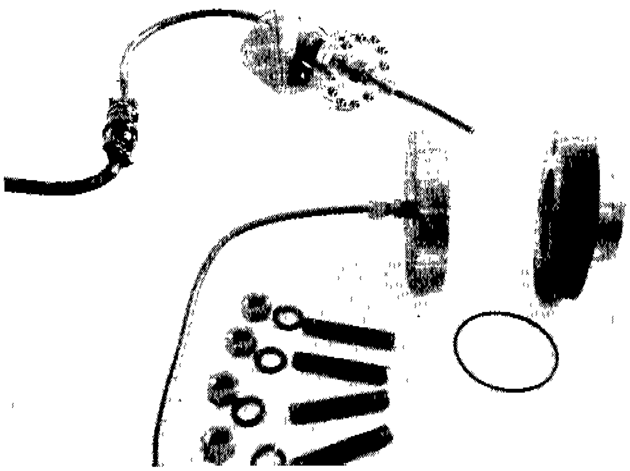

Fig. A-6. Transducer Mounting Assembly for Low Pressure Cell

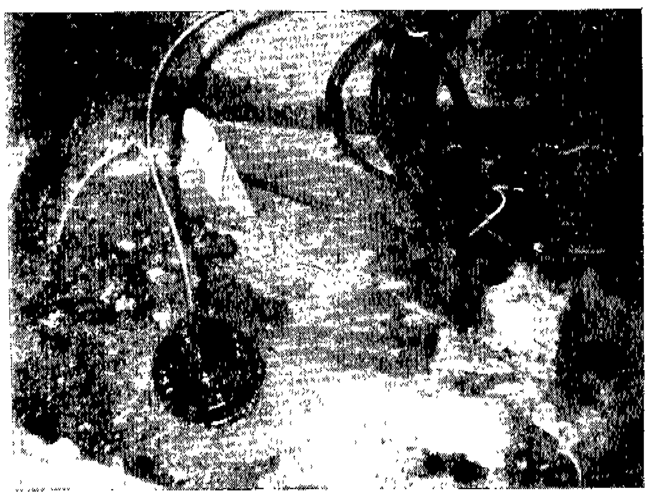

Fig. A-7. Completed High Pressure Transducer Mounted in Place Inside Tank

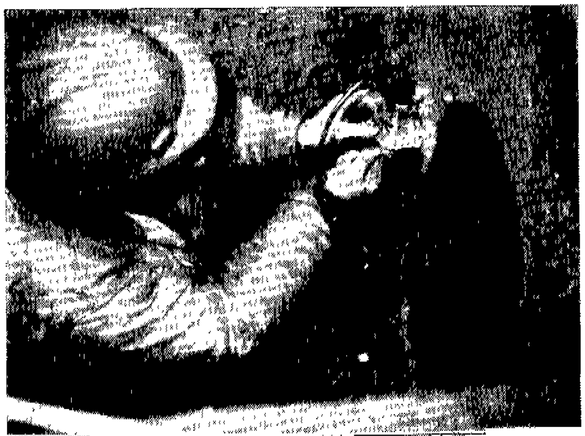

Fig. A-8. Low Pressure Cell Being Mounted with Bracket to Vertical Stiffner in Tank

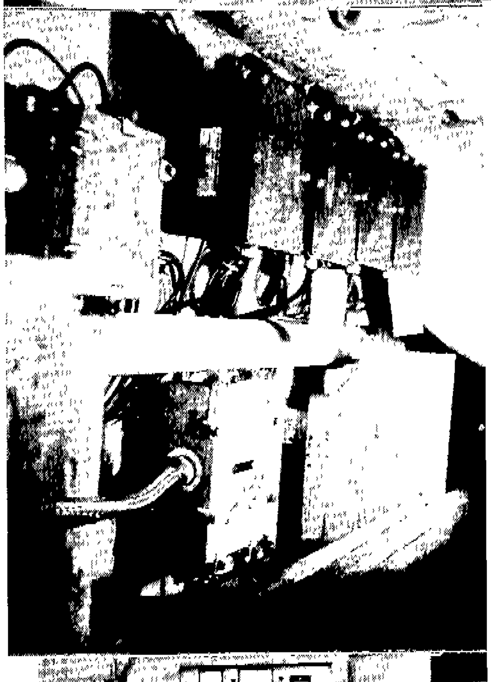

Fig. A-9. Pressure Cell Transmitter Mounting Location

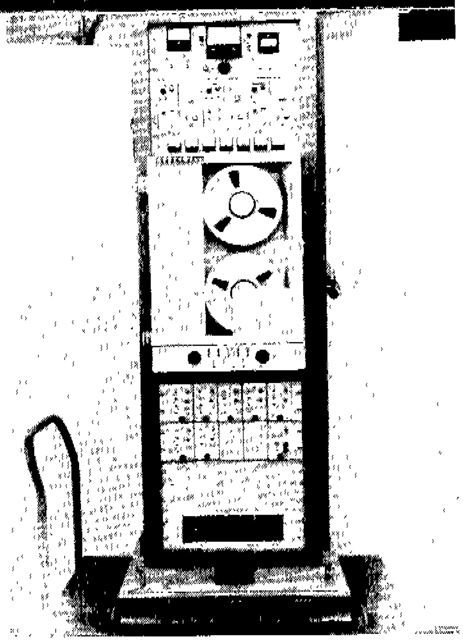

Fig. A-10. Magnetic Tape Record/ Reproduce System

In normal recording procedure a one-half hour data record, preceded by suitable calibration and system zero signals, was taken once in each four-hour watch period. Under rough sea conditions extended records were automatically obtained. An ordinary voyage would require one reel of tape for each crossing of the North Atlantic. The system incorporated one channel capable of playback at speeds of 0.3, 15, and 30 ips for checks on any data channel while still aboard ship.

a. Recording Electronics

The electronics portion of the recording system was mounted just below the tape deck. In addition to regulated electronic power supplies, the electronics consisted of recording oscillators (Figure A-11) and a playback discriminator (Figure A-12).

b. Programmer

The programmer was mounted at the top of the recorder console. It was this unit which caused the tape deck to operate once each four-hour period to make a one-half-hour data record. The programmer energized the system at other times under certain specified sea and operating conditions; e.g., when seas are rough and a preset level of stress is exceeded, or when the bow emerges from the water prior to slamming. Certain of the circuits contained within the programmer caused the system calibration and zero signals to appear on the tape as markers each four hours at the beginning of the normal one-half-hour records of data.

Figures A-13 and A-14 show the front and rear views of the programmer unit. Three indicating meters are mounted on the front panel. The right-hand meter is an elapsed time indicator which is used to determine where a particular data record is located on the tape. This permitted ship operating and seaway data from a log book, maintained by the watch officers, to be coordinated with the tape records. The center meter monitored port and starboard midship bending stress, whereas the left-hand meter monitored the static pressure at the forefoot of the bow. The center (stress) meter has two red pointers which may be set to positive and negative thresholds of stress. The single red pointer of the forefoot pressure monitor is set to a minimum pressure threshold, in this case standard atmospheric pressure which occurs when the bow emerges from the water just prior to a slamming impact. When any of these preset thresholds are encountered, the system is automatically turned on to make a special record of a previously determined length.

The row of seven small milliammeters located just above the tape deck (see Figure A-15) served to monitor the outputs of the seven active pressure cell channels. The first meter, at the left end of the row, monitors the low pressure cell at the bow (Location 21 or 22 on Figure A-3). This signal is also presented to the contact-making meter-relay at the left of the programmer front panel which serves as the indicator of bow emergence for automatic turn-on.

c. Signal Conditioning Equipment (Stress Channels)

Figure A-15 indicates the location of the stress transducer signal conditioning equipment above the tape deck. There are two active sets of Endevco Corporation Model 4401 Universal Signal Conditioning Modules (Figure A-16) and MB Electronics Model 518 D.C. Amplifiers (Figure A-17) and one set of spares mounted on the panel. The Universal Signal Conditioning Module contains the strain gage (d-c) power supply, and balancing and calibration circuits for the transducer. The d-c

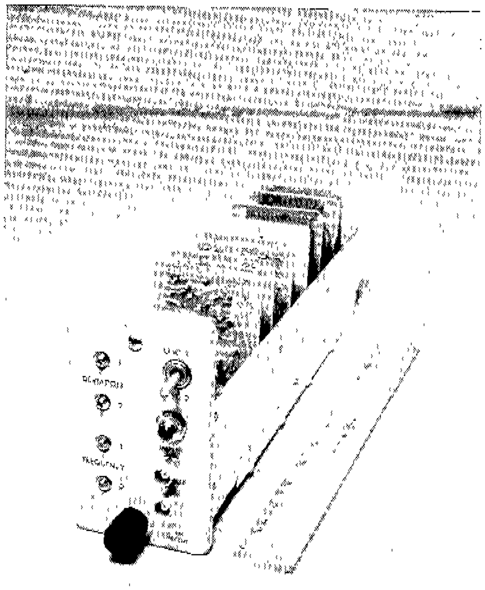

Fig. A-11. Recording Oscillator

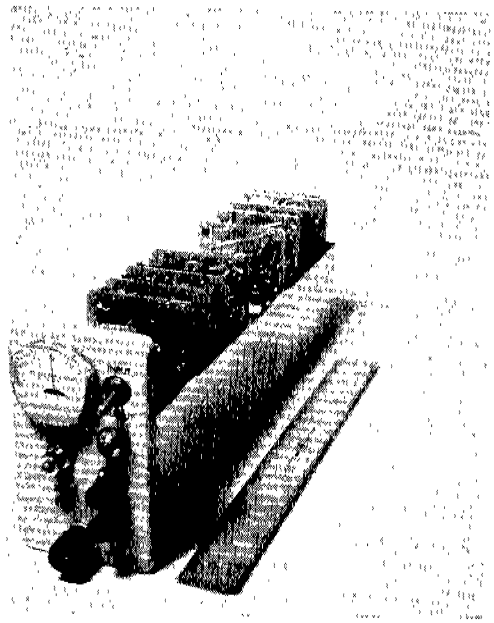

Fig. A-12. Playback Discriminator

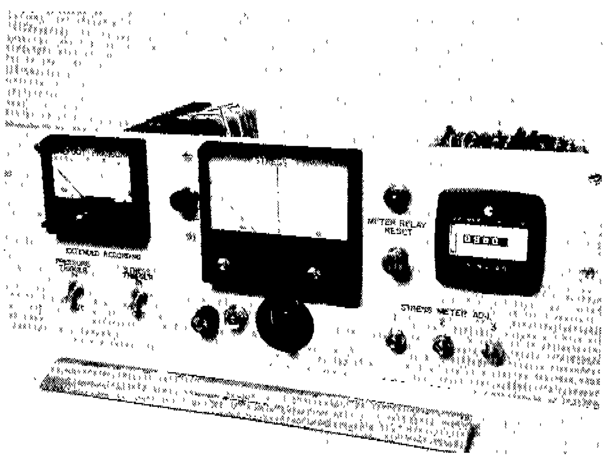

Fig. A-13. Front View of Programmer Unit

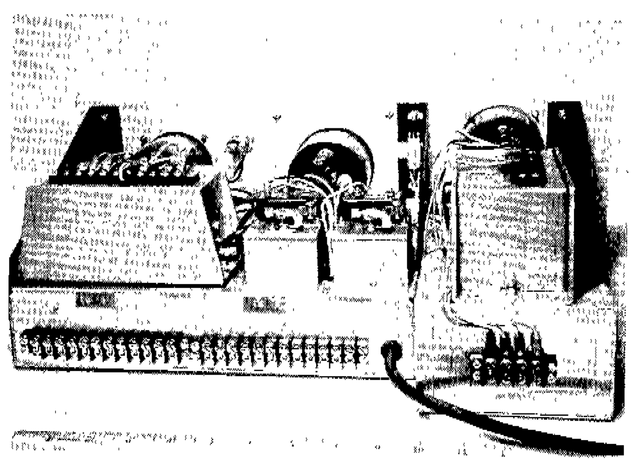

Fig. A-14. Rear View of Programmer Unit

Fig. A-15. Upper Protion of Tape Recorder Console

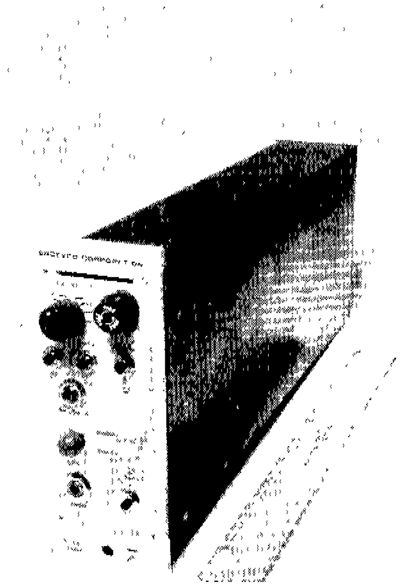

Fig. A-16. Universal Signal Conditioning Module

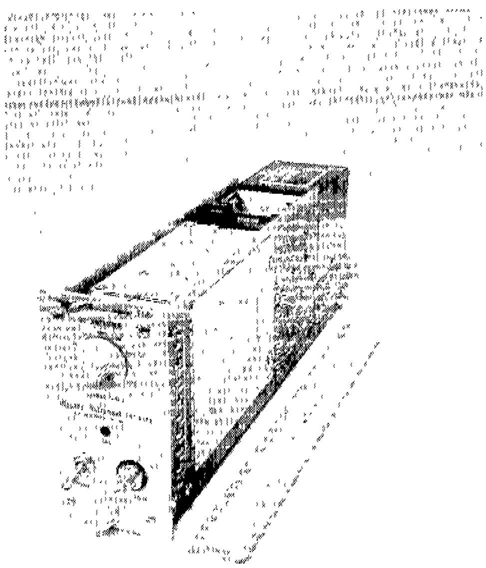

Fig. A-17. Stress Gage Channel D-C Amplifier

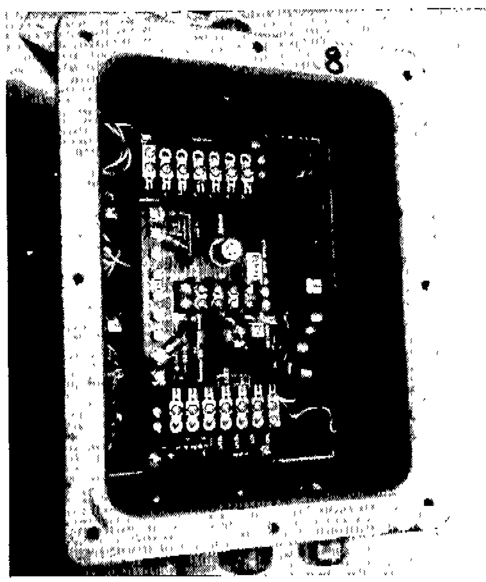

Fig. A-18. Internal Construction of Strain Gage Transmitter

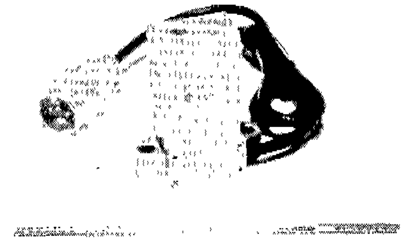

Fig. A-19. Unbonded Strain Gage Accelerometer

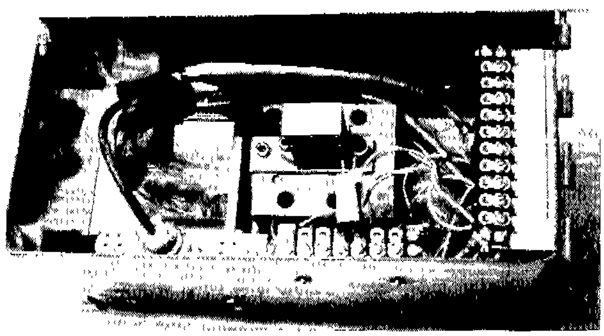

Fig. A-20. Interior of Accelerometer Housing

amplifier had a maximum gain of 2,000, with a bandwidth of d-c to 20 KHz, and was adjusted to provide the required level of input signal from the stress channel to the tape recorder.

2. Pressure Transducer Channels

The manner in which signals from the twenty pressure cells which were mounted in the bottom plating of the ship were conveyed to a one hundred terminal junction box located in No. 2 Hold is indicated schematically in Figure A-3. The signals from seven selected cells were passed through local signal conditioning units and transmitted over cables to terminal boxes in the Instrument Room. The pressure signals were recorded on seven of the available fourteen channels of the slow-speed magnetic tape recording system.

a. Pressure Cells

Two types of commercially available bonded strain gage pressure cells were installed on the vessel. The high pressure cells, Baldwin-Lima-Hamilton Corporation Type D-HFS, are rated at 350 psig full scale and have an overload capability of 200 to 250% of rating. The cells have a natural frequency on the order of 12,000 Hz and a response to linear accelerations of less than 0.01% of full-scale per g. Flush diaphragm pressure cells, mounted so as to be in as intimate contact as possible with the water, were selected in order that there would be no distortion of the characteristics of the slamming pressure pulse by entrapped air in the pathway to the pressure sensor.

The low pressure cells are Type 179 manufactured by Taber Instrument Corporation. These units are rated at 50 psig full scale, but will tolerate a maximum pressure of 500 psi by virtue of internal mechanical stops associated with the sensing diaphragm and by the construction of the sensing element itself, which is a one-piece proving ring to which precision stain gages have been bonded. The instrument has a sensitivity to linear acceleration of less than 0.08% of full scale per g in the axial plane, and is insensitive to acceleration in all other planes.

The outer cases and diaphragms of both types of pressure cell were made from high quality stainless steel to prevent corrosion. The details of the installation of both types of pressure cells were described in Section II.B., and are illustrated in Figures A-4, A-5, and A-6.

b. Signal Conditioning Equipment (Pressure Channels)

The signals from the pressure cells selected for recording were connected to terminal strips located in a one hundred terminal junction box. The junction box and the seven channels of signal conditioning equipment are located in the forward end of No. 2 Hold (see Figure A-3).

The signal-conditioning units are Model 881 Strain Gage Transmitters manufactured by BLH Electronics, modified to extend their frequency response to 2000 Hz. The purpose of the Model 881 Transmitter is to provide d-c power to the transducers in the pressure cell; to provide balancing circuitry; and to provide the amplification required by the magnetic tape recording system. Calibration circuitry was added to the rugged enclosure which houses the Transmitter. A photograph showing the construction of the Strain Gage Transmitter is presented in Figure A-18.

3. Acceleration Channels

A single linear vertically-oriented accelerometer was mounted in the forward end of No. 1 Upper 'Tween Decks and in the after end of No. 7 Upper 'Tween Decks, at the extreme ends of the cargo spaces and at the same level in the ship. Statham Instruments, Inc., Model A5-5-350 unbonded strain gage accelerometers have been used (see Figure A-19). These units have a range of 5g and a natural frequency of 190 Hz. Damping to 0.7 critical produces a frequency response which is essentially flat (uniform within 5%) from 0 (d-c) to about 125 Hz (70% of the natural frequency). An accelerometer with this frequency response was selected with the expectation that it would respond to both slowly varying (direct-wave-induced) accelerations and the high-frequency acceleration components produced by impacts resulting from slamming. The Model A5 has a transverse-to-axial acceleration sensitivity of 2% and will withstand overloads of three times its range. The accelerometer is mounted in an ammunition box for protection along with its signal conditioning equipment (Statham Instruments, Inc., Model CA9-56 Strain Gage Signal Amplifier) and calibrating circuits. See Figure A-20.

III. REFERENCES

1. Fritch, D. J., and Bailey, F. C., An Unmanned System for Recording Stresses and Accelerations on Ships at Sea, Ship Structure Committee Report SSC-150, June 1963.

2. Fritch, D. J., Bailey, F. C., and Wise, N. S., Preliminary Analysis of Bending Moment Data from Ships at Sea, Ship Structure Committee Report SSC-153, December 1963.

3. Bailey, F. C., Fritch, D. J., and Wise, N. S., Acquisition and Analysis of Acceleration Data, Ship Structure Committee Report SSC-159, February 1964.

4. Fritch, D. J., Bailey, F. C., and Wise, N. S., Results from Full-Scale Measurements of Midship Bending Stresses on Two C4-S-B5 Dry-Cargo Ships in North Atlantic Service, Ship Structure Committee Report SSC-164, September 1964.

5. Fritch, D. J., Bailey, F. C., and Wheaton, J. W., Data from Midship Bending Stress Measurements on Two Dry-Cargo Ships, Fifth Progress Report of Project SR-153 "Ship Response Statistics" to the Ship Structure Committee, May 1966.

6. Wheaton, J. W., Fritch, D. J., and Bailey, F. C., Acquisition and Installation of Shipboard Recording Equipment, Lessells and Associates, Inc., Technical Report No. 894/i21 to Ship Structure Committee, Final Report under Department of the Navy, Bureau of Ships Contract NObs-92134, January 1966.

APPENDIX B

Logbook Pages From

Voyages 277, 288, and 263

DATA LOG

SHIP *Wolverine State*

VOYAGE *277/278* FROM *Southampton* TO *New York* DATES *3-21-67* TO *3-24-67*

	Index No.	Date (M, D, Y) Time (GMT)	Time Meter Rdg.	SHIP: Noon Position Lat.	Long.	Course	Avg. Speed Knots (Past four hours)	Avg. Engine R.P.M.	Sea Temp.	Air Temp.	WIND: Knots Wind Speed	True Wind Dir.	Weather	Initials
277 W ↓ 63	61	1845 3-21	2034.4			258	16—	78.8	52	51	05	247.5 WSW	Mild	[illegible]
64	62	2345 3-21	2066.7			258	16	78.9	52	53	0	—	✓	[illegible] 3/0
65	63	3-22 0348	2098.8	48.5N	12.5W	258	16	78.3	52	53	06	WSW	✓	[illegible] 3/0
66	64	3-22 0715	2131.1			258	16	77.9	52	51	05	247.5 WSW	✓	[illegible] 3/0
67	65	3-22 1130	2163.7			270	16	78.8	54	54	05	168.75 S~~x~~E	✓	[illegible] 3/0
68	66	3-22 1635	2195.4	47.4N	25.8W	270	16	77.8	54	57	08	157.5 SSE	✓	[illegible] 3/0
69	67	3-22 2015	2227.0			270	15.5	77.5	52	58	08	S	✓	[illegible]
70	68	3-23 0030	2259.8			270	15.5	80.1	54	54	10	S	✓	[illegible]
71	69	3-23 0345	2291.9			270	15.5	79.2	54	55	15	S	✓	[illegible]
73	70	3-23 0935	2356.3			268	15.5	80.1	52	55	25	S	Mod	[illegible]
74	71	3-23 1236	2388.6			244	15.	79.0	~~58~~	58	18	180	✓	[illegible] 3/0
278 W [illegible]	72	3.23 1718	0018.2	47.4	35.5	246	14.0	77.6	54	56	28	WSW	Rough	[illegible]
INT 2	73	3-23 2122	0160.9			246	11.0	72.8	48	56	35	247.5 WSW	ROUGH	[illegible]
3	74	3-24 0200	0438.8			246	6	59.6	54	48	44	247.5 WSW	V. ROUGH	[illegible]

DATA LOG

SEA

	Index No.	Beaufort Sea State Number	Wave True Direction	Avg. Wave Height Ft.	Avg. Wave Period Sec.	Avg. Wave Length Ft.	Swell Avg. Height Ft.	Swell Avg. Length Ft.	Swell True Direc.	Barometer Reading & Sea Photo Number	Remarks (Changes of Course, Changes of Speed, Changes of Ballasting, Slamming, Rewind Recorder)
	61	1(2)	247.5 WSW	1-2	5	—	5	150	W	30.46	
	62	0	—	—	—	—	2	100	WNW	30.46	
	63	2	WSW	1-2	2	5	5	150	W	30.46	Pitching.
115	64	2	247.5 WSW	1-2	4	5	5	150	W	30.46	Pitching
	65		168.75 SXE	1	—	—	3	100	WXN	30.47	1000 A/C 270
AG	66	2	157.5 SSE	1	4	6	8	100	NW	30.41.	Rolling & pitching.
	67	2	180. SS	1	4	6	8	100	WNW	30.35	" "
	68	3	S	2	—		4	100	WNW	30.28	
	69	4	S	4	6	5	5	100	WNW	30.08	Rolling easily
	70	6	S	5	6	8	8	150	S	29.92	Rolling & Pitching moderate
	71	5	S 180°	4	confused		7	confused			A/C 246°
	72	5	WSW	4	12	30	8	150	W	29.80	New Reel Put on.
INT 2	73	7	247.5 WSW	6-8	10	20	11	150	WSW	29.82	TURNED ON CONTINUOUSLY AT 1926 GMT MTGR 0044.9
	~~[illegible]~~									~~[illegible]~~	2103 GMT SLOWED TO 70 RPM'S 2105 GMT SLOWED TO 65 RPM'S
3	74	9	247.5 WSW	15		250				29.86	[illegible]

2327 Red to 60 RPM; 0030 Red to 55; 0112 Red to 50; 0140 Red to 45

DATA LOG

SHIP *WOLVERINE STATE*

VOYAGE *277/278* FROM *SOUTHAMPTON* TO *NEW YORK* DATES *3-24-67* TO *3-26-67*

	Index No.	Date (M, D, Y) Time (GMT)	Time Meter Rdg.	SHIP: Noon Position Lat.	Long.	Course	Avg. Speed Knots (Past four hours)	Avg. Engine R.P.M.	Sea Temp.	Air Temp.	WIND: Knots Wind Speed	True Wind Dir.	Weather	Initials
4	75	3-24 0600	0677.2				6	45.0	55	48	35	258.75 WXS	Rough	[illegible]
5	76	3-24 1025	0944.0			246	9	61.6	54	49	35	270. W	Rough	AR
6	77	3-24 1425	1179.0			246	9	66.5	57	49	30	11.25 NXE	✓	R
7	78	3-24 1800	1396.9	45.8N	39.5W	246	15.5	78.3	56	51	20	NNW	✓	Dak
9	79	3-24 2156	1452.5			246	14.5	78.4	56	50	08	337.5 NNW	Mild	AR.
10	80	3-25 0245	1484.9			246	15	79.5		48	10	90. E	Rain	R.
11	81	3-25 0640	1517.2			246	15.5	71.2	44	46	12	E	"	Dak
12	82	3-25 1135	1549.3			246	15	63.6	44	48	12	E	Mod	AR.
13	83	3-25 1545	1581.5			255	16	78.4	64	56	6	E	Mild	R.
14	84	3-25 2000	1613.3	43.4	48	255	16	79.2	36	48	6	E	"	Dak
15	85	3-25 2315	1645.9			270	16	77.7	46	44	6	90. E	"	ARZ
16	86	3-26 0345	1677.5			270	16	78.0	47	44	1	180. S	rain fog	R.
17	87	3-26 0732	1710.2			270	15.5	79.0	44	44	20	67.5 ENE	Rain	Dak
18	88	3-26 1125	1742.3			270	15.5	78.6	44	48	08	202.5 SSW	Mild	AR
19	89	3-26 1530	1774.1			270	15.7	59.5	43	48	8	22.5 NNE	✓	R

DATA LOG

INT	Index No.	Beaufort Sea State Number	Wave True Direction	Avg. Wave Height Ft.	Avg. Wave Period Sec.	Avg. Wave Length Ft.	Swell Avg. Height Ft.	Swell Avg. Length Ft.	Swell True Direc.	Barometer Reading & Sea Photo Number	Remarks (Changes of Course, Changes of Speed, Changes of Ballasting, Slamming, Rewind Recorder)
		SEA									
4	75	9	WSW 247.5	20	15	250	—	—	—	29.86	
5	76	9	W 270.	8	10	25	15	150	W	29.98	INC TO 60 RPM AT 0705 GMT INC TO 55 " " 0710 GMT INC TO 65 " " 0721 GMT
	77	7	-1.0	10	—	40	10	150	W	30.14	1425 GMT INC TO FULL THROTTLE [illegible]
	78	6	NNW	9	15	40	—	—	—	30.24	INCREASE TO 14 NOZZ. 1722 GMT
	79	3	NNW 337.5	2	5	10	—	—	—	30.28	1826 GMT PUT ON AUX. AGAIN MTGR 1420.5
	80	3	E 90.	1	—	—	5	150	WNW	30.22	
	81	3	E	2	5	10	6	150	NE	30.10	0522-0630 Reduced to 60 RPM FOR REPAIRS IN ENG. ROOM
	82	3	E	2	5	10	6	150	E	30.04	[illegible] 0650 Reduced to 60 RPM 1051 Resume speed GMT
	83	2	E	1			6	120	N	30.04	1530 A/C 255° GMT
	84	2	E	1			6	120	N	29.90	
	85	3	E 90.	1	—	—	—	—	—	29.80	2045 GMT C/C 270
	86	1	—	—	—	—	—	—	—	29.66	
	87	5	ENE 67.5	7	8	50	—	—	—	29.60	
	88	3	SSW 202.5	3	5	10	7	100	NE	29.70	
	89	3	E 90.	2	—	—	10	200	NE	29.78	

DATA LOG

Issued: 8/1/67

SHIP: Wolverine State

VOYAGE: 288 FROM: CADIZ-SPAIN TO: NEW YORK DATES: 3/31/67 TO: ______

Index No.	Date (M,D,Y) Time (GMT)	Time Meter Rdg.	SHIP: Noon Position Lat.	Noon Position Long.	Course	(Past 4 Hours) Avg. Speed Knots	Avg. Engine R.P.M.	WIND: Wind Speed Knots	True Wind Direc.	SEA: Beaufort Sea State Number	True Wave Direction	(Ft.) Avg. Wave Height	(Sec.) Avg. Wave Period	(Ft.) Avg. Wave Length	INT
147	31 1100 5HRS	13240	—	—	267	16.2	79.7	15	S	4	S	2	2	5	
148	31 = 1500	1355.9	N 41-45	W 47-32	267	16.3	79.6	15	SSW	4	SSW	2	2	10	
149	31 - 1900	13883			266	16.5	80.0	10	SSE	3	SSE	2	2	5	
150	31 - 2200	1420.5	—	—	266	16.5	79.0	10	Nly	3	N	1	1	3	
151	01 = 0300	1452.8			266	16.5	79.3	10	ENE	2	ENE	1	2	10	
152	4/1 - 0700	1484.9			266	16.0	80.0	20	SSW	4	SSW	4	2	10	
153	1 - 1200 5HRS	1533.5 ~~1533.5~~	—	—	266	13.5	70.0	25	WNW	6	WNW	6	2	15	
154	01 = 1600	1560.0	41°28	58°11	285	3.5	40.6	35	NW	8	NW	10	6	100	
155	01 - 2000	1581.6	—	—	280	3.5	35.2	22	NW	8 (9)	NW	12	7	125	
156	2 - 0000	1620.5	—	—	266	3.5	36.5	15	NW	4	NW	6	3	5	
157	2 - 0400	1662.2	—	—	266	7.0	52.1	18	NW	4-5	NW	8	6	100	
158	2 - 0800	1710.5	—	—	266	11.0	55.7	02	WxS SW	2	WxS SW	1	1	4	
159	2 - 1300 5HRS	1743.0			266	12.0	70.0	20	WSW	5	WSW	5	2	10	
160	2 = 1700	1775.2	41°14	60°06	266	12	66.7	31	WSW	7	WSW	6	6	30	56
161	2 - 2100	1814.7			220	5	51.2	45	SW	9	SW	20	7	340	56

DATA LOG

Issue: 8/1/67

Index No.	SEA / SWELL Avg. Height'	Avg. Length'	True Direc.	Barometer Reading & Sea Photo#	Sea Temp.	Air Temp.	Weather	Initials	(Change of Course, Change of Speed, Change of Ballast, Slamming, Change Tape, and rewind ETM)
147	6	50	S	30:33	60	57	cloudy	P.W.B	
148	6	50	S	30.26	61	56	P.C	FF	
149	7	50	S	30.13	43	51	cldy lt. fog	FEM	
150	4	20	S	30.21	40	41	O'cast	P.W.B.	
151	4	50	E	30.10	60	44	Overcast	FF	
152	8	75	ESE	29.76	58	56	Ptly Cldy	FEM	
153	20	100	W	29.96	46	42	O'cast	P.W.B	Vessel pitching heavily
154	25	200	WNW	30.22	56	36	Overcast	FF	Vessel hove to
155	20	250	W	30.32	56	38	O'cast	FEM	" " "
156	15	200	NW	30.42	52	40	snow O'cast	P.W.B.	" " "
157	15	200	WNW	30.44	58	36	P.C	FF	
158	10	150	W 1/2 to NW	30.40	55	38	cldy	FEM	
159	15	200	WSW	30.30	~~46~~ 54	47	mostly cloudy	P.W.B	Reduced spd due to pounding INT
160	16	200	WSW	30.13	60	52	Overcast	FF	02-1450 CONTINUOUS OPERATION 56
161	20	300	SW	29.90	59	57	O'cast	FEM	56

DATA LOG

Issued: 8/1/67

SHIP: S.S. WOLVERINE STATE

VOYAGE: 288 FROM: CADIZ, SPAIN TO: N.Y. N.Y DATES: 3/3/69 TO:

Index No.	Date (M,D,Y) Time (GMT)	Time Meter Rdg.	SHIP: Noon Position Lat.	SHIP: Noon Position Long.	SHIP: Course	SHIP: (Past 4 Hours) Avg. Speed Knots	SHIP: (Past 4 Hours) Avg. Engine R.P.M.	WIND: Wind Speed Knots	WIND: True Wind Direc.	SEA: Beaufort Sea State Number	SEA: True Wave Direction	SEA: (Ft.) Avg. Wave Height	SEA: (Sec.) Avg. Wave Period	SEA: (Ft.) Avg. Wave Length	INT
162	3 0100		416	609	215	2	46.8	40	SW	8	SW	20	5	100	57
163	3-0500	2293.1	—	—	240	2	48.0	40	SW	9	SW	20	6	150	58
164	3-0900	2535.4	—	—	266	5	46.6	12	NNW	3	NNW	03	2	6	
165	3-1300		—	—	265	8	50.1	17	N'ly	5	N	07	5	10	
166	3-1700	0039.8	4057	6314	265	10	55.7	18	NW	5	NW	07	5	50	
167	3-2100				265	12.5	69.0	20	NW	5	NW	04	5	20	
168	4 0000	0106.1	—	—	265	15.0	77.9	15	NW	4	NW	04	5	15	
169	4-0500	01333.4	—	—	265	16.5	78.8	10	NW	3	NW	03	4	10	
170	4-0900	0167.5	—	—	265	16.5	79.7	5	SW	2	SW	02	2	4	
171	4 1200	0193.9	—	—	268	17.5	79.6	5	SW	2	SW	01	2	3	
172	4-1600	0226.0	40°34	71°50	267	16.5	79.5	7	SW	2	SW	01	2	5	
173	4-2100				266	17.0	78.9	7	S	2	S	02	2	8	

DATA LOG

Index No.	SEA — SWELL — Avg. Height'	SEA — SWELL — Avg. Length'	SEA — SWELL — True Direc.	Barometer Reading & Sea Photo#	Sea Temp.	Air Temp.	Weather	Initials	(Change of Course, Change of Speed, Change of Ballast, Slamming, Change Tape, and rewind ETM)	INT
162	20	100	SW	29.84	59	58	O'cast	PWB	Hove to in SW gale	57
163	30	350	SW	29.74	55	57	Overcast	OFF	Rolling Pitching heavily	58
164	20	250	SW	29.82	59	45	O'cast	FM	" " "	
165	20	350	SW	29.98	59	44	O'cast	PWB	" " "	
166	15	350	SW	30.08	59	40	P.C	OFF		
167	12	300	SW	30.15	50	37	Clear	FM	03-1410 INSTALLED TAPE TMR 86	
168	10	200	SW	30.24	44	39	Clear	P.W.B.	Rolling + pitching moderately	
169	7	100	SW	30.31	45	36	P.C	OFF		
170	3	50	SW	30.30	40	37	Clear	FM		
171	3	50	SW	30.34	40	41	clear	P.W.B.		
172	1	10	SW	30.32	40	42	clear	OFF		
173	3	75	S	30.22	40	42	Lt haze	FM		

DATA LOG

SHIP WOLVERINE STATE

VOYAGE 264 FROM SOUTHAMPTON TO NEW YORK DATES 6/3/66 TO 6/5/66

	Index No.	Date (M, D, Y) Time (GMT)	Time Meter Rdg.	SHIP: Noon Position Lat.	Long.	Course	Avg. Speed Knots (Past four hours)	Avg. Engine R.P.M.	Sea Temp.	Air Temp.	WIND: Knots Wind Speed	True Wind Dir.	Weather	Initials
	75	6/3 1530	0098.5			279	16.3	82.8	55	56	LT. AIRS		CALM	DFS 3/0
	76	6/3 0800	0130.8			273	16.0	82.8	54	57	AIRS		FOG Calm	PJC 3/0
	77	6/3 1120	0163.0			273	16.0	82.6	56	56	10	135. SE	Calm	AR 3/0
	78	6/3 1530	0195.3	50.8N 50°46'N	17.7W 17°43'W	273	16.5	82.3	56	54	15	225. SW	HAZE MILD	DFS 3/0
INT	79	6/3 2000	0227.4			270	16.5	82.2	53	55	15	202.5 SSW	MOD	PJC 2/0
9	80	6/4 0024	0280.0	METER	RUNNING	270	15.0	81.5	54	55	20	238.25 SWxW	Mod-Heavy	AR 3/0
10	81	6/4 0423	0522.0	METER	RUNNING	270	14.5	77.8	53	55	25	247.5 WSW	ROUGH	DFS 3/0
11	82	6/4 0840	0783.0	METER	Running	264	12.0	65.0	52	54	30	W	Very Rough	PJC 2/0
12	83	6/4 1243	1026.6	METER	Running	264	10.0	62.1	54	54	30	W	V. Rough	AR 3/0
13	84	6/4 1600	1225.8	METER	RUNNING	265	7.0	63.4	53	54	30	270. W	V. ROUGH	DFS 3/0
14	85	6/4 2048	1516.5	Meter	Running	265	11.0	68.8	50	51	10	281.25 WxN	Heavy Swell	PJC 2/0
	86	6/5 0023	1733.3	METER	Running	265	16.0	80.6	52	50	10	258.75 WxS	MOD Swell	AR 3/0
	87	6/5 0359	1796.1	METER	RUNNING	265	16.0	82.0	54	52	10	247.5 WSW	MOD SWELL	DFS 3/0
	88	6/5 1000	1854.8			265	16.0	81.3	48	52	15	0 N	MOD	PJC 3/0
	89	6/5 1330	1886.8			258	16.0	80.8	51	50	15	315. NW	MOD	AR 3/0

6-4-6

DATA LOG

	Index No.	SEA: Beaufort Sea State Number	Wave True Direction	Avg. Wave Height Ft.	Avg. Wave Period Sec.	Avg. Wave Length Ft.	Swell: Avg. Height Ft.	Swell: Avg. Length Ft.	Swell: True Direc.	Barometer Reading & Sea Photo Number	Remarks (Changes of Course, Changes of Speed, Changes of Ballasting, Slamming, Rewind Recorder)
	75	1	N 0.	1	3	4	—	—	—	30.12	
	76	1	S 180.	2	4	4	—	—	—	30.08	0530 GMT C/C 273°
	77	2	SE 135.	2'	5'	5'	2'	50'	S	30.03	
	78	3	SWxS 213.75	2	5	5	3'	50	SW	29.90	
INT	79	5	SSW 202.5	4	5	5	4'	50'	SSW	29.78	1715 GMT C/C 270° T
9	80	5	SWxW 236.25	5'	5'	4	8'	20'	SW	29.70	AT 0030 GMT 9/4 RECORDER SET ON CONTINUOUS OPERATION AR 10 GMT
10	81	5 (6)	WSW 247.5	6'	5'	4	10'	20'	WSW	29.62	0227 Reduce To 14 Nozzles - Pounding 0240 Reduce To Full Throttle 0320 Reduce To 65 RPM - Pounding
11	82	7	W	8'	10	20'	10'	40'	W	29.64	0620 GMT C/C 264° T. 0820 GMT Reduce Speed to 60 RPM's
12	83	6	W	8'	8	15'	10'	40'	W	29.72	Vessel Pitching & Occ. Pounding
13	84	6	W 270.	8'	10	15'	10'	40'	W	29.71	1400 GMT C/C 265° T PITCHING - OCC POUNDING
14	85	4 5.	WxN 281.25	5'	8	15'	10'	40'	W	29.84	1725 GMT Inc. TO 65 RPM's 2037 GMT Inc. TO 70 RPM's
	86	4	WxS	4'	6	15'	8'	50'	W	29.78	2126 GMT INC To Full Throttle 2327 GMT INC To 15 Nozzles
	87	4	WxS 258.75	4	5	15'	8'	50'	W	29.54	6/5 0115 GMT. Recorder Put ON AUX. [illegible]
	88	5	N 0	4	5	15'	8'	50'	W	29.70	
	89	4	NW 315.	4	5	15'	8'	50'	NW	29.90	1042 GMT C/C 258° T

6-9-69

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2b GROUP

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4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report

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Cyrus H. Kano Fred C. Bailey

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11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Naval Ship Systems Command

13. ABSTRACT

The stress recording system aboard the "S.S. Wolverine State" was expanded to include pressure transducers and accelerometers. Stress, pressure, and accelerations signals were recorded on magnetic tape over a period of three years, and data on hundreds of slams were recorded.

Slamming occurred only at Beaufort numbers above 5, and under relative headings within about 30 degrees of head seas. Reduction of speed did not appear to reduce the frequency of slamming, but the forward draft was a significant factor. Ochi's predictions of the statistical distribution of slamming occurrences were confirmed, as were his model data relating pressure and relative velocity at impact. The bow acceleration was found to be a sensitive indicator of slamming phenomena, and relationships between acceleration, velocity, and pressure were established. Slamming pressure levels were consistent with ship model test results, but were less than other full-scale and drop-test data reported in the literature.

UNCLASSIFIED
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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
CARGO SHIP						
SLAMMING						
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