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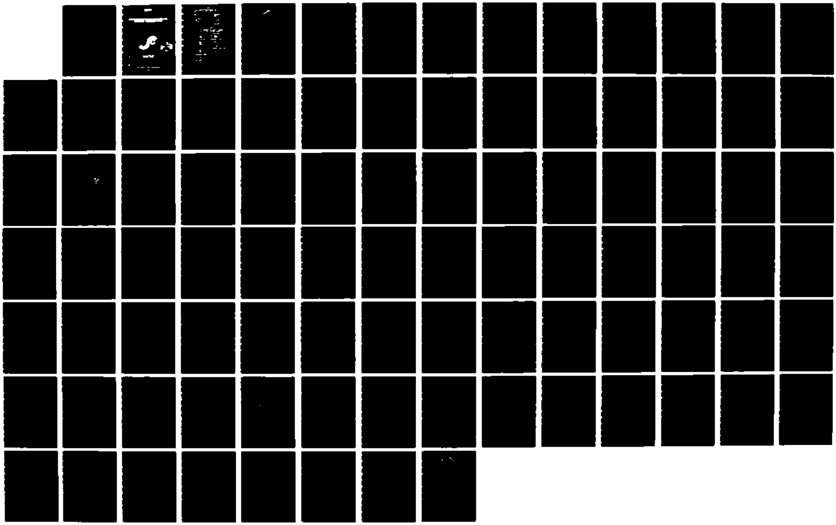

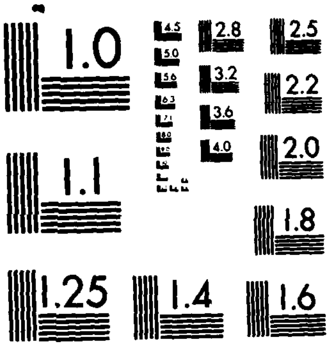

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Ship Structure Committee

An Interagency Advisory Committee
Dedicated to the Improvement of Marine Structures

Address Correspondence to:

Secretary, Ship Structure Committee
U.S. Coast Guard Headquarters, (G-M/TP 13)
Washington, D.C. 20593
(202) 426-2197

SR-1285

One of the long term objectives of the Ship Structure Committee (SSC) is to be better able to predict the fracture toughness of ships based upon the testing of laboratory material specimens.

One factor in the toughness equation is the strain rate experienced by the material. This report conveys the analysis of a survey of stress/strain data which was assessed to determine the feasibility of obtaining the strain rates experienced by ships in actual service. This strain rate could then be used in materials testing programs for improved correlation.

The authors have determined that this is feasible and such a project is presently under consideration by the SSC.

CLYDE T. LUSK, Jr.
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

The material testing techniques that are currently used to determine the toughness of ship structural steels load material specimens at various loading and strain rates. Since the toughness, nilductility and the yield strength characteristics of ship structural steels varies with strain rate, it has become necessary to determine the extent to which the strain rates produced by materials testing techniques are representative of ship service experience.

A survey of existing shipboard stress/strain data is presented and the data bases are evaluated to determine the feasibility of obtaining strain rates. The results of the survey indicate that it is feasible to determine strain rates from existing ship data; however, the stress/strain data require additional data reduction and analysis before detailed strain rates may be obtained. Preliminary calculations of strain rates that are comparable to the order of magnitude of strain rates given for current material toughness tests were obtained from existing data. Two methods are outlined to obtain ship structural strain rates from analytical predictions or in conjunction with future full-scale instrumentation programs. Keywords:

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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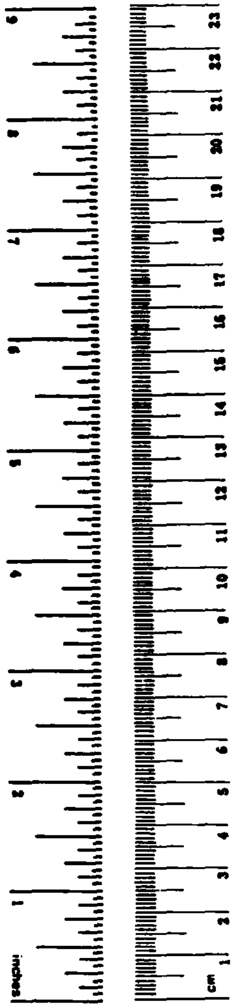
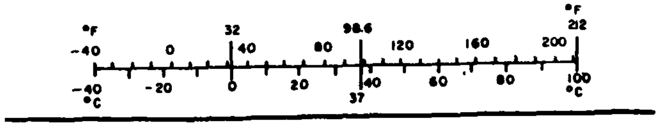
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

The demanding environment in which ships operate requires that the toughness of the hull structural material be evaluated and classified in an effort to minimize the incidence of catastrophic failure. The materials testing techniques that are used to determine the toughness of ship structural steels load material specimens at various loading and strain rates. Since the toughness of ship steels varies with loading and resulting strain rates, it has become necessary to define the representative range of strain rates encountered by ships in service. The definition of ship service strain rates will allow the material research engineers to judge the amount of conservatism inherent in the materials testing techniques that are currently used to classify the toughness of ship steels.

This study involves the review of numerous existing full-scale instrumentation programs to evaluate the feasibility of obtaining strain rate information from measured data. The instrumentation programs which cover a range of ship types are evaluated in depth. The representative ship types include two containerships, several large tankers, two general cargo vessels, an oceangoing bulk carrier, a Great Lakes bulk carrier, and an icebreaker. The review and evaluation of the existing data indicate that strain rates may be obtained from existing data within the frequency limitations of the data acquisition systems. However, in all cases the data require reanalysis before detailed information may be obtained directly. Preliminary calculations of strain rates were obtained from samples of existing data that are representative of the order of magnitude of strain rates encountered by ships inservice. This information is consistent with the order of magnitude of strain rates reported for material toughness testing techniques. Two methods are presented for obtaining strain rate information from analytical predictions and in conjunction with future full-scale instrumentation programs. Obtaining strain rate information in conjunction with future full scale programs would provide data for ships that have not been instrumented and provide more detailed strain rate information if material tests are updated or changed as a result of future demand.

2.0 BACKGROUND ON STRAIN RATE INFORMATION AND DATA REQUIREMENTS

The Ship Structure Committee has initiated a series of projects aimed at the development of suitable criteria for qualifying steels and weldments for ship hull structures. In 1974 Rolfe in SSC-244 (1) proposed a tentative criterion for ensuring adequate structural properties of a wide range of ship steels and weldments for primary structural applications. Rolfe (1) hypothesized that shipboard loading rates are of an intermediate loading rate between the static tensile and Charpy V-notch material tests. Later in 1974, Hawthorne in SSC-248 (2) presented a limited data base on 1-inch thick ship steels and weldments for the purpose of evaluating the criterion proposed in SSC-244 (1).

More recently two parallel efforts were carried out at Southwest Research Institute dealing with the same problem. In SSC-276 (3) the emphasis was placed on fracture behavior of manual and submerged arc automatic welded specimens, as measured primarily by Charpy V-notch, dynamic tear, explosion crack starter and explosion tests.

Francis reported in SSC-275 (4) on the effects of loading rates on fracture toughness; dynamic yield stress was studied based on laboratory experiments. The authors of SSC-244 (1) and SSC-275 (4) suggest that there is an uncertainty in the range of strain rates occurring during ship operation that impeded comparison with current material testing techniques. The dynamic loading experienced by the ship structure requires a more precise definition so that material property data can be developed based on rational requirements.

Yield-strength, nilductility temperature and fracture toughness all depend upon the strain rate at which the material test is conducted. Generally, for mild steels used in shipbuilding and considered in this study, the fracture toughness decreases with increases in strain rate at a given temperature. The material tests currently used to characterize the toughness of ship structural materials produce a wide range of strain rates. The rate at which the material toughness tests are conducted also effects the yield strength of low carbon steels like ship's steels. Table 2-1 presents the strain rates produced by various material toughness tests as reported by Francis (4) and Shoemaker (5). This order of magnitude information plays an important role in assessing the accuracy of information required to define the range of strain rates that are produced in ship structures. It is, therefore, necessary to look for loading rates corresponding to actual ship primary structure loading conditions in order to input the effects of load rates into the fracture toughness test procedures. The amount of conservatism inherent in the existing materials testing techniques may then be judged.

3.0 REVIEW EXISTING SHIPBOARD LOAD DATA WHICH MAY REVEAL THE RANGE OF FULL-SCALE STRAIN RATES

The feasibility of obtaining strain rate information from existing shipboard strain data has been determined by reviewing numerous full scale data bases and evaluating them according to predetermined criteria.

3.1 DESCRIPTION OF THE EXISTING FULL-SCALE DATA BASES THAT HAVE BEEN REVIEWED

Concurrent with the SSC projects discussed in Section 2.0, there have been a large number of full-scale ship instrumentation programs carried out by the SSC and other sponsors. These programs covered a wide variety of ship types and instrumentation packages of various complexities. Ship types covered include tankers, bulk carriers and containerships, to name a few.

There are numerous full-scale instrumentation programs which provide a source of data which may reveal the range of full-scale strain rates. In this study many were investigated and dropped from further consideration

TABLE 2-1

Loading Rates Produced By Current Material Toughness Testing Techniques

Laboratory Test Example	Approximate Nominal Straining Rate, in/in/sec.
Quasi-static Tension Test	10^{-5}
Tension Test at Fastest Rate of Loading in Universal Testing Machine	10^{-3}
Dyanmic Tear Test	10^{-1}
Charpy V-Notch Test	10^{1}

(From References 4 and 5)

because of inadequate data acquisition techniques, lack of data availability or duplication of ship type. The instrumentation programs reviewed cover an appropriate range of ship types and data types for determining the feasibility of obtaining strain rates from existing data. Although none of the ship hull response programs were intended to measure strain rate specifically, the measured stress and strain time histories could yield strain rate information. Each program has been inspected thoroughly for applicability and quality of recorded stress and strain data. The characteristics of the instrumented ships reviewed are presented in Table 3-1. A brief discussion of the data bases that have been reviewed are summarized below.

3.1.1 ABS Instrumentation Program on Oceangoing Tankers and Bulk Carriers

In early 1967 the American Bureau of Shipping (6) formulated a program of full-scale stress measurements aboard large tankers and oil carriers. The primary purpose of the full-scale project was to provide statistical data on midship stresses that could be interpreted in terms of wave-induced bending moment for bulk carriers and tankers of different size, type and service and that could be extrapolated to longer periods of time. Secondary objectives for certain cases were the determination of shear stresses in the vicinity of quarter points and the longitudinal distribution of bending moments. This was expanded to simultaneously record the stress levels at five different locations on three of the vessels but only for a limited period of time. The bulk carrier FOTINI L was also instrumented on the side shell plating to record hull girder shearing stresses in the vicinity of the after quarter point. One other vessel, the tanker ESSO MALAYSIA, was instrumented to register the dynamic stress levels occurring in the forward transverse bulkhead of No. 1 center cargo tank where there was a strong probability of a slack tank in the ballasted condition.

Although not feasible at the beginning of the program, the opportunity arose to expand the hull girder bending instrumentation to permit simultaneous recording of the stresses at as many as five different locations along the deck. This was accomplished for a limited period of time toward the end of the program in the case of two ships, the UNIVERSE IRELAND and FOTINI L.

The vessels chosen for instrumentation provided a range in size from 66,000 to 326,000 deadweight tons and included the following:

IDEMITSU MARU - Tanker
FOTINI L - Bulk Carrier
R. G. FOLLIS - Tanker
ESSO MALAYSIA - Tanker
UNIVERSE IRELAND - Tanker

3.1.2 Ship Structure Committee Instrumentation Program

The earliest SSC effort in achieving a better understanding of the loads experienced by ships in service was the long-term project "Ship Response

TABLE 3-1

List of Characteristics of the Ships Involved in Full-Scale Instrumentation Programs and Data Bases That Have Been Reviewed as a Source of Strain Rates

	LBP	Beam	Depth	Draft	DWT L Tons	Route	Inst. Sea Time
SL-7 SEA-LAND McLEAN	880'-6"	105'-6"	68'-6"	30'	27,315	N.Alt.	3 Seasons
UNIVERSE IRELAND	1076'	175'	105'	81'-5"	312,000	PG/NE	11 Voyages
FOTINI L	800'	106'	60.04'	44'-6 1/2"	61,000	Pacif.	18 Voyages
ESSO MALAYSIA	1000'	154.76'	77.76'	60'-5 1/2"	190,000	PG/NE	13 Voyages
STEWART J. CORT	1000'	104.5'		20'-7"		G.Lakes	
BOSTON	496'	71'-6"	45'-6"	30'-6"	20,250	N.Alt.	2 Seasons
WOLVERINE STATE HOOSIER STATE	496'	71'-6"	54'	30'	15,348	N. Alt. N.Pac.	44 Voyages
MACKINAW	280'	70'		19'		G. Lakes	

Abbreviations:

NE - North Europe
PG - Persian Gulf
N.Alt. - North Atlantic
G.Lakes - Great Lakes
N.Pac. - North Pacific

Statistics." Initiated in 1959, this project obtained statistical records of longitudinal bending moments experienced by various types of ships operating on different trade routes. Emphasis was placed on extreme bending moment values. The first four ships instrumented were: HOOSIER STATE, WOLVERINE STATE (7,8), MORMACSAN and CALIFORNIA BEAR (9). The results of the instrumentation program on the four-ship series led in 1968 to the design and installation of an expanded instrumentation package on the containership BOSTON (10,11), a converted near-sister ship of the WOLVERINE STATE. The intent of this program was to compare data obtained from the BOSTON and WOLVERINE STATE and assess the effects of open decks on structural response. The instrumentation package included vertical and horizontal bending stress, and hull torsional shear stress. Accelerometers were installed at the bow, midship and stern locations and two pendulum transducers were located at midship to provide pitch and roll data. During these tests a wave buoy was launched to provide wave data.

The latest SSC instrumentation program is, of course, the package installed on the SL-7 containership SEA-LAND McLEAN (12,13,14). Its instrumentation package was much more involved but appears to be a descendant from the BOSTON instrumentation package with provisions for obtaining additional measurements.

The primary measurements made on the SEA-LAND McLEAN were:

- Midship vertical bending stresses
- Torsional shear stresses
- Principal stresses at the four extreme "corners" and at the neutral axis of the midship section
- Gross hull acceleration
- Accelerations of forward and aft deckhouse.

The data channels were also supplemented by log book entries of environmental and operational conditions.

3.1.3 U.S. Coast Guard Great Lakes Ore Carrier Instrumentation Program

The USCG has been sponsoring an extensive instrumentation program to obtain structural response data on Great Lakes ore carriers. The USCG has been aided in this study by SSC, the Navy, ABS and several educational institutions. Numerous ore carriers have been instrumented for strain data with an emphasis on springing. These instrumented ships include the ROGER BLOUGH, EDWARD L. RYERSON, BURNS HARBOR and the STEWART J. CORT.

The Great Lakes ore carrier M/V STEWART J. CORT (15) was instrumented beginning in 1971 to study the bending stresses experienced by the vessel during normal operations. A key phenomenon of interest in this program is springing. Recognizing the need for research in this area, the USCG has undertaken a four-part program to obtain a more thorough understanding of springing. The Ship Structure Committee has contracted DTNSRDC to collect full-scale pressure distribution measurements on the CORT. Fifteen 50 psi pressure transducers have been installed in the forward section of the vessel. The pressures are scheduled to be analyzed by ABS in conjunction with a time-domain analysis of the wave heights.

3.1.4 U.S. Coast Guard Research Program to Obtain Design Information on the USCGC MACKINAW

A research program sponsored by the USCG to obtain design information was conducted on the USCGC MACKINAW (16). The program was primarily oriented toward obtaining ice resistance information, however, strain gauges were applied to the bow area structure to measure strain information during the test icebreaking operations.

3.2 DATA BASE EVALUATION CRITERIA

The full-scale instrumentation data bases described above have been reviewed and evaluated to determine the range of strain rates experienced by the ship hull structures. The criteria for evaluation are divided into three basic areas: ship type, ship operational parameters and data acquisition and reduction techniques.

Each type of ship has inherent structural design characteristics which affect the strain rate experienced by the hull strain and are of interest in determining the range of strain rates. Differences in the structural design from ship type to ship type could include longitudinal vs. transverse framing or various frame and stiffener arrangements. These differences affect the magnitude of strain experienced by various ships, hence the magnitude of strain rate. The structural areas of interest relating to determining strain rates in ship hull structures are those areas where the hull girder material classification is desired. These structural areas have been identified in SSC-244 (1) as the load-carrying plate members within the center 40% of the hull length and include the upper deck, bottom shell, side plating and longitudinal bulkheads. The stiffeners were identified as primary load-carrying members but were not considered for material classification because they are not connected to each other and failure of one stiffener will not necessarily lead to failure of adjacent stiffeners, provided the hull plating has sufficient toughness for crack arrest. Rolfe (1) indicates that the material performance characteristics are for the primary load-carrying plate members in the upper deck and bottom shell since the stresses in the ship hull vary from extreme levels to zero at the neutral axis as shown in Figure 3-1. Rolfe (1) assigned less stringent structural toughness criteria for secondry and tertiary areas. The material characteristics of secondary and tertiary structures should not be neglected. Many times cracks which start in the secondary and tertiary areas may propagate into primary areas.

The areas of stress concentration for particular ships also have an influence on the magnitude of strain rate and are of interest in material classification when they occur in the primary hull structure.

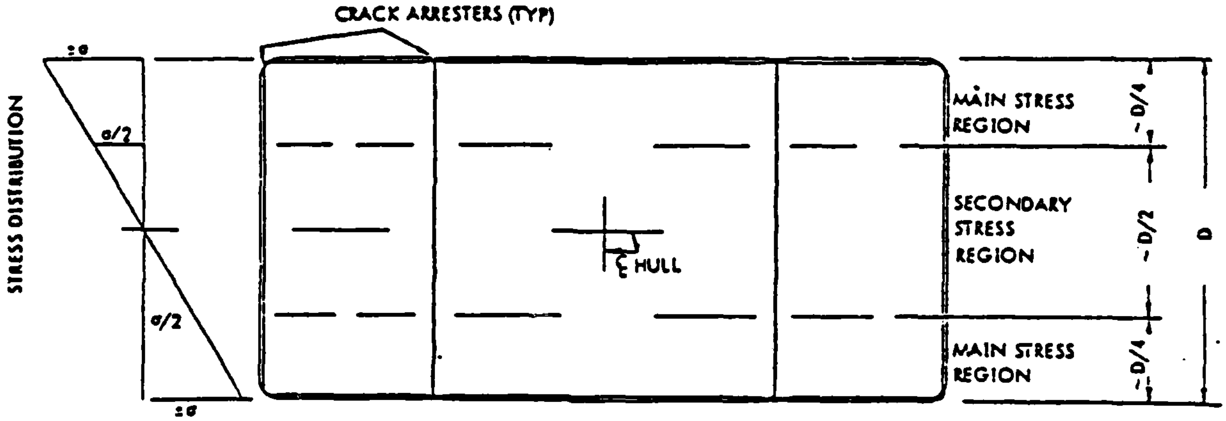


Figure 3-1

Schematic Cross Section Showing Primary Load Carrying Members in Main and Secondary Stress Regions (Ref. 1)

Generally, all ships at sea experience wave bending strains which occur at approximately the wave encounter frequency; however, ships are prone to different types of impact loads (i.e., slamming, shipping of green water and springing), cargo shifting or sloshing, or loads imposed by collisions, groundings, blast loads or ice loads which generally increase the magnitude of strain rates. These factors affect the strain rates for different ship types.

The ship environmental, operational and repsonse parameters are of interest in collating the strain rate information obtained from the data bases. Environmental parameters such as wave height and wave direction (ship heading with respect to the waves) influence the magnitude of strain rates. Other operational parameters such as ship speed, air and water temperature and general log book information supplement the strain data for identification and collation purposes. Ship motions information such as roll, pitch, heave, surge and sway is not directly related to strain rates, however, there may be circumstances where this information would be useful for collation purposes.

The techniques used in data acquisition, reduction, documentation and the availability of data are of specific importance in determining strain rates from existing data. The data acquisition techniques used for the instrumentation programs reviewed are very similar in approach. The primary instrumentation used by the researchers involved in the full-scale measurement programs were either "stress" gauges and/or strain gauges.

The "stress" gauges (17) were used to infer midship longitudinal stresses from measured strain in the majority of instrumentation programs including the UNIVERSE IRELAND, ESSO MALAYSIA, FOTINI L, BOSTON, SL-7 SEA-LAND McLEAN and the STEWART J. CORT. A "stress" gauge consists of two strain gauges placed in a dyadic configuration. This arrangement of two strain gauges compensates for Poisson effects and the output is proportional to stress rather than to strain. The two gauges are also incorporated in the typical Wheatstone bridge circuit. The mathematical relationship of the stress gauge becomes:

$$\sigma_x = \frac{E}{1-\upsilon^2}(\varepsilon_x + \nu\varepsilon_y)$$

The strain relationship is:

$$\varepsilon_x = \frac{1}{E}(\sigma_x - \nu\sigma_y)$$

Which reduces to:

$$\varepsilon_x = \frac{\sigma_x}{E}$$

when there is no lateral (or y) constraint and

$$\varepsilon_x = (1 - \upsilon^2)\frac{\sigma_x}{E}$$

where the lateral constraint is infinite. The "stress" gauges are placed in locations where lateral constraint is minimal.

Where:

σ_x = longitudinal stress
σ_y = lateral stress
E = modulas of elasticity
ν = Poissons ratio (.28 for mild steels)
ε_x = strain in the longitudinal direction
ε_y = strain in the lateral direction

Strain gauges were also employed on the instrumentation programs reviewed. The strain gauges were used to measure amidship vertical bending strain in the HOOSIER STATE and WOLVERINE STATE and on local areas away from amidship on the BOSTON and SL-7 SEA-LAND McLEAN and the icebreaker MACKINAW.

The recorded strain from the strain gauges was converted to stress by simple calibration constants.

The stress and strain information was recorded as an analog signal on magnetic tape for all the instrumentation programs reviewed except the STEWART J. CORT where the stress data was converted to a digital signal and recorded on magnetic tape. The analog signals from the HOOSIER STATE, WOLVERINE STATE, BOSTON and SL-7 SEA-LAND McLEAN were recorded by high fidelity equipment on magnetic tape with a resolution from DC to 50 H_z.

The data from the instrumentation programs exist on magnetic tapes in either analog or digital form (the STEWART J. CORT data is digital). They have been recorded in 20- to 30-minute intervals with appropriate calibration factors including time. The resulting stress or strain time histories require additional data reduction to obtain strain rate information. The analog and digital data may be processed and strain rates calculated after additional computer software is developed to differentiate the strain data with respect to time.

3.3 REVIEW AND EVALUATION OF EXISTING DATA BASES THAT COULD REVEAL THE RANGE OF STRAIN RATES IN SHIP HULL STRUCTURES

Of the numerous existing full-scale data bases, the ones discussed in Section 3.1 have been inspected in depth based on the evaluation criteria presented in Section 3.2.

A summary of the review and evaluation criteria of the existing data bases is presented in Table 3-2. Several observations pertaining to the information presented in Table 3-2 are presented below.

The primary observation about the existing data bases is that it is feasible to obtain strain rate information from existing ship hull structure instrumentation programs. However, in all cases the data have to be reanalyzed before detailed information on strain rates may be

TABLE 3-2

REVIEW OF FULL-SCALE DATA BASES THAT MAY REVEAL THE RANGE OF STRAIN RATES IN SHIP HULL STRUCTURES

	SL-7 McLean SSC 71-74	Universe Ireland ABS 67-70	Fotini L ABS 67-70	M/V Stewart J. Cort USCG 78-81	Boston SSC 68-69	Hoosier State Wolverine State SSC 61-64	Mackinaw Ice Breaker	ESSO Malaysia ABS 67-70
Accessibility of Data	X	X	X	X	X	X	X	X
Documentation	X	X	X	X	X	X	X	X
Instrumentation "Stress" Gauge	X	X	X	X	X			X
Strain Gauge	X				X	X	X	
Strain Measurement Midship Vertical Bending	X	X	X	X	X	X		X
Strain Measurement Stress Concentrating in Primary Structure	X				X			
Strain Measurement Areas Other Than Amidships on Primary Load Members & Plates	X	X	X		X		X	
Strain Measurement of Cargo Loading		X	X					
Strain Measurement Of Cargo Shifting Sloshing								X
Bulk Shifting								
Strain Measurement Collisions Other Ship								
Grounding								
Docking								
Environmental Data for Validation of Analytical Techniques				X				
Calibration by Applying a Known Load	X	X	X		X			X
Supporting Ship Data Motions	X			X	X			
Logbook	X	X	X	X	X		X	X
Primary Route								
GL				X			X	
NA	X		X		X	X		
PAC			X					
Tanker		X	X					X
Data Reduction Reanalyze for Strain Rate	X	X	X	X	X	X	X	X

obtained directly. This involves reprocessing the existing analog strain data. Although the majority of the data has been obtained by recording equipment with a 50-H_z upper bound filter it is unlikely that significant structural response of interest relative to material classification has been eliminated. In quantitative terms if yield strain (.001 in/in) is reached in .02 seconds, the resulting strain rate would be 5. x 10^{-2} in/in/sec which is well below that required to affect the material yield strength behavior of mild steels used for ship structures. A second observation from Table 3-2 is that in all cases the full-scale data are accessible for further analysis with regard to strain rate information. Documentation has been published for the data bases reviewed.

As can be seen in Table 3-2 there are gaps in the quantity of specific and supporting information required to determine the range of strain rates in ship hull structures based on existing data. However, the majority of the information has been obtained for the given data bases and ship types in question. Significant gaps in the data bases exist for collision induced strain rates and environmental data needed to validate analytical techniques that may be used in predicting the range of strain rates in ship hull structures. The validation of analytical predictions of strain rates should remain a long-term goal after the techniques for predicting strain in the time domain have been validated. Environmental information is also desirable for collation of the strain rate information.

4.0 PRELIMINARY CALCULATION OF STRAIN RATES FROM EXISTING DATA AND SUMMARY OF RELATED OBSERVATIONS

The ability to carry out a meaningful or representative collation of strain rate data depends on the extent to which existing data for ship types allows one to derive strain rate information. As discussed previously, it is feasible to obtain strain rate information from existing data; however, the existing data would require reprocessing before the full range of strain rate information could be obtained.

The strain data from several existing full scale data bases were reviewed and preliminary calculations of strain rates for the hull structure performed. The data analysis consisted of determining the strain rate as required for comparison to the strain rates produced by the material testing techniques. For each of the data bases investigated the maximum strain rate was determined for recorded intervals of data (typically 20-30 minutes).

4.1 DATA REDUCTION REQUIRED TO OBTAIN STRAIN RATE INFORMATION FROM EXISTING DATA

The data reduction techniques required to compute strain rates from existing data are developed so that they may be compared to the strain rates produced by existing material toughness tests (i.e., tensile tests, dynamic tear, Charpy V-notch). Ideally the material toughness tests should be developed to simulate the variable nature of strain and strain rates produced by shipboard operation. The type of data reduction required to obtain strain rates for variable loading material tests and future strain rate data reduction is presented in Section 5.2.4. This type of data reduction would constitute a long-term goal for material classification procedures.

The dynamic strains have been measured and recorded in the form of analog signals for all of the data bases discussed with the exception of the STEWART J. CORT data which are in digital form. For practical considerations, full-scale data have traditionally been collected in sampling patterns. Typically, these patterns consist of recording data for 20- to 30-minute periods at predetermined intervals.

In most of the data bases reviewed the data acquisition methods were oriented toward obtaining stress and time data. While stress was the desired quantity in all instances, techniques were employed to infer stress from measured strain. Section 3.2 comments on the instrumentation and frequency ranges used to gather the existing data. The signals themselves record all changes in strain within the given ranges of the instrumentation. Typically, wave-induced strains are recorded for the recording intervals. These recorded strains occur primarily at the wave encounter frequency (low frequency wave-induced strain). Superimposed on the low frequency wave-induced strain are transient responses of the structure to impact-type loadings which vary from ship type to ship type. These transient structural responses occur at frequencies higher than wave encounter (typically at the first mode of the hull structural response) and can achieve large amplitudes in certain instances. The high frequency transient structural responses result from slamming and flare shock, and are known as whipping responses. Springing is also a phenomenon of hull vibration which has been observed primarily in Great Lakes ore carriers and certain oceangoing vessels. The springing response is identified as being primarily one of fundamental hull frequency matching the encounter frequency of waves possessing sufficient energy for hull excitation.

The recorded strains vary from interval to interval and are caused by shifts in cargo and ballast as well as thermal effects. Typically the shifts in mean strain are recorded and referenced to the state of strain when the ship leaves port at which time the gauges are zeroed. Although the state of strain is not recorded upon departure for each voyage the initial mean strain is not required for calculation of strain rate.

A representation of a strain time history is presented in Figure 4-1. The most notable feature depicted in Figure 4-1 is that in areas where the strain time history is sinusoidal in nature, the maximum strain rate occurs at the average strain and the minimum strain rate occurs where the strain is at a maximum or minimum as would be for typical sinusoidal signals. The exceptions to the generalization occur where there are high frequency transient structural responses such as whipping. The high frequency strain produces higher strain rates where the instantaneous state of strain is other than the average (not necessarily zero). It becomes apparent that the specific information needed to describe the level of strain rate that is of interest to materials engineers requires definition.

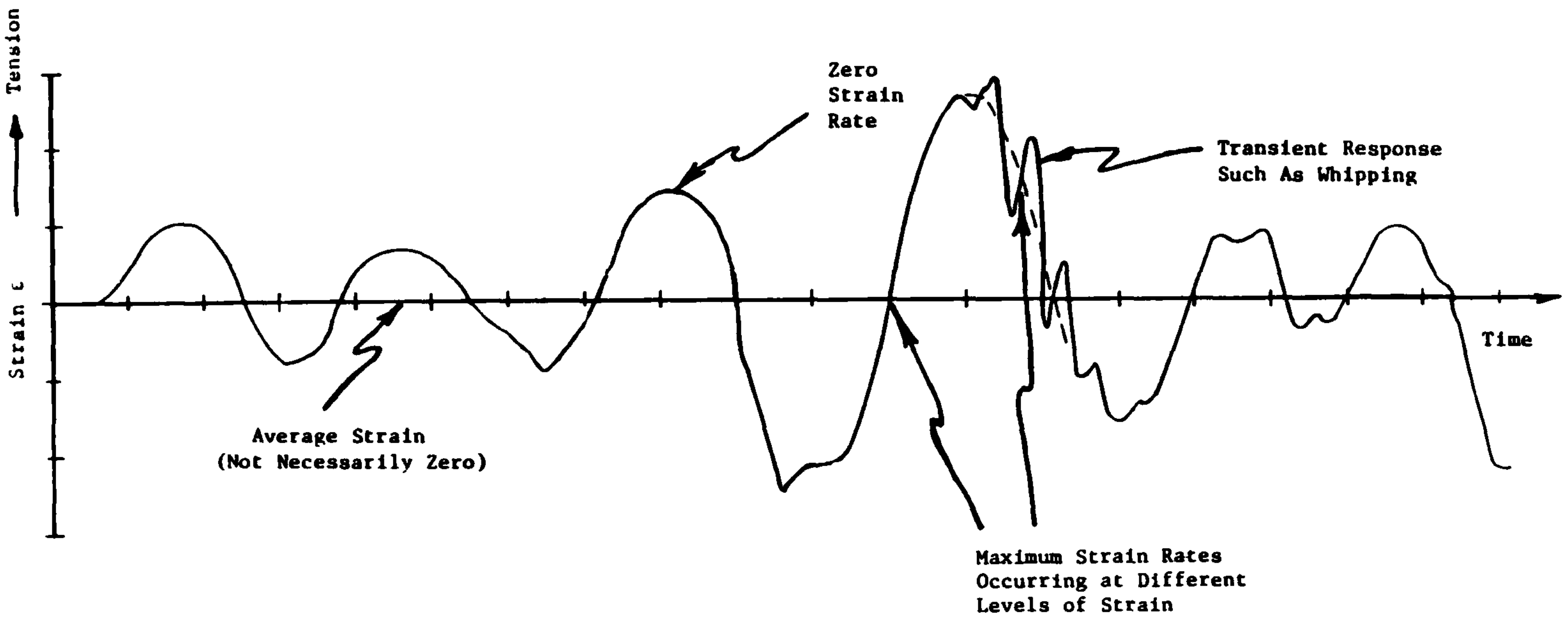


Figure 4-1

Representation of a Strain Time History Used for Illustrative Variance of Strain Rate Throughout the Signal

The existing techniques used to classify materials in the study presented in SSC-275 (4) were (static) tensile, dynamic tear (DT) and Charpy impact tests. These tests produce a wide range of strain rates as indicated in Table 2-1. The method used to determine the strain rate for the three standard material tests is to infer the strain at maximum load and divide by the total test time. For the tensile tests the strain rate is controlled at a constant value. For material tests which produce a nearly constant strain rate, the materials researchers report the strain rate that best approximates the nearly constant strain rate. The procedure is different for material tests that produce a variable strain rate. A typical load time history for a dynamic tear test is shown in Figure 4-2. The strain rate produced by the dynamic tear test is variable. The maximum loading rate occurs when the loading magnitude is increasing, and the load rate is at a minimum when the load magnitude is at a maximum. For a variable strain rate test such as the dynamic tear test, the materials engineers report an average strain rate for the duration of the test. This is normally determined by dividing the maximum strain by the test duration in time which yields an overall average strain rate. This procedure is also used to approximate the strain rate produced by a Charpy V-notch materials test.

The strain rates experienced by ships at sea are also variable in nature as represented in Figure 4-1. The strain rate data reduction which would best characterize these variable strain rates is the average strain rate for a given strain excursion. This average strain rate information obtained from ship strain records would be compatible with the strain information obtained from current material tests.

Preliminary calculations of strain rates have been obtained from several of the data bases described previously. The specific type of strain rate calculation is compatible with the strain rate information obtained from material tests as described above. For most of the calculations of strain rates presented in this report the source of loading (i.e., thermal effects, low frequency wave-induced, transient high frequency wave-induced, etc.) has been identified. The identification was primarily from visual inspection from the hard copy stress time histories. The strain rates presented for the low frequency and transient high frequency wave-induced strains have been calculated from the combined stress records as represented in Figure 4-1. The effects of calculating the strain rate from separated signals (separated by filtering) was investigated as part of this study. The results of the preliminary calculations indicated that estimation of strain rate from combined or separated signals was generally similar in magnitude, however, this conclusion needs to be reviewed for each specific case. In some instances the phase information between signals is lost after separation by filtering. The reason the strain rates were calculated from combined signals is so the strain rate could be estimated at areas where the strain magnitude is largest. The preliminary calculation of strain rates at areas of maximum strain excursions provides information that is consistent with the strain rate information measured from current material tests.

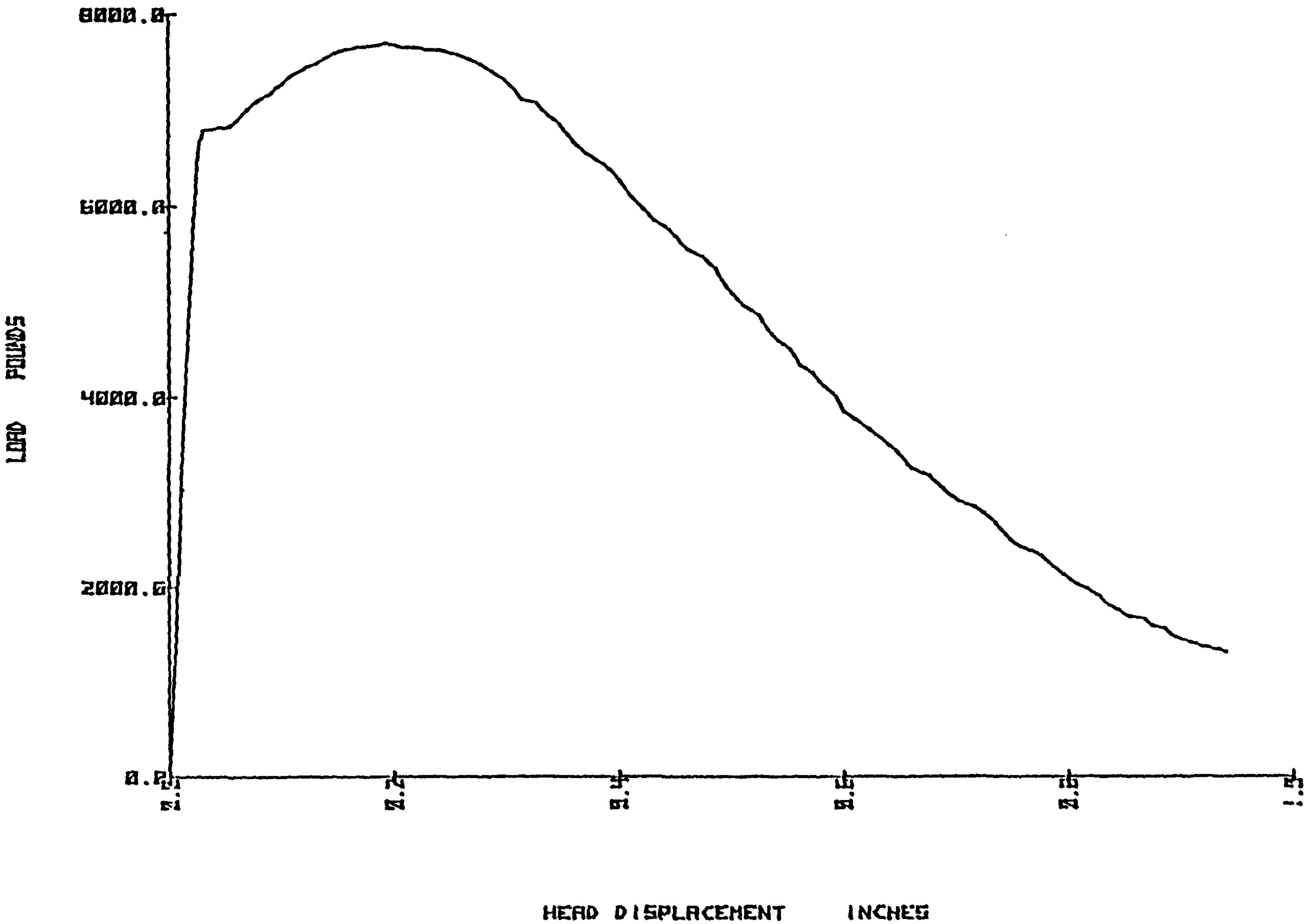


Figure 4-2 Typical Load Displacement Curve Produced by Dynamic Tear Test, Approximately 1-in/sec Load Rate, EH-32 Steel (Reference 5)

The accuracy and extent of data reduction required to determine the range of strain rates occurring in ship structures is comensurate with the reported values of strain rates from material tests as shown in Table 2-1. The strain rates produced by material tests are generally reported and compared by order of magnitude. The preliminary calculation of strain rates from existing data are within the order of magnitude required to define the range of strain rates for this study.

4.2 PRELIMINARY CALCULATION OF STRAIN RATE INFORMATION FROM EXISTING DATA

The data bases from which preliminary calculations were obtained include: The SL-7 SEA-LAND McLEAN (12,13,14,18,19,20), UNIVERSE IRELAND (6), FOTINI L (6) and the STEWART J. CORT (15). The ships are a containership, tanker, ocean going bulk carrier and a Great Lakes ore carrier, respectively. These ships were constructed of mild structural steels. Although the current trend in ship building materials is tending toward utilization of higher strength steels, the steels are within the broad category of mild steels generally used for ship construction. The preliminary calculations of strain rates were obtained from stress time histories using the appropriate factors relating stress to strain. The time reference for stress time histories was used to calculate rate. Although the original analog signals were recorded from DC to 50 H_z the signals were filtered for the development of stress time histories used for the preliminary calculations. The analog signals were all filtered through a 2 H_z low pass filter for play back and development of stress time histories to minimize the shipboard propeller-induced hull vibration in the recorded data. In all cases the researchers indicated that there were no stresses or strains of significant magnitude that were eliminated by the low pass filtering procedure. The majority of the stress time histories that were used to obtain preliminary strain rate information are presented in Appendix A. The strain rates that were calculated for the SL-7 SEA-LAND McLEAN and STEWART J. CORT have been tabulated along with operational information including observed wave height, ship heading and speed. The tabulated strain rates are presented in Appendix B. The highlights of the preliminary calculation of strain rates from the existing data are presented below.

The SL-7 SEA-LAND McLEAN data base was examined in the greatest detail with regard to preliminary calculation and collation of strain rate information. Figure 4-3 presents an expanded trace of amidship vertical bending stress of a slam and resulting whipping stress in a severe storm. The reported wind speed reached 100 knots, the observed wave height was 50 feet, and the ship was hove-to. The stresses recorded during the expanded time represent the maximum amidship vertical bending stress measured for the three seasons of data acquisition on the SL-7 SEA-LAND McLEAN. The strain rate induced by the whipping response is 1.1×10^{-3} in/in/sec in the vicinity of maximum load (stress).

The forward hatch corner of the SL-7 SEA-LAND McLEAN was known to be a highly stressed area. The data associated with the stress concentration of the forward hatch is presented in Appendix A. These areas appear to produce a stress (and corresponding strain) which is greater in magnitude

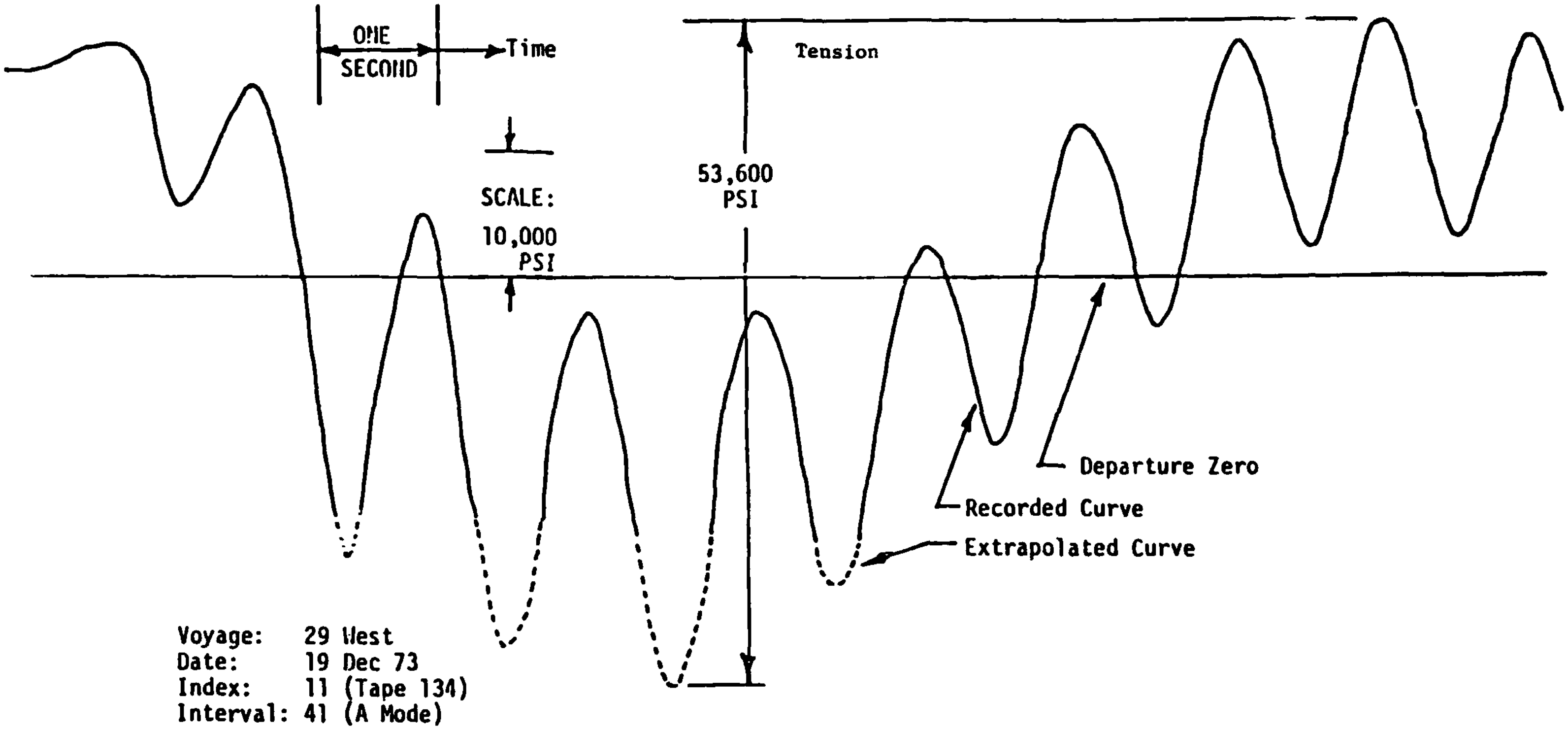


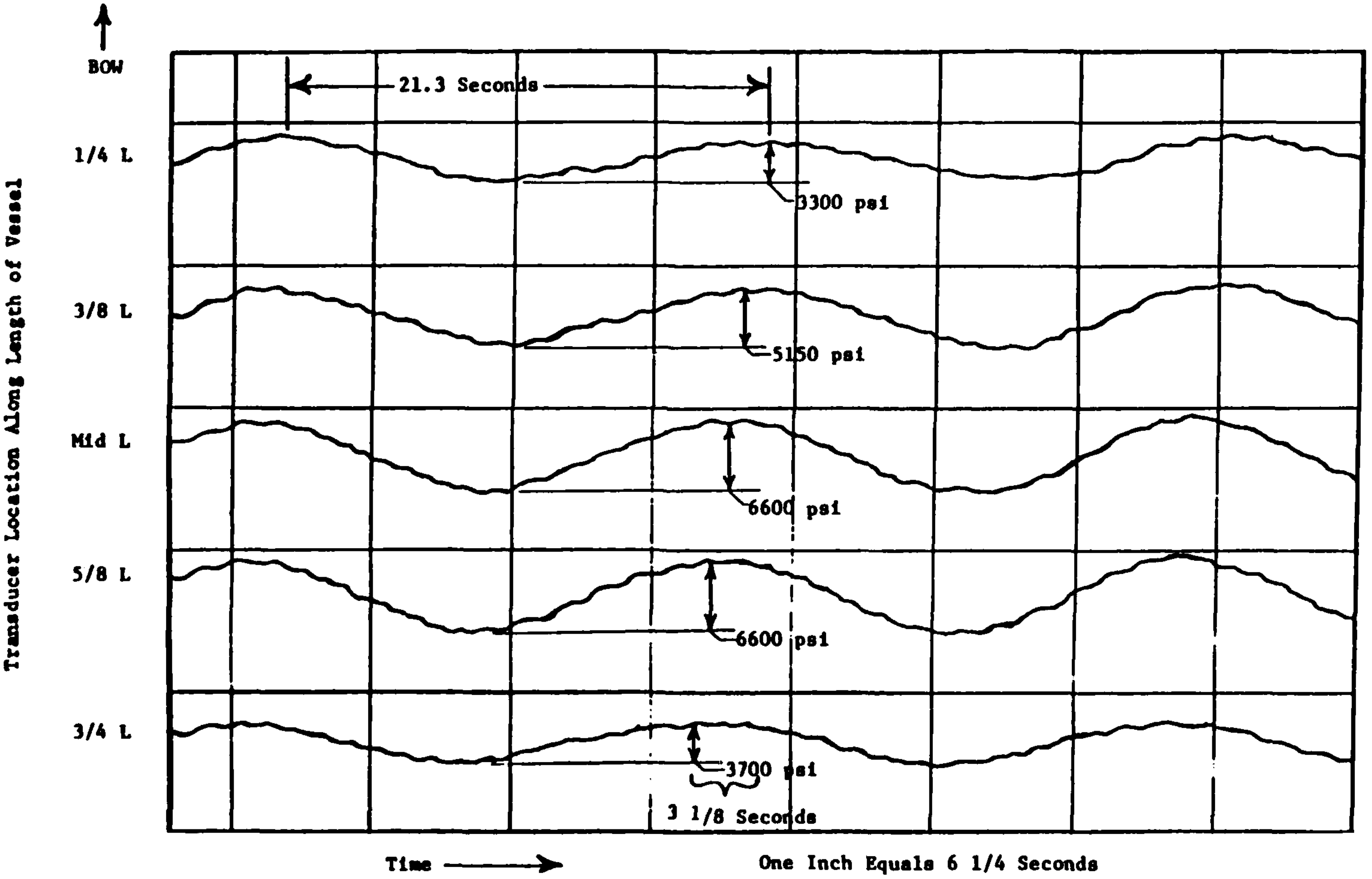
Figure 4-3 Expanded Trace of Vertical Bending Stress (Ref. 19)
SL-7 SEALAND McLEAN

than the amidship longitudinal vertical bending stress for the conditions indicated for the recorded interval. However, the strain is occurring at approximately the same frequency, thus the strain rate is increased. The stress concentration factor would vary for other ship headings and environmental conditions.

The UNIVERSE IRELAND (6) data base provides some interesting observations of the range of strain rates. Figure 4-4 presents a series of stress time histories for wave-induced vertical bending at several points along the ship's hull in a following sea (swell condition). The comparison of stress time histories indicates that the magnitude of stress (and therefore strain) is maximum near amidships. Since the frequency of stress is nearly constant for each location along the hull, the resulting strain rate is largest near amidships. The influence of a following swell decreases the magnitude of strain rate compared to waves of shorter period since the frequency of wave encounter is decreased. This further confirms the observation that strain rate is not only influenced by the height of the encountered wave but also the frequency of the wave encountered. The approximate strain rate in the following swell is 5×10^{-6} in/in/sec. The low magnitude of high frequency transient stresses in the UNIVERSE IRELAND has been documented in SSC-287 by Dalzell (21). The nature of high frequency wave-induced transient strain rates (found to be the greatest magnitude of strain rate occurring in the SL-7) is dependent on ship type.

The Great Lakes Ore Carrier STEWART J. CORT (15) also provides an interesting source of strain rate data. The stress time histories for the STEWART J. CORT appear in Appendix A. An example stress time history measured on the STEWART J. CORT is presented in Figure 4-5. The high frequency springing is evident. Hull girder springing is a phenomena that occurs where the fundamental frequency of hull vibration is excited at wave encounter frequencies. Springing is characteristic of Great Lakes ore carriers but is not necessarily restricted to that specific type of ship. The springing-induced strain rate is dependent on the strain magnitude since the strain frequency is nearly constant. There appears to be little relationship between strain rate and ship speed or encountered wave height. The reason for this is that the springing response on the STEWART J. CORT occurs primarily at the first mode of hull vibration. The strain rates for the maindeck are noticeably larger than those observed for the bottom of the hull girder. Strain rates were also calculated for thermal effects and ship cargo loading on the SL-7 SEA-LAND McLEAN, FOTINI L , and the UNIVERSE IRELAND. The strain rates estimated for these conditions are in the 10^{-8} in/in/sec. order of magnitude which is low compared to whipping induced strain rates inferred from SL-7 SEA-LAND McLEAN data.

It is apparent that the strain rates produced by thermal effects, ballast shifts and cargo loading are lower in magnitude than wave-induced strain rates and are of lesser importance for determination of strain rates to material toughness classification.



SS UNIVERSE IRELAND

Figure 4-4 Ship Response to Following Swells

CONDITION 6

```
M/V S J CORT FALL TRIALS
          RUN            117          POINT         17
          DATE    09-DEC-79           TIME    15104184
          DURATION OF RUN IN MINUTES IS           25.000
          NORTH LATITUDE (DD MM)             87 13
          WEST LONGITUDE (DD MM)             43 20
          VESSEL'S SPEED (MPH - XX.X)      13.5
          VESSEL'S HEADING (DEGREES)        180
          VESSEL'S DRAFT (FEET)              27
          WIND DIRECTION (DEGREES)          263
          WIND SPEED (KNOTS)                 14
          WAVE DIRECTION (DEGREES)          190
          WAVE HEIGHT (FEET)                  3
REMARKS
MICHIGAN SOBND;HEAD SEA
2-3 FT SWELL

End-of-run message
```

19.52 psi/count

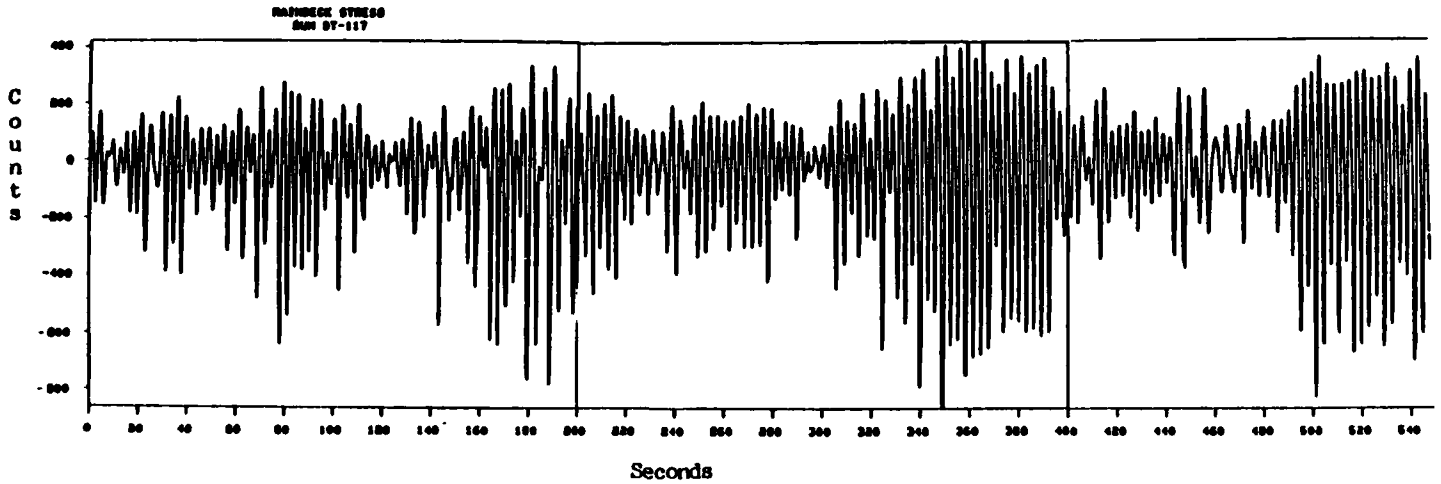


FIGURE 4-5

As indicated in the review of existing data bases there is no data available to date on collision loads. A test plan has been developed (22) for the U.S. Coast Guard to obtain full-scale collision data, however, at this time the test plan has not been implemented.

Collision model tests of ship structural areas were performed by GKSS* of Hamburg, Germany, to validate analytical predictions. Results of these tests are presented by Chang (23). Preliminary calculation of strain rates from a model scale force time history (assuming yield strain is reached in a load rise time of .032 sec.) produced a strain rate of 3.2×10^{-2} in/in/sec.

No indication of scaling laws was given by the authors that presented the data since the analytical techniques were validated on the model scale. Unfortunately, strict scaling is not possible for strain-rate sensitive materials. Material strain rate sensitivity exercises a more powerful influence on smaller structures than geometrically scaled larger ones. This occurs because both distances and deformations scale geometrically so that strain, which is the ratio of these quantitites, does not scale. Time, on the other hand, does scale. However, tests on small structures can be used to develop strain-rate sensitive constitutive equations for materials and to assess the strain-rate sensitive characteristics of materials.

Other types of loading were considered as possible sources of strain rates that would be of interest for material classification. These included cargo dropping, cargo shifting, sloshing, ship grounding and blast loads. Strain data was recorded on the ESSO MALAYSIA by ABS at a forward bulkhead in an effort to record sloshing induced strains but has not been presented in a form appropriate for preliminary calculations of strain rates. No data was found on strain produced by cargo dropping, shifting or ship grounding. The full-scale data on blast loading is of interest primarily to naval vessels and is closely held by the Navy and not available to the general public.

4.3 SUMMARY OF OBSERVATIONS PERTAINING TO STRAIN RATES OBTAINED FROM EXISTING DATA

The preliminary estimates of strain rates from existing data provides valuable insight to the range of strain rates encountered by ships inservice. In this section a summary of the strain rates obtained from existing data are presented along with observations on the primary factors which affect the magnitude of strain rates encountered by ships during operation. Finally, an attempt is made to qualify the preliminary calculations of strain rates by relating them to the initial problem of determining the amount of conservatism inherent in the existing material testing techniques.

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*Gesellschaft fur Kernenergieuerwertung in Schiffban und Schiffahrt mbH., Hamburg.

Table 4-1 presents a summary of the preliminary estimates of strain rates as discussed in the previous sections. The largest strain rate (1.1×10^{-3}) estimated from existing data (within the frequency ranges of the data) occurred on the SL-7 SEA-LAND McLEAN during a storm that caused the ship to slam. Local bow impact pressures were encountered during slamming on the WOLVERINE STATE (24). The pressure rise times measured occurred at a loading rate as high as .05 sec. These local impulse pressures on the bow area induced a whipping two-noded response in the hull girder at the fundamental frequency of hull girder vibration. The resulting whipping of the SL-7 SEA-LAND McLEAN induced the highest amidship vertical bending strains measured during three seasons of operation. The large strain rate (9.0×10^{-4} in/in/sec.) measured from the bulk carrier FOTINI L data is also quite large and is caused by a whipping response.

Several observations are presented below which pertain to the preliminary calculation and collation of strain rate information. They are:

a.) Strain rates induced by the encounter of waves vary according to ship type, structural location from amidship and areas of stress concentration.

b.) Strain rates induced by encountered waves vary with the magnitude of wave height as well as encounter frequency, ship heading and ship length.

c.) Strain rates induced by high frequency transient responses are generally larger in magnitude than the strain caused by the encounter of waves.

d.) Strain rates induced by high frequency transient loads are related to strain magnitude and in many instances wave magnitude. The frequency of transient strains (such as whipping, springing) are nearly constant and are dependent on the first mode of structural response for given ship types.

Table 4-2 presents a summary of the primary factors which influence the ranges of strain rates in ship hull structures based on the preliminary calculations presented in this report. The strain rates obtained from the preliminary calculations were for a high speed containership, larger tanker, Great Lakes ore carrier and an oceangoing ore carrier. The strain rates would differ for other ship sizes and types as influenced by the factors listed in Table 4-2.

The current methods used to determine material toughness are tensile tests, dynamic tear tests and Charpy V-notch tests as indicated in Table 2-1. The strain rates that are produced by these tests are given in orders of magnitude values. At this time it would not be economical to pursue the definition of shipboard strain rates much further than the order of magnitude values presented for material testing techniques. Table 4-1 presents preliminary strain rates derived from existing data

TABLE 4-1

Summary of Preliminary Estimates of
Strain Rates From Existing Data
(Mild Steels)

Strain Rates Given as in/in/sec.*

	Collation Information	Strain Rate
Containership ** (SL-7)	Whipping, 50' seas, hove-to	1.1×10^{-3}
	Fwd hatch corner, wave-induced 50' seas, hove to	3.0×10^{-4}
Tanker** (UNIVERSE IRELAND)	Wave-induced, following swell	5.0×10^{-6}
Ocean Bulk Carrier** (FOTINI L)	Whipping	9.0×10^{-4}
	Springing	2.6×10^{-4}
Great Lakes Ore Carrier (STEWART J. CORT)	Springing 3' head seas	5.1×10^{-4}

* For comparison, if the strain reached yield (.001 in/in) at the frequency whipping (1/4 cycle) on the SL-7 (1.25 cycles/sec), the resulting strain rate would be 3.2×10^{-3} in/in/sec. by design for operational loading.

** The analog signals for these calculations were obtained from stress time histories that were filtered by a low pass filter with a cut off at 2 H_z. All strain rates were calculated from data measured amidship unless otherwise noted.

TABLE 4-2

Summary Table of the Primary Factors Which Influence the Magnitude and Range of Strain Rates

Factors which influence strain rates for a given ship:

a) Location from amidship and the neutral axis of the hull structure

b) Areas of stress concentration

c) Operational environment (route)

d) Wave encounter frequency (function of ship speed, heading and wave period).

Factors which influence strain rates for different ships:

a) Type of impact loading (i.e., springing, whipping, slamming, flare shock, etc.)

b) Structural design

c) Ship length/wave length ratio

d) Operational environment (route)

e) Operational procedures.

that have been identified by the instrumentation operators as the highest strain measured during the instrumentation programs (i.e., 1.1 x 10^{-3} in/in/sec. estimated from whipping stresses on the SL-7 SEA-LAND McLEAN). Preliminary observations from the existing data indicate that the whipping strains induce the highest strain rates where whipping occurs. The preliminary calculations have produced order of magnitude information required to assess the amount of conservatism inherent in the current material toughness classification methods. Variations in strain rates for other ship types, sizes and operational procedures would not be expected to produce strain rates that are orders of magnitude different than those presented in Table 4-1.

Again, the low pass filter frequency cut off has eliminated strains that occur in the stress time histories above 2 H_z. It is no coincidence that the 2H_z cut off filters were chosen since strains occurring at higher frequencies are generally of low strain magnitude and would produce low strain rates.

In the future, there may be demand for material testing techniques which characterize ship steel toughness at variable loadings and variable strain rates occurring during ship operation. A more precise definition of strain rates may eventually be required. However, until the variable loading material tests are developed, an extensive research program oriented toward gathering strain rate information from ships in operation is not warranted. When the demand requires it, strain rate information may be economically obtained in conjunction with future instrumentation programs.

5.0 RECOMMENDATIONS TO OBTAIN STRAIN RATE INFORMATION FROM ANALYTICAL PREDICTIONS AND FULL-SCALE INSTRUMENTATION

Historically material tests used to characterize ship steel material toughness have tested material specimens in tension basically at one increasing load or with explosion tests as discussed in Sections 2.0 and 4.1. The preliminary information on strain rates presented in Section 4.2 is comparable to the order of magnitudes of strain rates reported by others (2,3,4,5,) for the particular types of material tests. This inspection of existing ship strain data has indicated that the strain rates experienced by ships in service are variable in nature as discussed in Section 4.1.

If demand dictates, strain rates may be obtained through either analytical predictions or in conjunction with instrumentation programs that may be conducted in the future. The next two sections outline the procedures necessary to obtain a more precise definition of strain rates for given ship types. It is anticipated that these methods will be required when material toughness classification tests are developed to produce variable loading and strain rates that are representative of ship service experience.

5.1 ANALYTICAL PREDICTIONS REQUIRED TO OBTAIN STRAIN RATE INFORMATION

Strain rates may be predicted by analytical techniques for ship hull primary structure in service. The techniques vary in complexity from relatively simple hand calculations to expensive computer predictions. The preliminary estimates of strain rates obtained from existing data indicate that strain rates induced by wave impact loading (slamming, flare shock and deck wetness) and resulting whipping are of the greatest magnitude for normal ship operation. A simplistic calculation of whipping-induced strain rates was presented for the SL-7 SEA-LAND McLEAN as shown in Table 4-1. The calculation assumed that yield strain (.001 in/in mild steel) was reached in 1/4 the time one full cycle of whipping response at 1.25 sec/cycle. This produced a strain rate of approximately 3.2×10^{-3} in/in/sec. This may be somewhat simplistic but is comparable to the highest whipping strain rates encountered by the SL-7 SEA-LAND McLEAN of 1.1×10^{-3} in/in/sec. The whipping response or two-noded vibration of the primary hull structure of a ship may be predicted from various methods ranging from simple beam theory to finite element analysis depending on the degree of accuracy required.

More detailed calculations of wave-induced strain rates can be obtained indirectly from time domain computer programs such as the ROSAS structural seaworthiness digital computer program (25). The ROSAS time domain program simulates the hull girder structural response of a ship, including dynamic effects in head seas of regular or irregular wave forms. Hull response calculations include the ship rigid and elastic body motion, bending moment and shear. Vibratory hull girder modes can also be determined from the effect of bow flare, bottom slamming and springing. Figure 5-1 presents an example of hull bending moment predictions as compared to full-scale data. Strain rates could be inferred from this type of bending moment and hull response information since the calculations are produced in the time domain.

Hull girder loading from deck wetness and bottom slamming can be predicted by the methods discussed in references 26 and 27, respectively. Techniques were developed to predict not only the occurence and magnitude of impact loading, but also to estimate the time duration of loading. This information would be valuable for sensitivity-type analyses of strain rates resulting from impact loadings. The validation of the analytical predictions of strain rates should remain a long-term goal as demand for more precise strain rate data indicates. Many of the prediction techniques require validation with respect to strain and time information before they can be validated to predict strain rates.

Existing analytical methods for predicting loads and accelerations resulting from collisions have been presented by Chang (23), Gotimer (28) and Reckling (29). Reckling (29) has predicted the collapse of structural members of a containership occurring in approximately .18 seconds. This would induce a strain rate of approximately

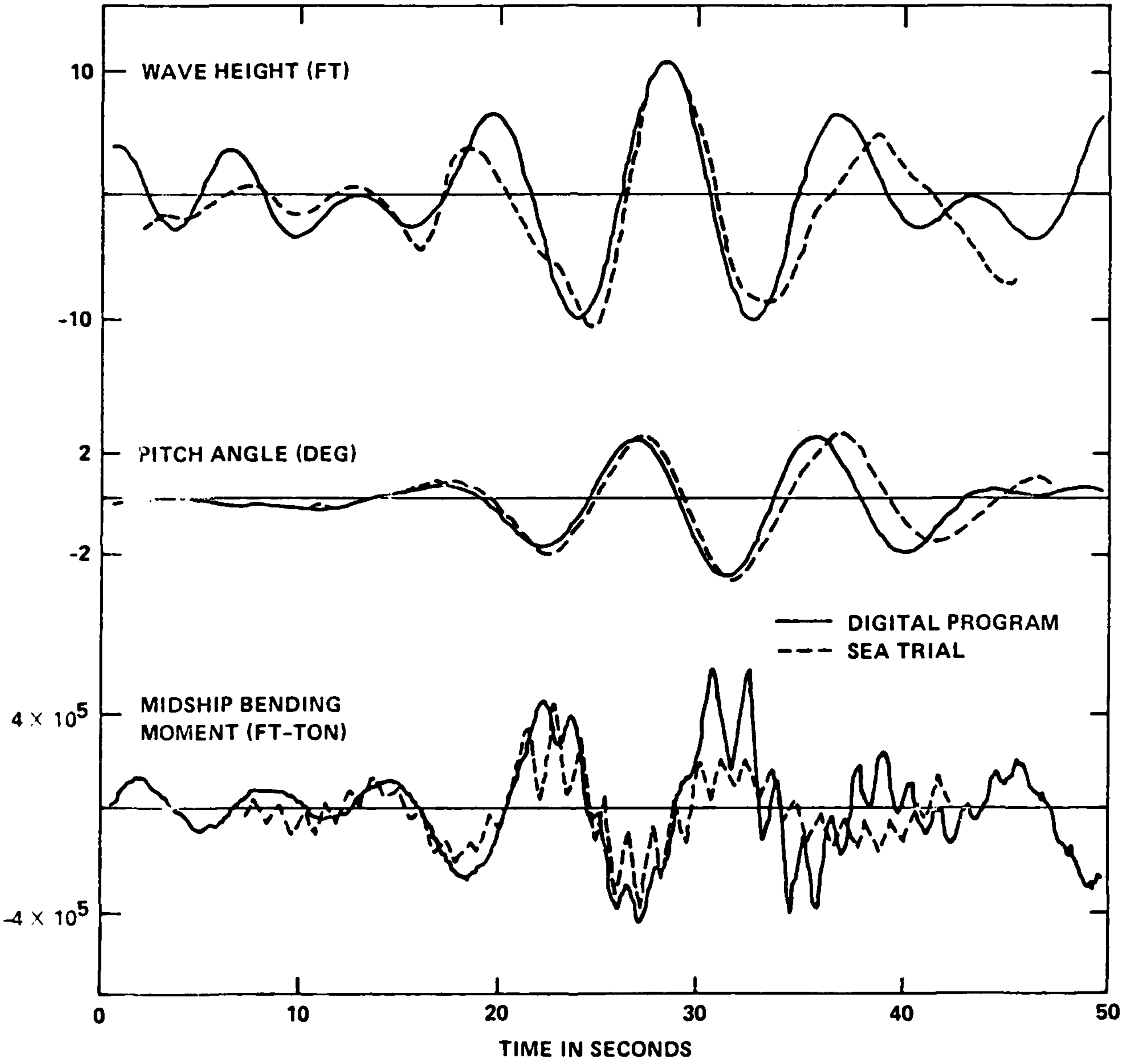


Figure 5-1 Comparisons Between ROSAS Output and Sea Trial Data from the ESSEX aircraft carrier (Ref. 25)

6×10^{-3} in/in/sec. This calculated value of strain rates induced by collisions is comparable to those induced during modeling tests of ship sections that were described in Section 4.2 as 3.2×10^{-2} in/in/sec in model scale. A review and evaluation of methods for prediction of structural response from collisions are presented by Van Mater in reference 30. These methods incorporate finite element computer programs and may be used to calculate strain rates. The predictive methods developed by Chang (23) have been compared to collision model tests; however, no full-scale ship collision data exists to validate load and response prediction methods.

5.2 OUTLINE OF A METHOD TO OBTAIN STRAIN RATE INFORMATION IN CONJUNCTION WITH A FUTURE FULL-SCALE INSTRUMENTATION PROGRAM

The preliminary calculations of strain rates from existing full-scale shipboard response data indicate that a separate full-scale instrumentation program to obtain strain rates is not warranted at this time. When material toughness classifiction tests become sophisticated enough to produce variable loading and variable strain rate it may be appropriate to obtain a more precise definition of strain rates produced by ship service experience. Strain rates may be obtained in conjunction with future full-scale instrumentation programs.

The approach to obtain strain rates in conjunction with a future full-scale program would involve additional program management and additional data acquisition, reduction and analysis. It is assumed that the instrumentation program has its own individual objectives that would not be affected by the additional requirements for obtaining strain rate information. It is further assumed that the instrumentation program would have arrangements made for instrumentation, (strain gauges) data recording equipment and data reduction equipment so that the strain rate data could be obtained from the strain time information to be recorded. As indicated for the existing strain data the strain rates would be reduced and analyzed separately from normal strain data reduction where peak-to-trough information was the primary data reduction goal.

The program management required to obtain strain rates in conjunction with a future instrumentation program would consist of test planning and general support engineering. The additional program management, as for any project of this nature, would result primarily from the extra information being obtained that requires planning, scheduling and controlling. The general engineering support would be required to ensure that the technical requirements of data acquisition, reductions and analyses are met.

The data acquisition and reduction should involve:

a. possible instrumentation modification to ensure the frequency range of hull girder straining encountered by ships inservice is covered;
b. reduction of strain and time data to obtain strain rates;

c. computer time required to analyze the data;

d. analysis of the reduced strain rate data including collation of data with respect to ship speed, heading and encountered wave conditions.

The following sections outline the items that must be considered to obtain strain rate information from a future full-scale ship instrumentation program.

5.2.1 Number and Types of Ships to be Instrumented

The review of full-scale existing instrumentation data provides valuable insight into the number and type of ships needed to collect strain rate information in conjunction with future full-scale instrumentation programs.

The review of existing data indicates that there is a lack of full-scale collision data. It would be extremely valuable to obtain strain rate information if and when full-scale collision tests are conducted. A preliminary collision test plan has been presented by Van Mater in reference 22. The recommendations developed to obtain full-scale strain rates may be incorporated into the existing preliminary full-scale collision test plan. The preliminary collision test plan (22) is oriented toward obtaining full-scale collision information on tankers, both crude and LNG carriers.

The preliminary calculations indicate that the largest strain rates occurred on the SL-7 SEA-LAND McLEAN for the existing data bases involved. This should be no surprise since the SL-7 SEA-LAND McLEAN was a large, high-powered containership that operated in the North Atlantic. Table 4-2 lists the factors which influence the magnitude of strain rates from ship type to ship type.

To a large extent the exact types of ships to be instrumented for future programs will depend on other factors other than strain rates. Currently there are test plans being developed to obtain full-scale strain data on slamming (SR-1295), still water bending moments (SR 1283), and ice loads on the icebreaker POLAR STAR (SR-1291). If the general guidelines presented in this section are applied to the data acquisition then the data may be reduced to obtain strain rates as demand requires.

5.2.2 Structural Areas and Members to be Instrumented

The structural areas and members to be instrumented that pertain to material classification have been described in Section 3.2 as part of the criteria used to evaluate the structural areas instrumented for past instrumentation programs. Candidate areas to obtain strain rates for material classification are the primary structure in the midship 40% and high stress areas that would threaten the integrity of the hull girder. The structural areas that are instrumented for future programs will probably be influenced by the areas that are of interest to ship structural designers and analysts with respect to hull girder strength. For example, strain gauges were placed on the forward hatch corner of the SL-7 SEA-LAND McLEAN to record strains in an area of anticipated stress concentration. This approach will be compatible with the selection of areas to obtain strain rates since the areas of interest to structural engineers would be of interest to material engineers for material classification. For icebreakers the structure bow area where severe ice loading occurs would be a candidate for strain rate data acquisition to aid in icebreaker hull material toughness classification.

5.2.3 Types of Instrumentation with Suitable Alternatives

Traditionally, strain gauges have been used to obtain strain information from the response of ship hull structures. A review of the current literature indicates that strain gauges have been used extensively in the civil engineering and aerospace fields for measurement of strain information. The current practice within the materials testing community provides insight as to the applicability of measuring strain rates. In addition, the data acquisition and reduction techniques associated with using strain gauges are examined.

The materials testing industry currently uses one of four basic methods to obtain strain rate information for material tests. The methods include:

a) High speed photography for explosion testing of materials.

b) Crack Opening Device (COD) for obtaining strain rate information from material tests such as dynamic tear tests on dynamic tear specimens.

c) *Electro-mechanical strain gauges for tensile tests.*

d) Electrical strain gauges for dynamic tear tests.

The most common method to measure dynamic strain is the electric strain gauge. The strain gauges used to obtain shipboard structural strain information are compatible with the strain information obtained from the instrumentation used for material tests. The strain gauge is ideally suited for dynamic measurement of strain and obtaining large amounts of data for data reduction by computer and calculation of strain rate from the resulting strain time history.

Strain rate has been defined by the materials testing engineers as the change of strain with time. Strain information may be obtained from strain gauges and the strain rate may be inferred from the measured strain data if the dimension of time is added by analog or digital recording procedures. Strain gauge instrumentation is capable of measuring strain at various ranges of frequencies. The limiting factors for strain measurement are generally associated with data acquisition methods. The filtering and digitizing frequencies have to limit the range of interest.

5.2.4 Instrumentation Installation and Data Reduction

Generally, the instrumentation used to obtain strain information should be placed to assure measurement of the gross representative bending stress where longitudinal vertical hull bending stresses are of interest. In each case the substructure should be studied to make certain that the transducers are not located near complex configurations such as cutouts in the longitudinal girders. The presence of lateral girders or bulkheads in the vicinity of the transducer does influence the lateral strains locally but does not have any measurable effect on the accuracy of the longitudinal stress or strain measurements. Instrumentation may be placed near areas of stress concentrations where they exist in primary structure. Secondary and tertiary structural areas are also of interest for development of material classification criteria but are of a lesser priority for instrumentation than primary structures.

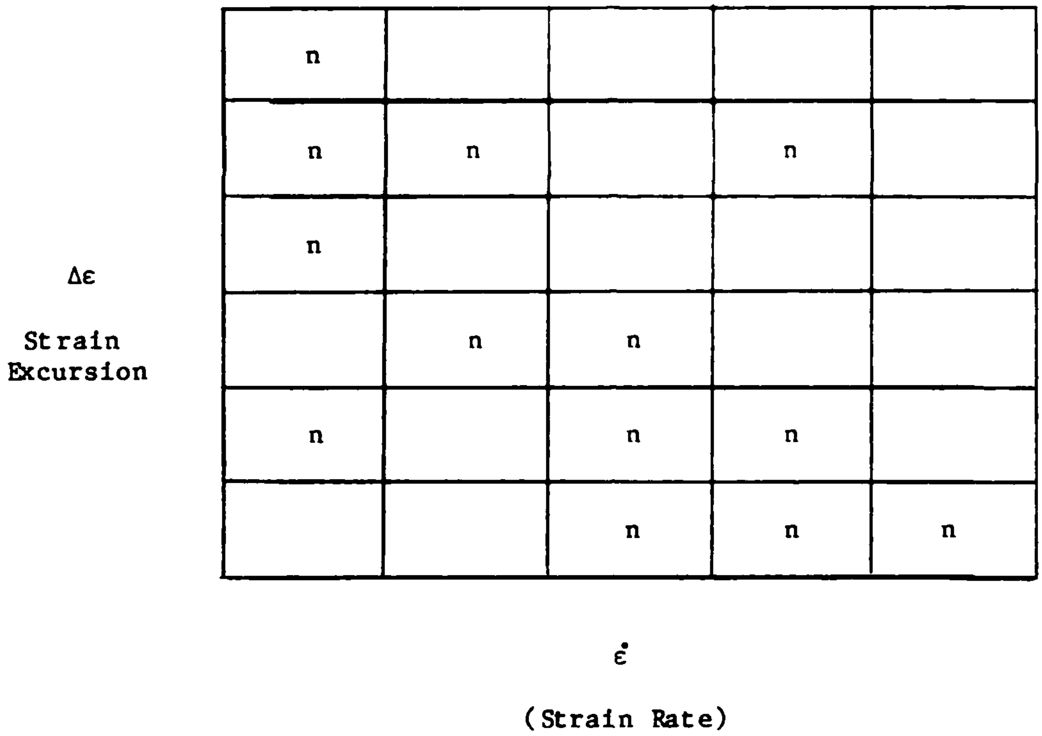
Either analog or digital data acquisition methods are suitable for acquiring strain rate information provided they cover the frequency range of interest (generally wave-encounter to plate vibration frequencies).

If strain rates are obtained in conjunction with another instrumentation program it would be most economical to reduce and analyze the data as the rest of the strain data are being reduced. Ideally, the strain rate data reduction from future instrumentation should reflect the variable nature of strain rates. The variable nature of strain and strain rate experienced by ships inservice has been depicted in Figure 4-1. If future material tests are developed that simulate the strain and strain rates experienced by ships inservice, then the data reduction described in Section 4.1 would require modification. Histograms of strain excursion vs. strain rate would be compatible with material toughness tests if future tests are developed that produce variable loadings and strain rates. A representative of a strain/strain rate histogram is presented in Figure 5-2.

5.2.5 Pertinent Measurements to Support Strain Rate Information for Collation Purposes

The primary factors which influence the magnitude of strain rates during normal operation have been determined by preliminary calculations of strain rates and are summarized in Section 3.3. The pertinent measurements included wave height, wave-encounter frequency (wave period and ship speed) and ship heading with respect to the wave environment. Air and water temperature have been measured in past instrumentation programs. This information provides service temperatures at which the materials can be tested.

Measurement of the wave environment has been a major limitation of the utility of existing full-scale data (14). Attempts have been made to measure the wave environment in several instrumentation programs (10,11,12,17) but they have not produced data that are suitable for rigorous analysis of seaway loading and structural response. An improved



n				
n	n		n	
n				
	n	n		
n		n	n	
		n	n	n

"n" represents the number of occurrences for each range of strain excursion and rate.

Figure 5-2 Representation of a Histogram Accounting for Variations in Strain and Strain Rates Compared with Variable Strain and Strain Rates Encountered in Ship Operation.

wave measurement system has recently been utilized as part of the STEWART J. CORT (15) research programs; however, experience at this time has been limited to lower sea states. Observed wave height and Beaufort sea state information has been used for data collection and statistical extrapolation of data obtained from previous instrumentation programs

This information has proven to be marginally adequate but is used for lack of better information on encountered wave environments.

5.2.6 Desirable Ship Routes, Best Seasons, General Extent and Duration of Tests to Collect Meaningful Data

The routes that are of interest in determining strain rates depend on normal operational routes for given ship types. In anticipation of a future instrumentation program the routes of interest include North Atlantic & Pacific routes for general cargo ships and container ships. The tanker routes to the Middle East would be of interest in tanker instrumentation programs.

The seasons of operation are not critical if statistical techniques are used to evaluate data provided adequate wave height information or estimates are obtained. The statisticians (31) group ship response data according to weather groups and develop separate long-term predictions for each weather group. The resulting predictions may then be combined for any given weather distribution according to the operating area of the ship. This procedure permits extrapolation taking into account the environmental conditions which are the causes of the ship response data. The studies that have been conducted in analyzing existing data seem to always recommend additional tests in an extreme operational condition. It would be best to record data as a minimum during winter seasons or seasons which produce the most severe conditions.

The methods commonly used to determine the general duration of tests include comparisons with previous samples, conducting pilot studies and/or the use of sample size estimators.

Previous studies conducted on structural response data provide insight as to the duration of tests to obtain strain rate information. Band (31) concluded that the 1,713, 20-minute intervals of data allowed him to extrapolate WOLVERINE STATE data to the lifetime of ship operation applying the extrapolation method of weather grouping. Dalzell (21) concluded that the 5,000 intervals of SL-7 SEA-LAND McLEAN strain data were sufficient to subdivide the data beyond the weather grouping categories (i.e., into groups of ship heading, speed and wave height).

The sample size estimates for predicting the extent of data required to be statistically meaningful are presented in references 32, 33 and 34. The sample size estimates should be used prior to future full-scale tests. Generally the sample size for a future instrumentation program will most likely depend on factors other than strain rates. The precision and sample size required to define strain rates for ships inservice will depend on the future demand. Requirements for additional strain rate data should be specified in conjunction with other full-scale instrumentation programs.

5.2.7 Cost Estimates Required to Obtain Strain Rate Information in Conjunction with Other Full-Scale Tests

In anticipation of future full-scale instrumentation programs, it is only possible to estimate the additional cost involved in obtaining strain rate information in conjunction with another program with slightly different objectives. The additional expenses involved in obtaining strain rate information as part of a full-scale instrumentation program are incurred primarily from additional program management, data acquisition, data reduction and documentation. The strain gauges and data acquisition used for the full-scale instrumentation program should be compatible with the requirements for obtaining strain rates with adjustment of frequency ranges as required for strain rates. The costing was developed on a 1982 $/channel of strain rate data basis assuming a 3-season instrumentation program similar to the SL-7 SEA-LAND McLEAN program (12). The cost required to develop the additional data reduction software for determination of strain rates was estimated as a separate item. Once the data reduction software has been written the several channels of data may be reduced at little additional cost impact. Table 5-1 presents a breakdown of the cost estimate required to obtain strain rate information in conjunction with a 3-season full-scale instrumentation program. The bottom line cost is approximately $21,000/channel with approximately $5,000 required for the software development for data reduction and for the number of channels anticipated to obtain strain rates. The number of additional channels required for strain rates would vary from ship type to ship type (i.e., for containerships, tankers or bulk carriers). The number of channels needed for strain rate determination would range from 2 to 10 depending on the particular ship structural design.

6.0 CONCLUSIONS AND RECOMMENDATIONS

1. The evaluation of existing data from shipboard instrumentation programs indicates that it is feasible to obtain strain rate information from existing data; however, the existing data would require reprocessing before detailed analysis of the range of strain rates may be determined. The existing data from past shipboard instrumentation programs reviewed for this study were acquired by analog recording equipment with a reduction range from 0 to 50 Hz. It is unlikely that there were significant levels of strain eliminated by application of this frequency range. The levels of strain occurring at a frequency of greater than 50 Hz would be substantial in magnitude to affect material behavior.

TABLE 5-1

Approximate Additional Cost* to Determine Strain Rates in Conjunction With a Full-Scale Instrumentation Program

		Cost (1982 $)		
	Manhours	Labor	Materials/Travel	Total
<u>Additional Program Management</u>				
Test Planning	130	4160	1400	5560
General Engineering Support	40	1280	-	1280
<u>Additional Data Acquisition & Reduction</u>				
Instrumentation *Modification* (Increase in Frequency Range)	20	640	150	790
Reduction of Data	260	8320	-	8320
Computer Time	-	-	850	850
<u>Analysis of Data (Collate)</u>	140	4480	-	4480

$21,280/channel for 3 seasons of strain rate data.

*Costing Assumptions:

1. Cost information is in $/channel of strain rate data.
2. The cost is given for 3 seasons of data similar to the SL-7 instrumentation program.
3. The software development for determining strain rates from existing data would be a fixed cost regardless of the number of channels; 160 Manhours, $5120 Labor Total.

2. There are significant gaps in the eixsting shipboard strain data with respect to determining the range of strain rates. These gaps include strain data from collisions and environmental wave data required to validate analytical techniques that may be used in predicting the range of strain rates in ship hull structures. The validation of analytical predictions of strain rates should remain a long-term goal after the techniques for predicting strain in the time domain have been validated.

3. Preliminary estimates of strain rates from existing data indicate that ship service experience produces strain rates up to 10^{-3} in/in/sec. This order of magnitude information is comparable in accuracy with the order of magnitude of strain rates reported for current material toughness testing techniques. The effects of calculating the strain rate from separated signals (separated by filtering) was investigated as part of this study. The results of the preliminary calculations indicated that estimates of strain rate from combined or separated signals were generally similar in magnitude; however, this conclusion needs to be reviewed for each specific case.

4. Several observations are presented below which pertain to the preliminary calculation and collation of strain rate information. They are:

   a) Strain rates induced by the encounter of waves varies according to ship type and structural location from amidship and areas of stress concentration.

   b) Strain rates induced by encountered waves vary with the magnitude of wave height as well as encounter frequency and ship heading.

   c) Strain rates induced by high frequency transient responses are generally larger in magnitude than the strain caused by the encounter of waves.

   d) Strain rates induced by high frequency transient loads are related to strain magnitude and in many instances wave magnitude. The frequency of transient strains (such as whipping and springing) is nearly constant and dependent on the first mode of structural response for given ship types.

5. The strain rates produced by ship service loadings are variable in nature. For example, strain rates produced by ship hull girder whipping are quite variable for levels of strain excursion. The variability of strain rates for given strain excursion from service experience differs from the strain rates produced by current material toughness tests for given strain excursions. If the development of material classification criteria is pursued to a more detailed level than currently exists, the material testing techniques will require reevaluation and possible modifiation to

produce variable strain rates that are comparable with those experienced by ships in service.

6. An extensive instrumentation program geared solely toward obtaining strain rate information is not warranted at this time. In the event that strain rate information is required as material testing techniques are updated, the strain rate information may be obtained in an economical manner in conjunction with other future instrumentation programs.

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APPENDIX A

Stress Time Histories Used for Preliminary Calculations of Strain Rates

The following figures present samples of stress time histories used to obtain preliminary calculations of strain rates. The data reduction procedures used to obtain preliminary strain rates from the stress time histories is described in Section 4.1 of the report.

Figures A-1 through A-4 show stress time histories of longitudinal vertical bending measured on the SL-7 SEA-LAND McLEAN rising the midship stress gauge as a point of reference and stress inferred from measured strain at forward hatch corners (R and F gauges) and hatch corners just forward of the aft deck lounge (A and S gauges). The stress time histories presented in Figures A-1 through A-4 were obtained from Reference 20. The collation information of observed wave height, relative wave direction (degrees from the bow, port or starboard) and ship speed are indicated in the figures.

Sample stress time histories of data measured on the SL-7 SEA-LAND McLEAN during the second season were obtained from Mr. Dalzell at Stevens Institute of Technology. These stress time histories originally appeared in SSC-287 (21) and are presented in Figure A-5 through A-12. The sample stress time histories are 70 second samples obtained from 20-minute interval data. Preliminary estimates of strain rates were obtained from the information presented in Figures A-5 through A-12 and presented in Appendix B along with collation information indicated on summary sheets obtained from Teledyne Engineering Services, Inc.

Several oscillograph records (stress time histories) of midship vertical bending stress from the SL-7 SEA-LAND McLEAN data were analyzed for strain rates. These stress time histories were not included in this Appendix because the light sensitive oscillograph records cannot be reproduced by copying techniques. However, the results of the strain rates are reflected in the observations presented in Table 4-2.

Stress time histories as measured on the STEWART J. CORT and obtained from reference 15 are presented in Figure A-13 through A-24. The springing response is evident in the stress time histories. The effects of springing response as related to strain rates have been discussed in Section 4.3 of the report. The strain rates obtained from the stress time histories are presented in Appendix B and collated with appropriated environmental information.

Stress time histories measured on the UNIVERSE IRELAND and FOTINI L during cargo loading observations were obtained from Reference 6 and are presented in Figures A-25 and A-26. The strain rates induced by the loading conditions were mentioned in Section 4.2 of the report and are not generally of interest to material classification.

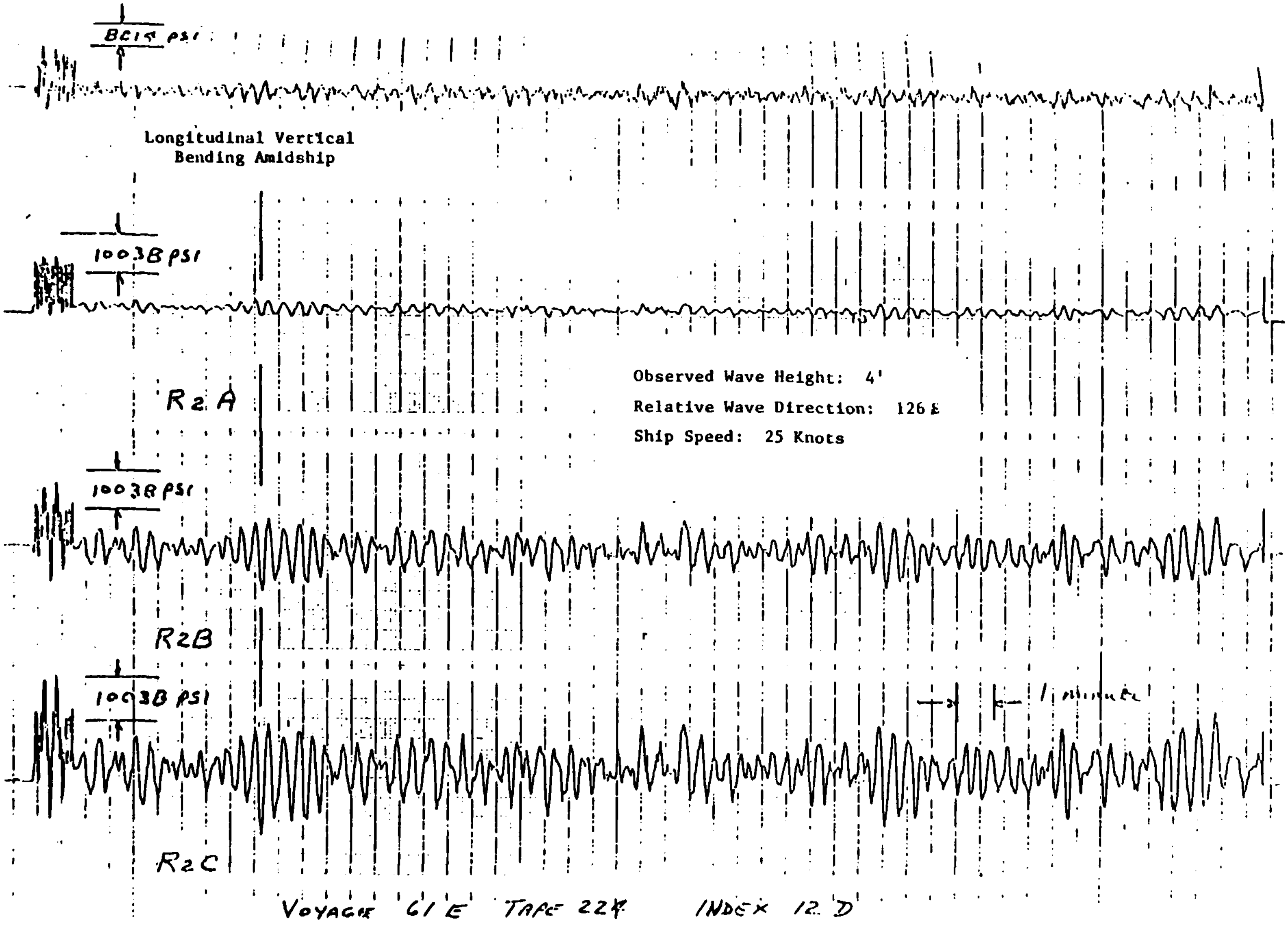
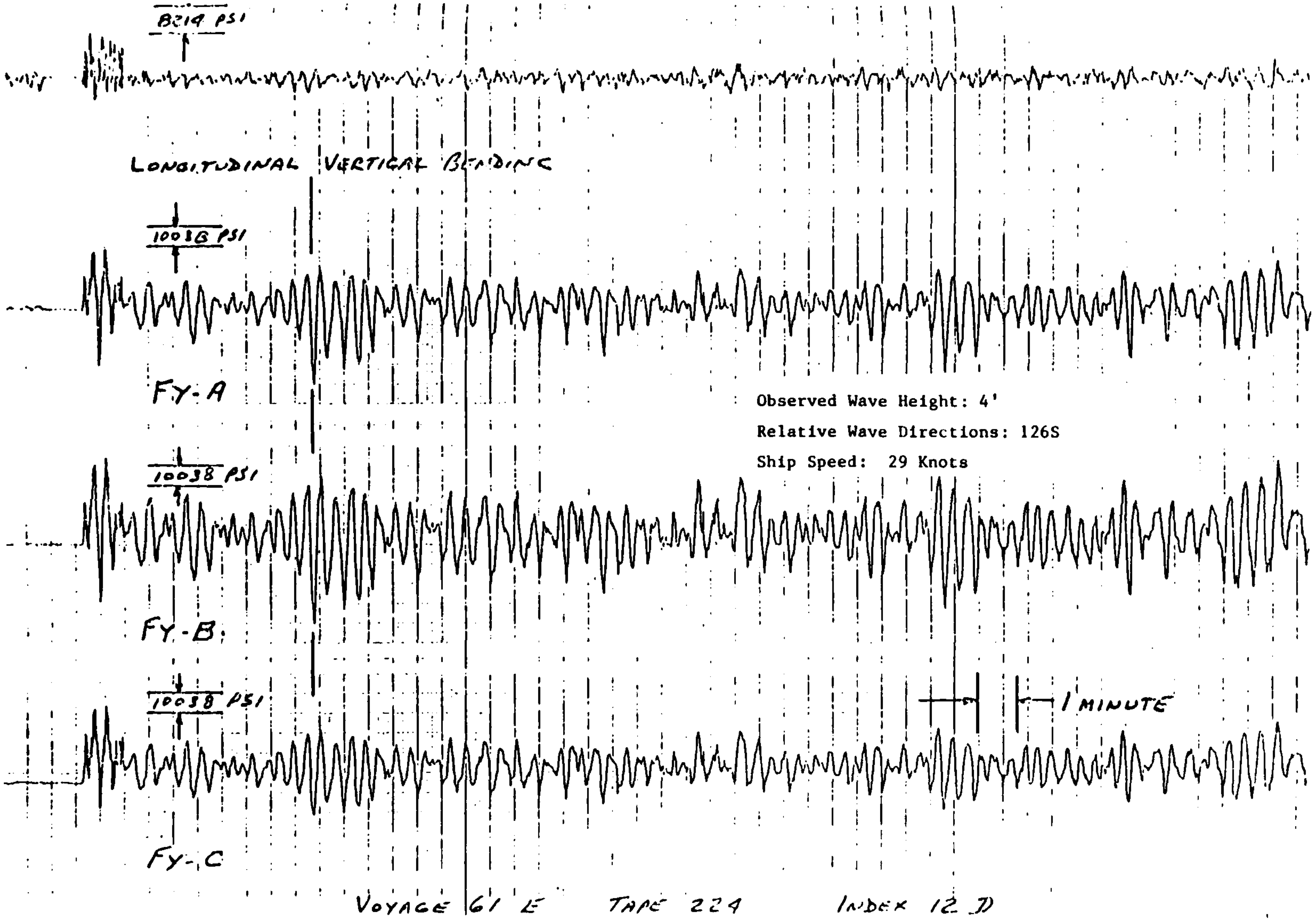


Figure A-1 SL-7 SEA-LAND McLEAN, Stress Measured at the Forward Hatch Corner by a 3 Arm Rosette R_2A, R_2B, R_2C

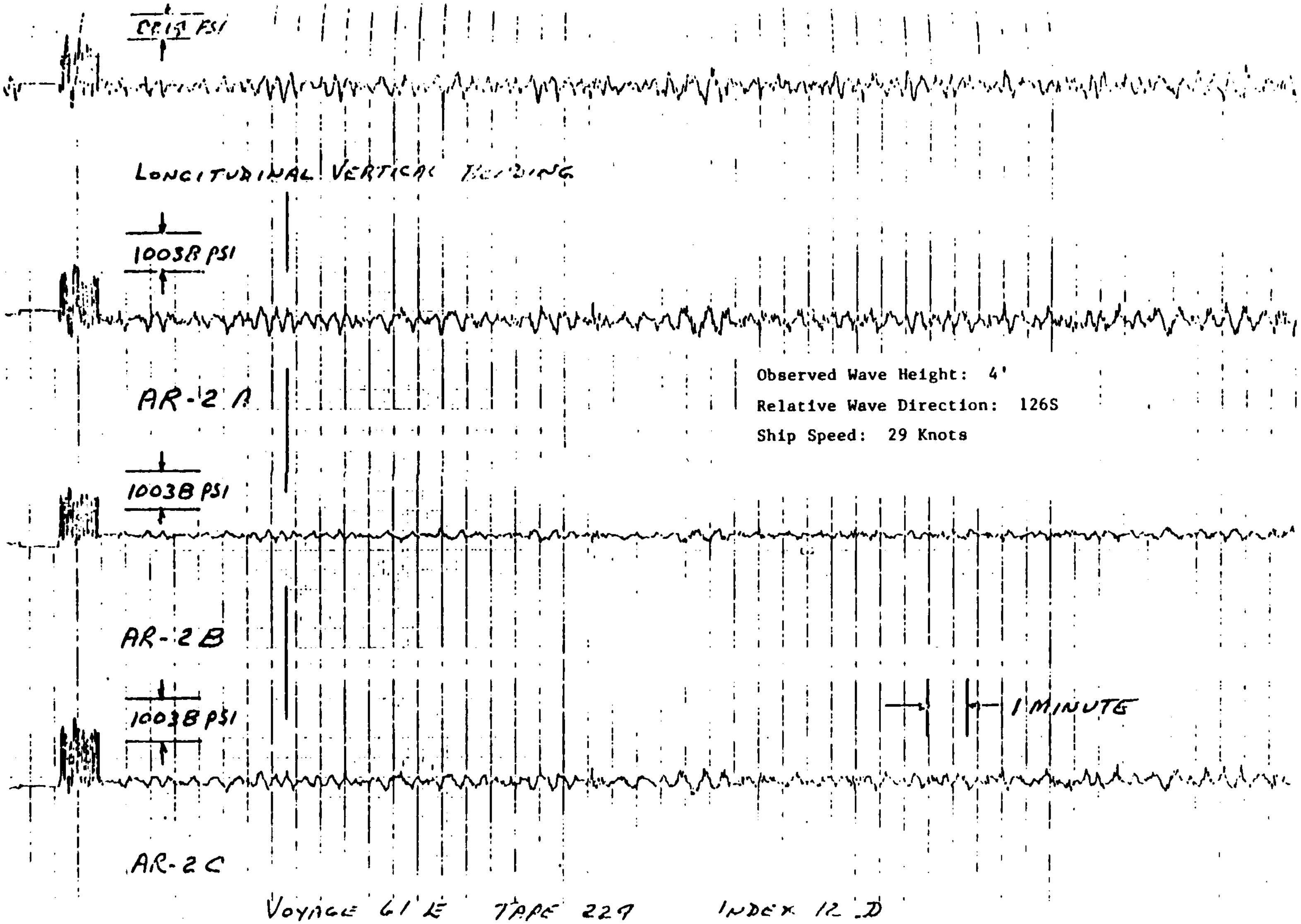


Observed Wave Height: 4'

Relative Wave Directions: 126S

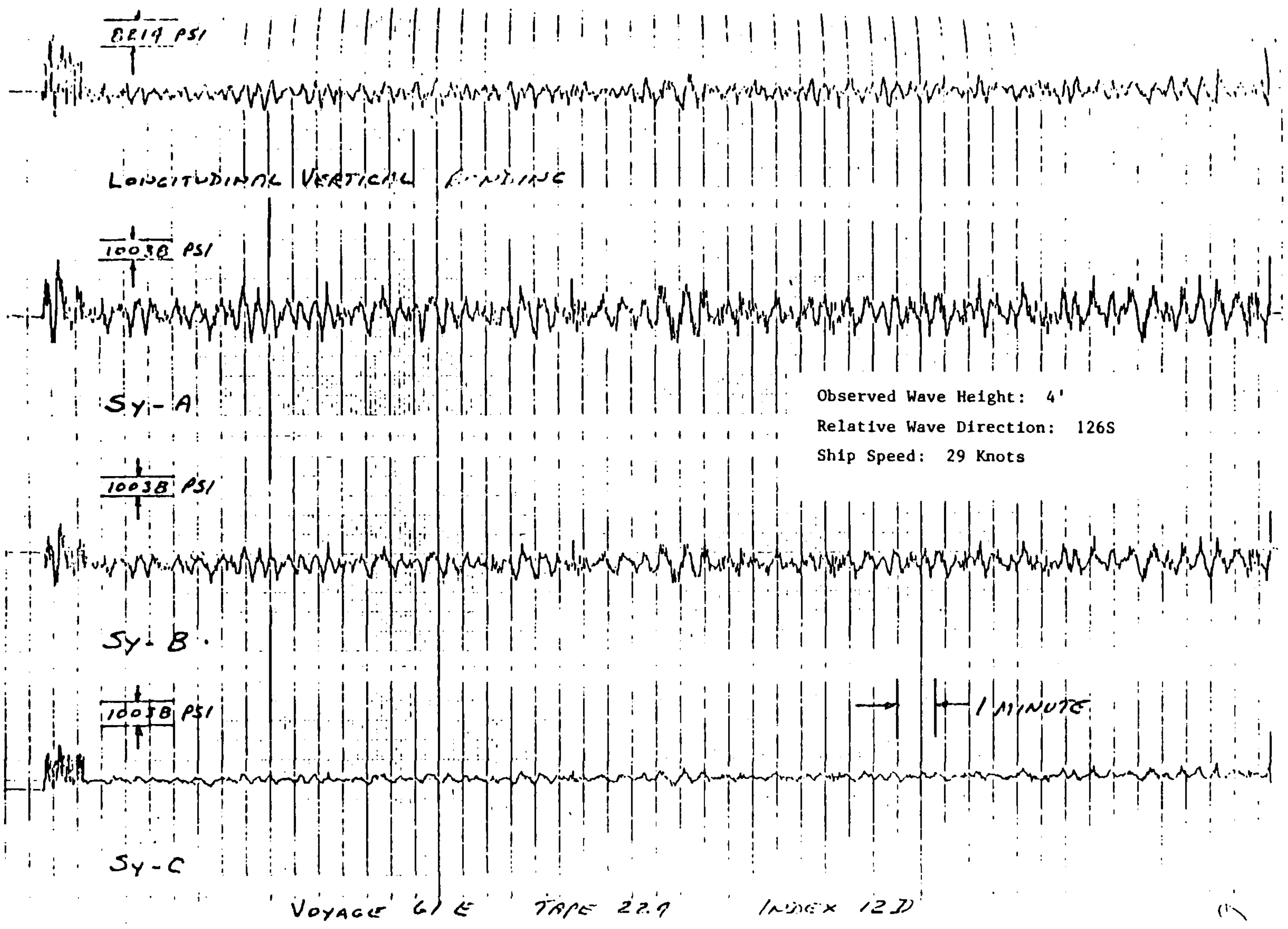
Ship Speed: 29 Knots

Figure A-2 SL-7 SEA-LAND McLEAN, Stress Measured at the Forward Hatch Corner Cut Out



Observed Wave Height: 4'
Relative Wave Direction: 126S
Ship Speed: 29 Knots

Figure A-3 SL-7 SEA-LAND McLEAN, Stress Measured at the Hatch Corner Just Forward of the Aft House



Observed Wave Height: 4'
Relative Wave Direction: 126S
Ship Speed: 29 Knots

Figure A-4 Stress Measured at the Cut Out Hatch Just Forward of the Aft House

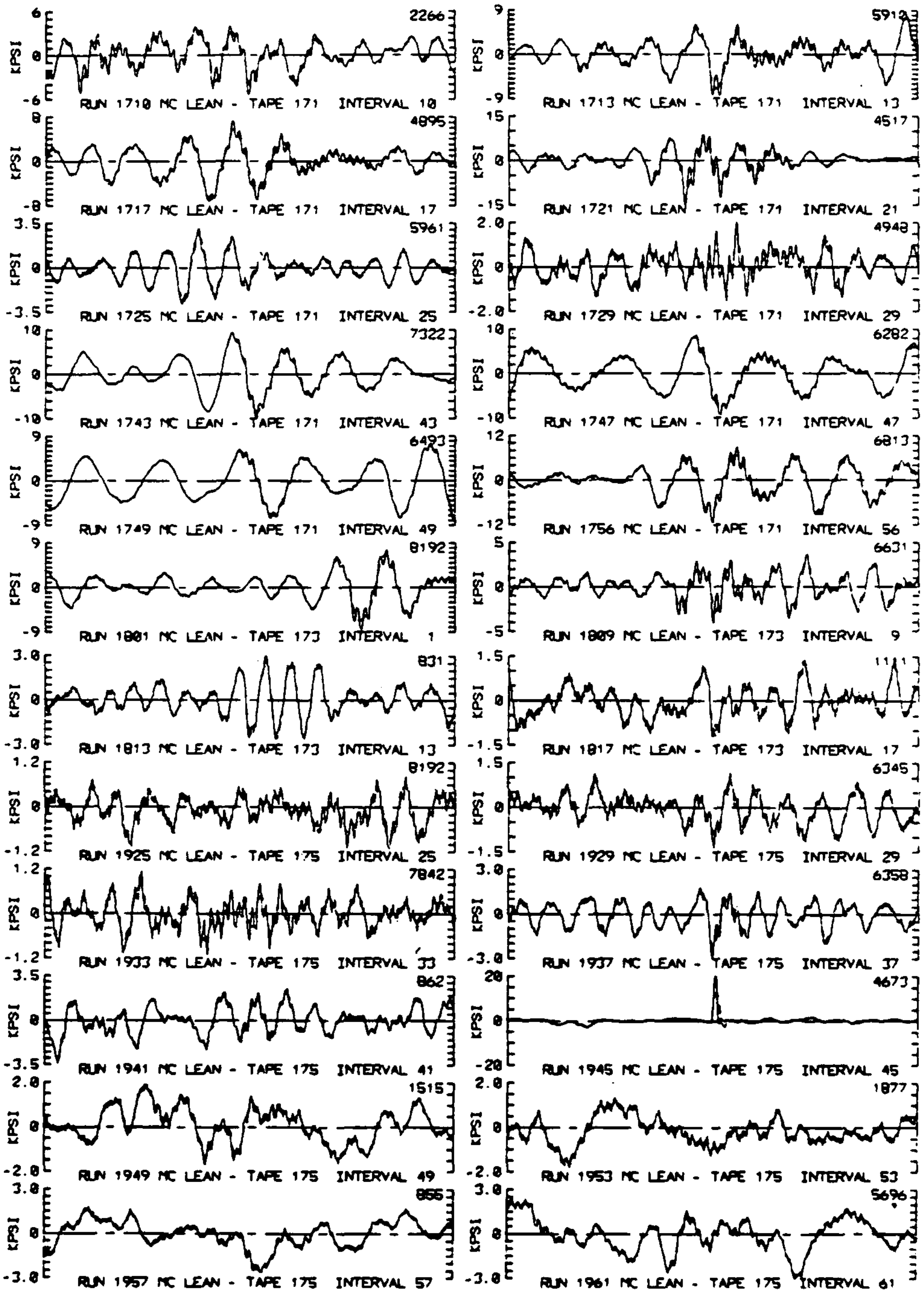


Figure A-5 Sample Time Histories, SL-7 Data Subset

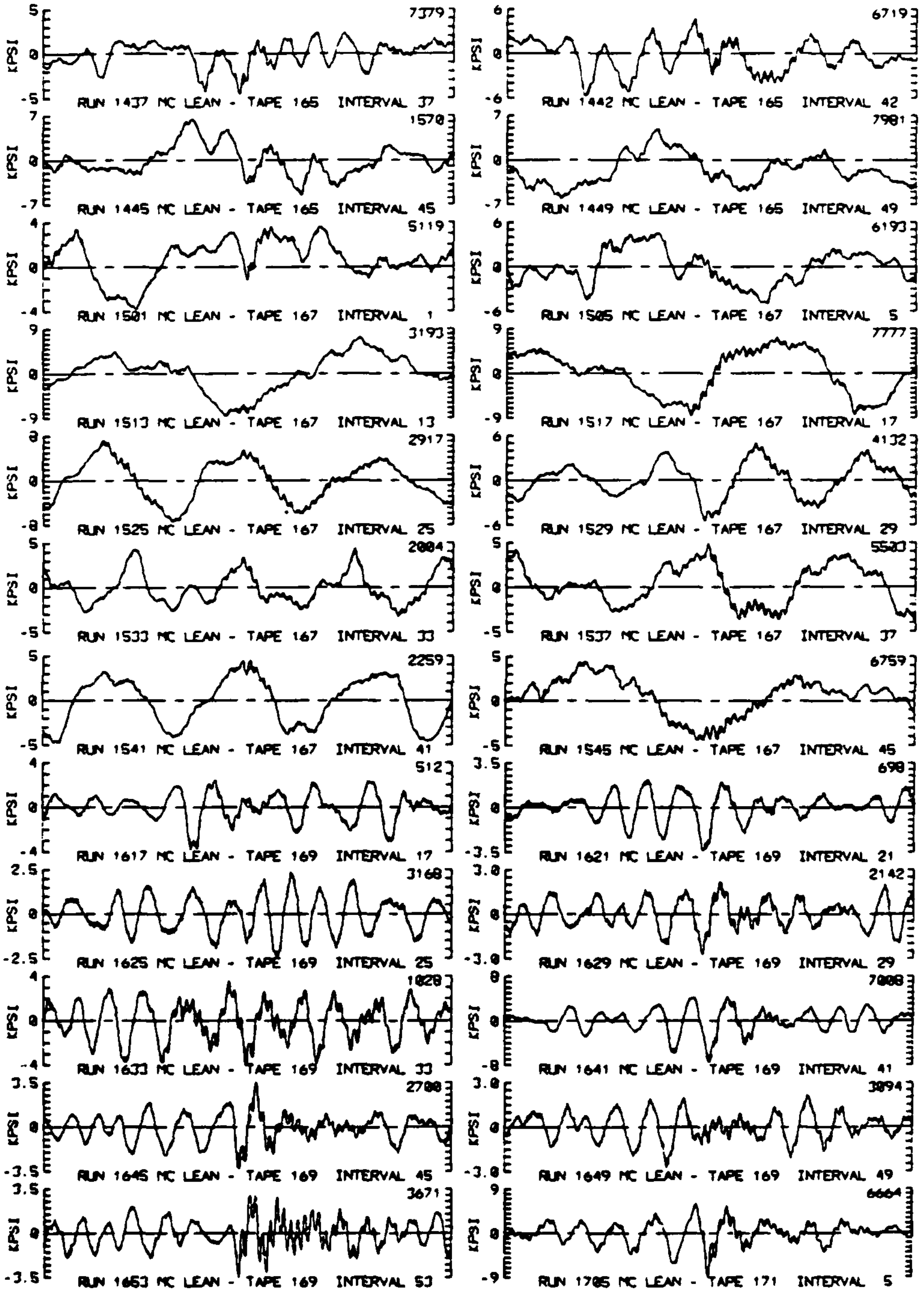


Figure A-6 Sample Time Histories, SL-7 Data Subset

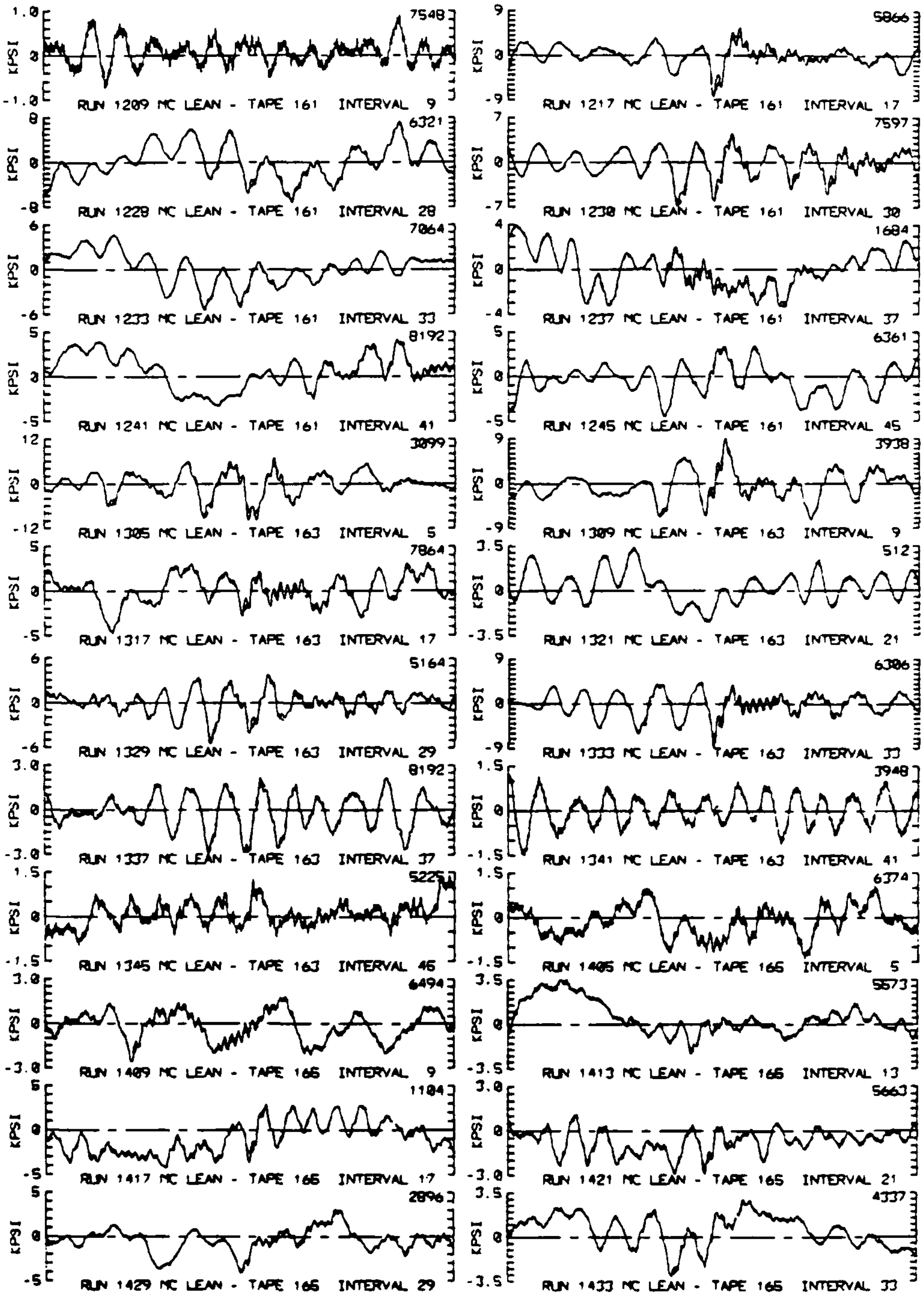


Figure A-7 Sample Time Histories, SL-7 Data Subset

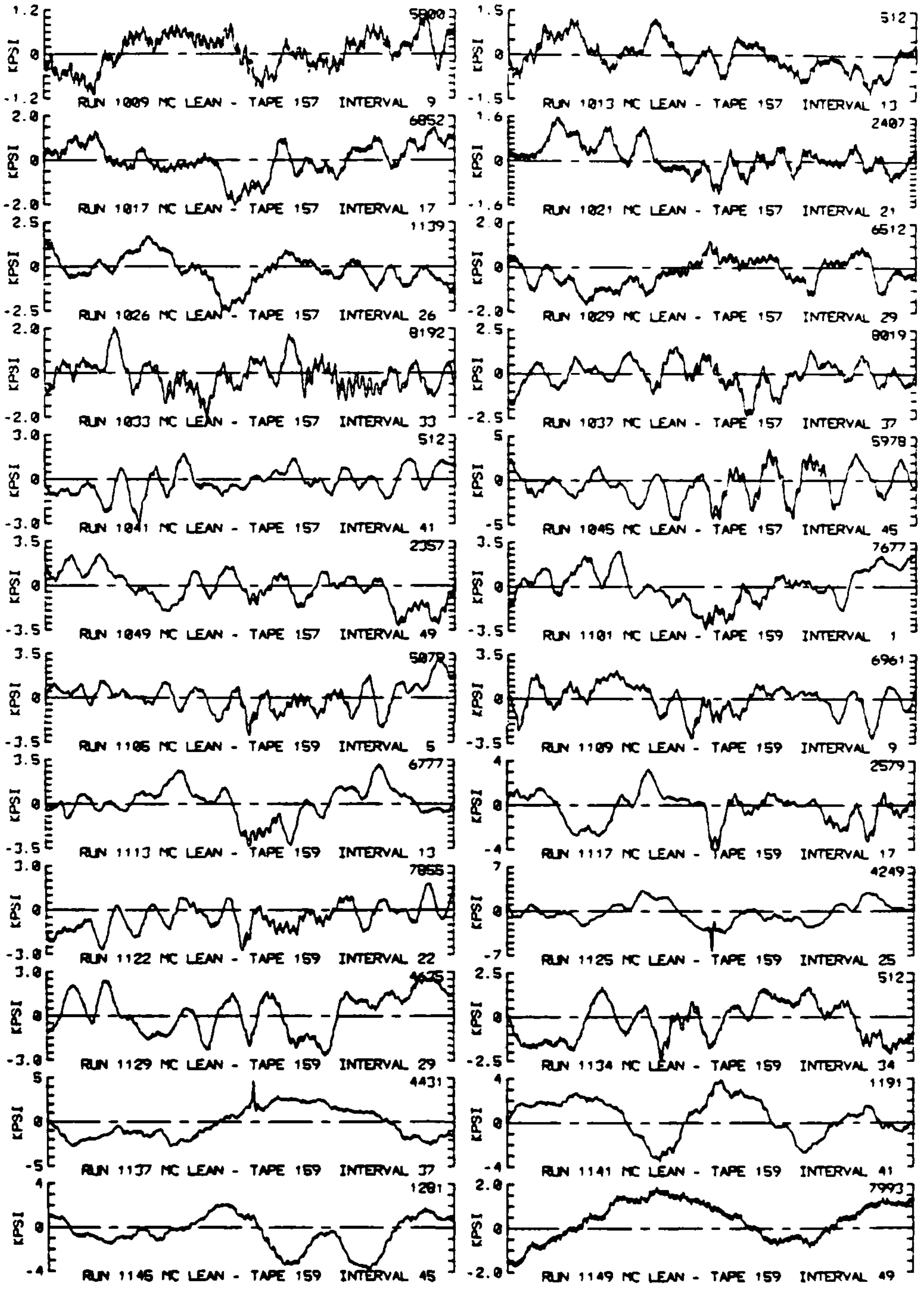


Figure A-8 Sample Time Histories, SL-7 Data Subset

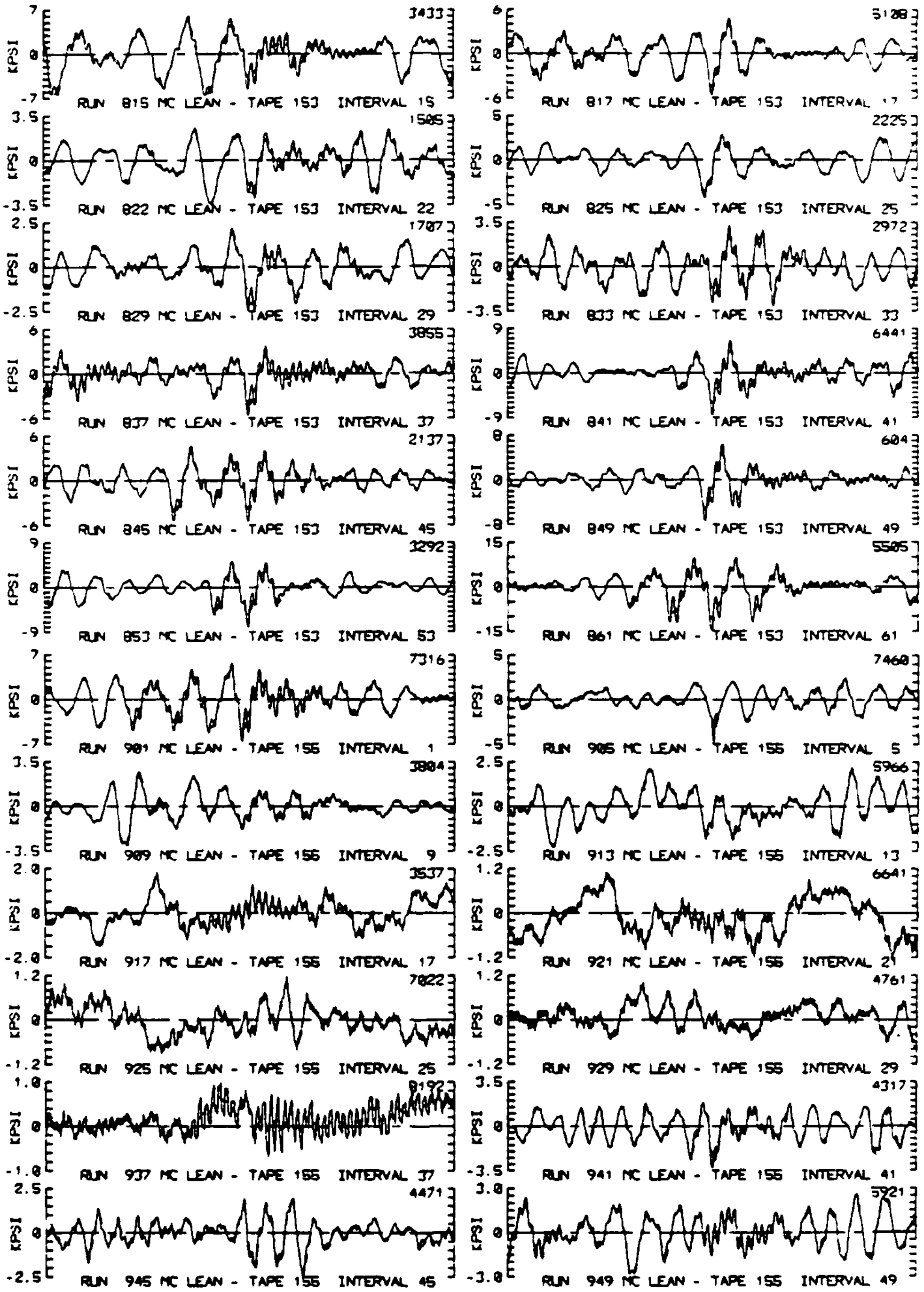


Figure A-9 Sample Time Histories, SL-7 Data Subset

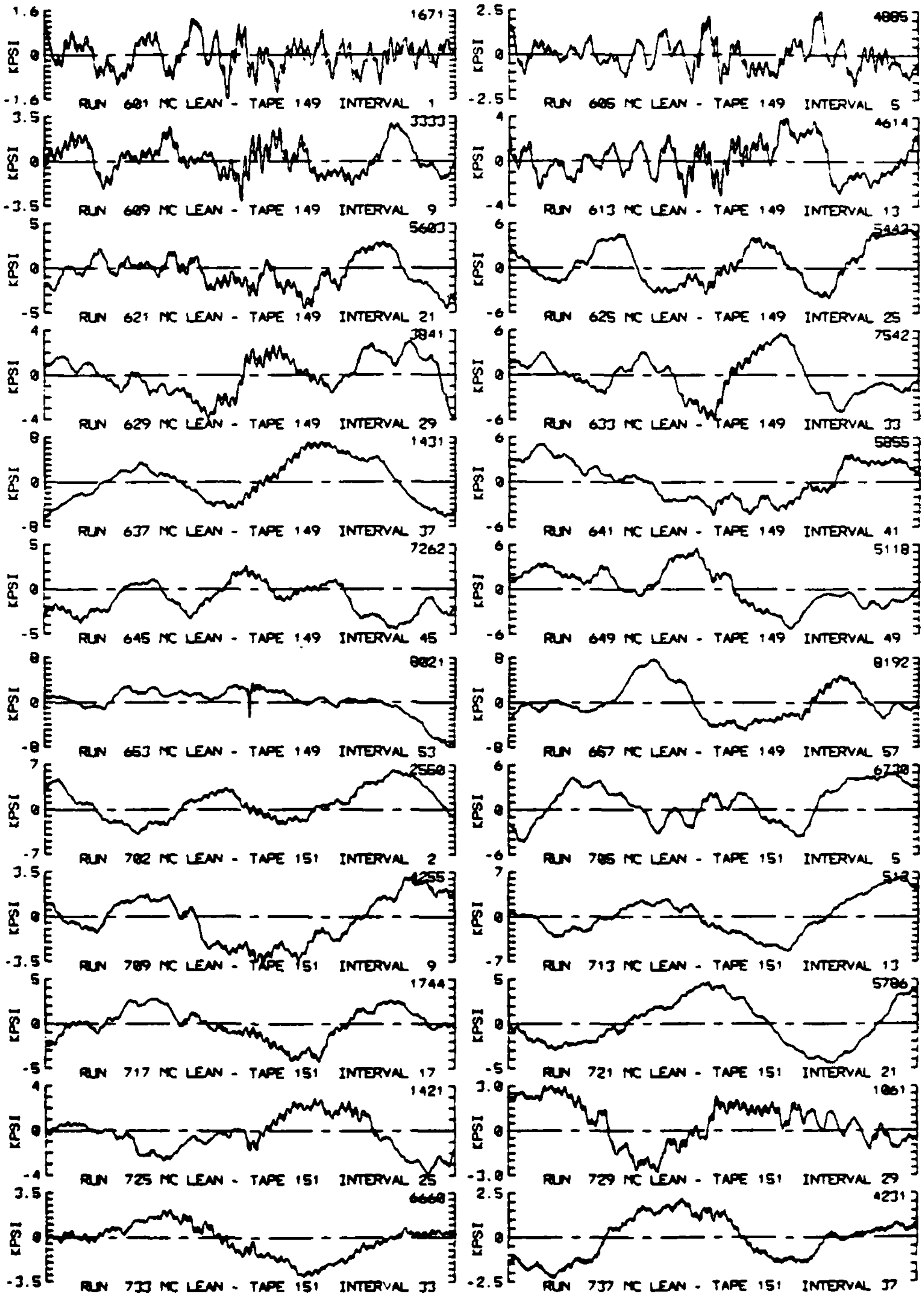


Figure A-10 Sample Time Histories, SL-7 Data Subset

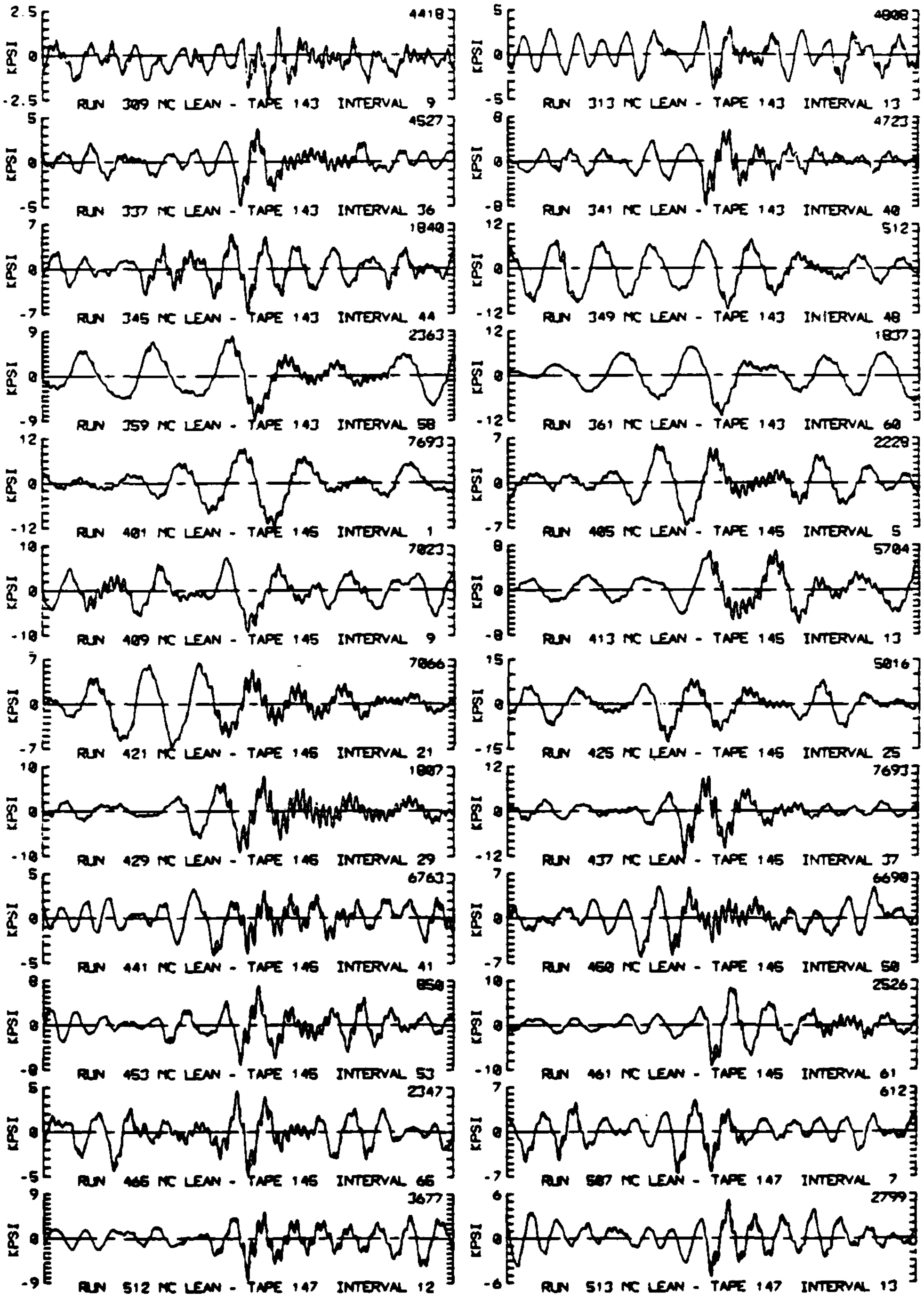


Figure A-11 Sample Time Histories, SL-7 Data Subset

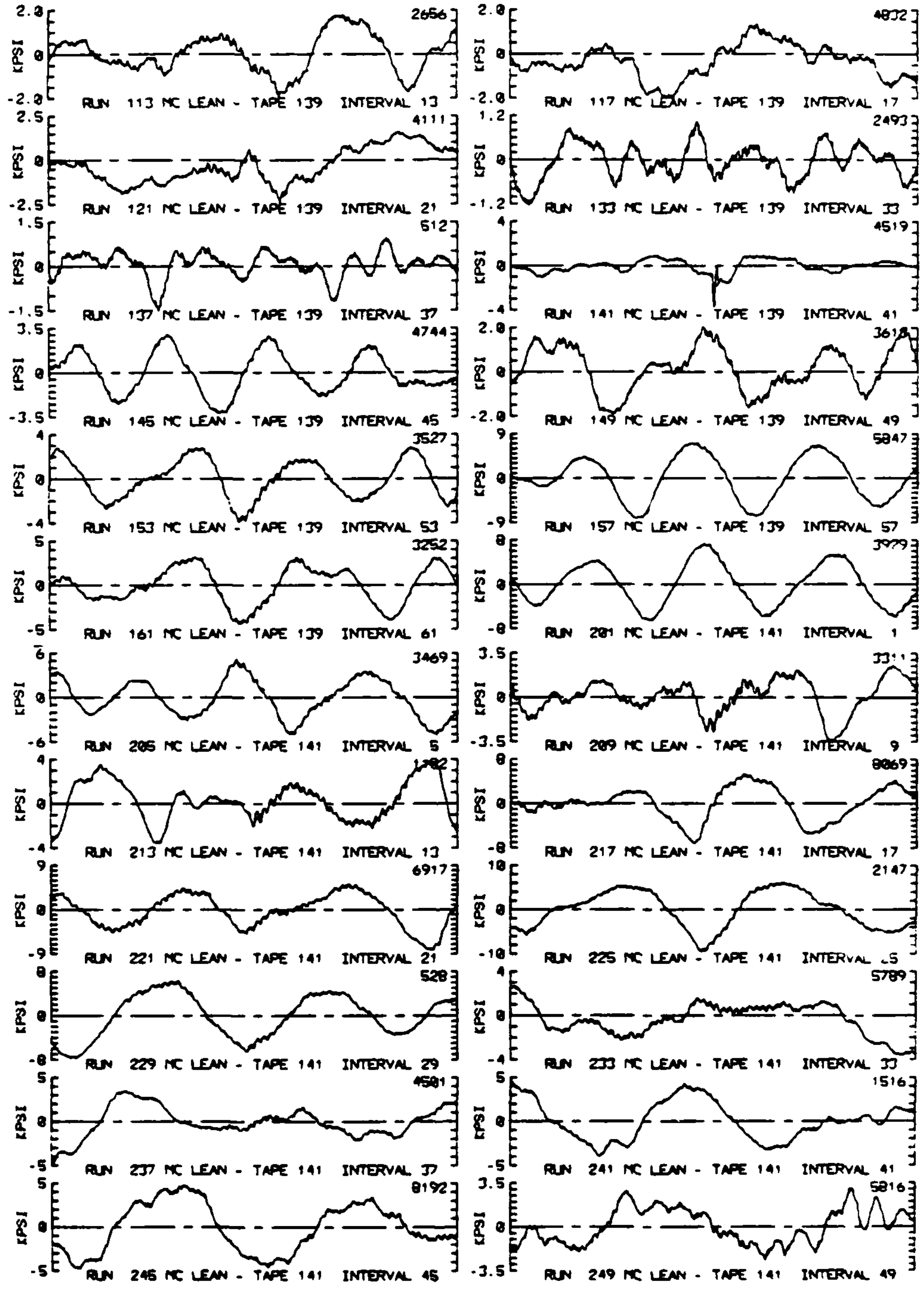
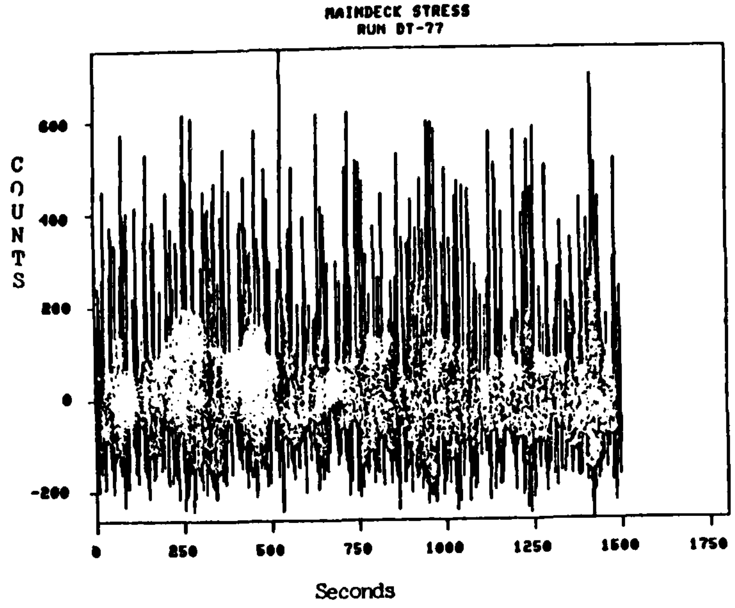


Figure A-12 Sample Time Histories, SL-7 Data Subset

CONDITION 1

```
M/V S J CORT FALL TRIALS
          RUN              77          POINT          29
          DATE  .16-NOV-79             TIME     10:26:41
          DURATION OF RUN IN MINUTES IS          25.000
          NORTH LATITUDE (DD MM)            47 15
          WEST LONGITUDE (DD MM)            89 20
          VESSEL'S SPEED (MPH - XX.X)     14.4
          VESSEL'S HEADING (DEGREES)       236
          VESSEL'S DRAFT (FEET)              19
          WIND DIRECTION (DEGREES)         240
          WIND SPEED (KNOTS)                 29
          WAVE DIRECTION (DEGREES)         230
          WAVE HEIGHT (FEET)                  6
REMARKS
SUPERIOR UPBND. FULL BALLAST
WEST OF KEEWEENAW. LSI CLOCK

End-of-run message
NONE
```



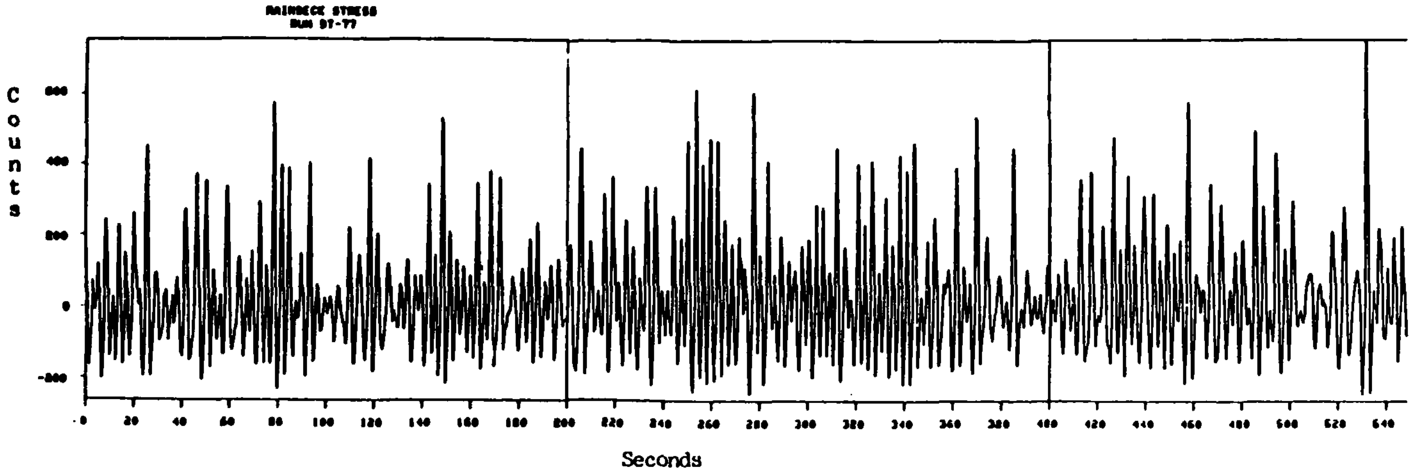


Figure A-13 Stress Time History Measured on the STEWART J. CORT

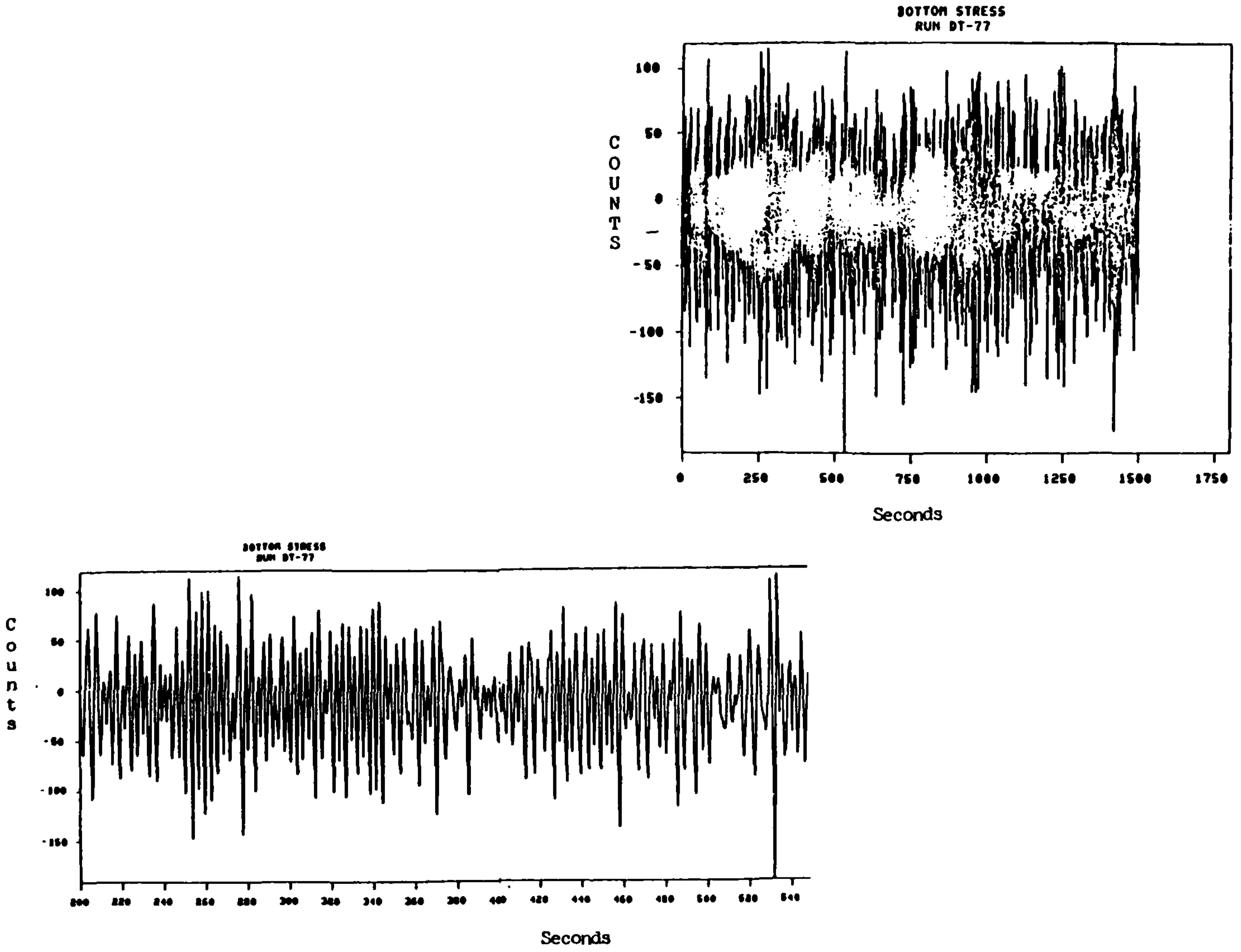
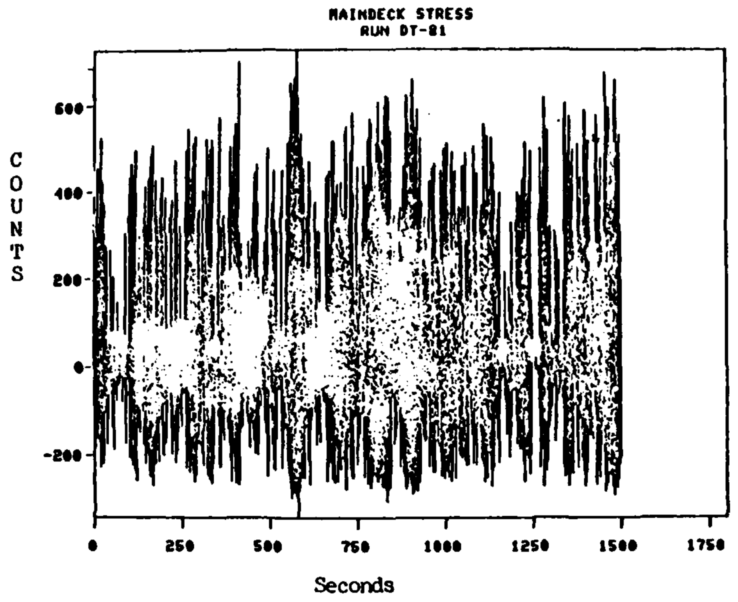


Figure A-14 Stress Time History Measured on the STEWART J. CORT

CONDITION 2

```
R/V S J CORT FALL TRIALS
          RUN              81 .        POINT        5
          DATE    16-NOV-79            TIME   12:47:34
          DURATION OF RUN IN MINUTES IS          25.000
          NORTH LATITUDE (DD MM)             47 15
          WEST LONGITUDE (DD MM)             90 15
          VESSEL'S SPEED (MPH - XX.X)      14.4
          VESSEL'S HEADING (DEGREES)        256
          VESSEL'S DRAFT (FEET)              28
          WIND DIRECTION (DEGREES)          240
          WIND SPEED (KNOTS)                 29
          WAVE DIRECTION (DEGREES)          245
          WAVE HEIGHT (FEET)                  6
REMARKS
UPBND SUPERIOR WEST OF KEEWEENAW
LSI CLOCK

End-of-run message
```



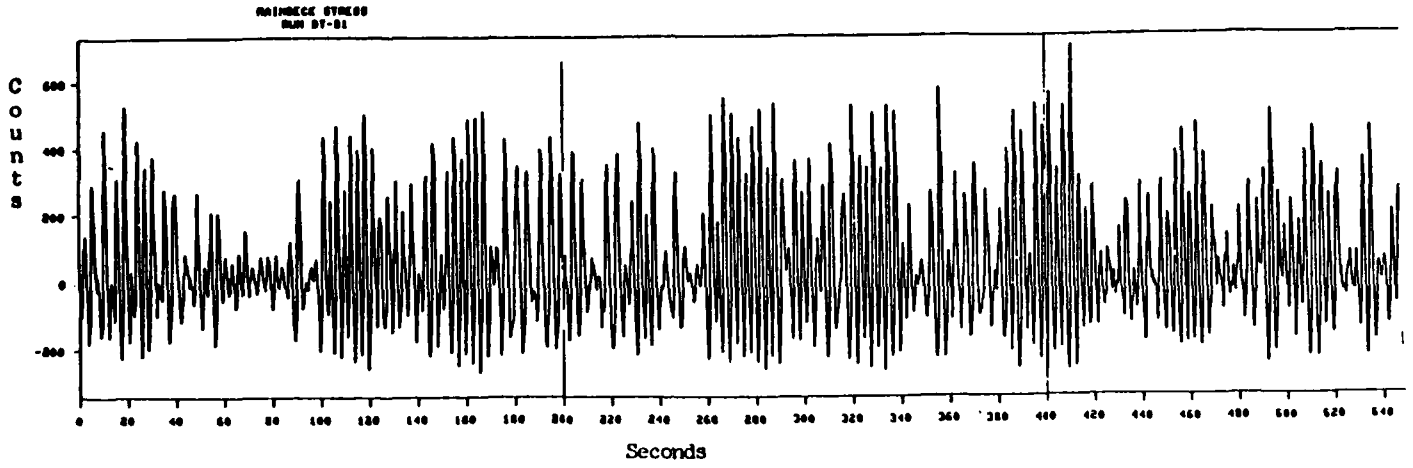
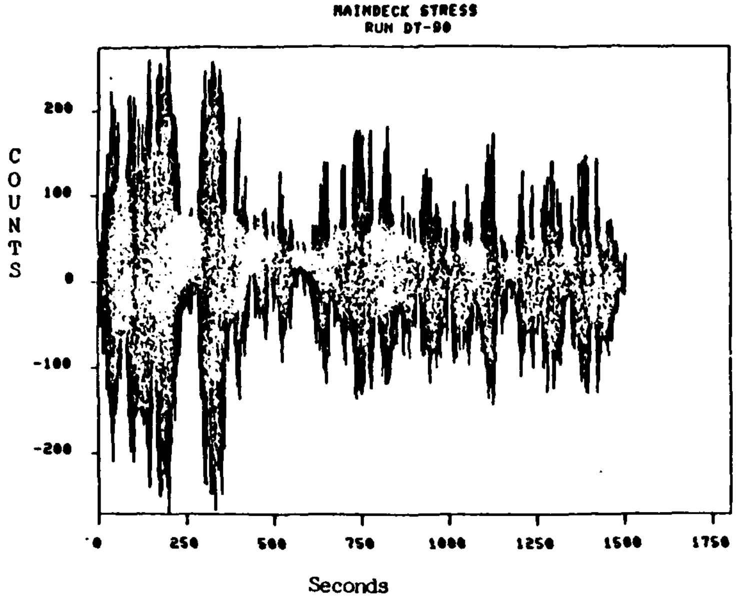


Figure A-15 Stress Time History Measured on the STEWART J. CORT

CONDITION 3

```
M/V S J CORT FALL TRIALS
          RUN              90          POINT          23
          DATE   18-NOV-79             TIME     15:22:45
          DURATION OF RUN IN MINUTES IS          25.000
          NORTH LATITUDE (DD MM)              46 55
          WEST LONGITUDE (DD MM)              85 25
          VESSEL'S SPEED (MPH - XX.X)       14.7
          VESSEL'S HEADING (DEGREES)         114
          VESSEL'S DRAFT (FEET)               27
          WIND DIRECTION (DEGREES)           130
          WIND SPEED (KNOTS)                  16
          WAVE DIRECTION (DEGREES)           120
          WAVE HEIGHT (FEET)                   3
REMARKS
SUPERIOR UPBND, NORTH OF CRISP POINT, HEAD SEA
LSI CLOCK

End-of-run message
```



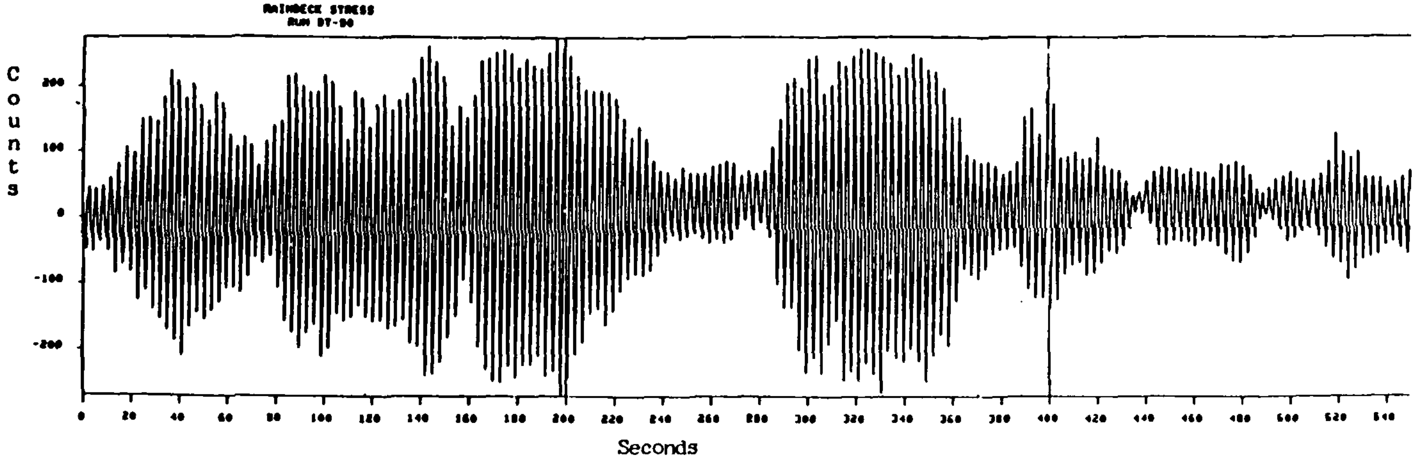


Figure A-16 Stress Time History Measured on the STEWART J. CORT

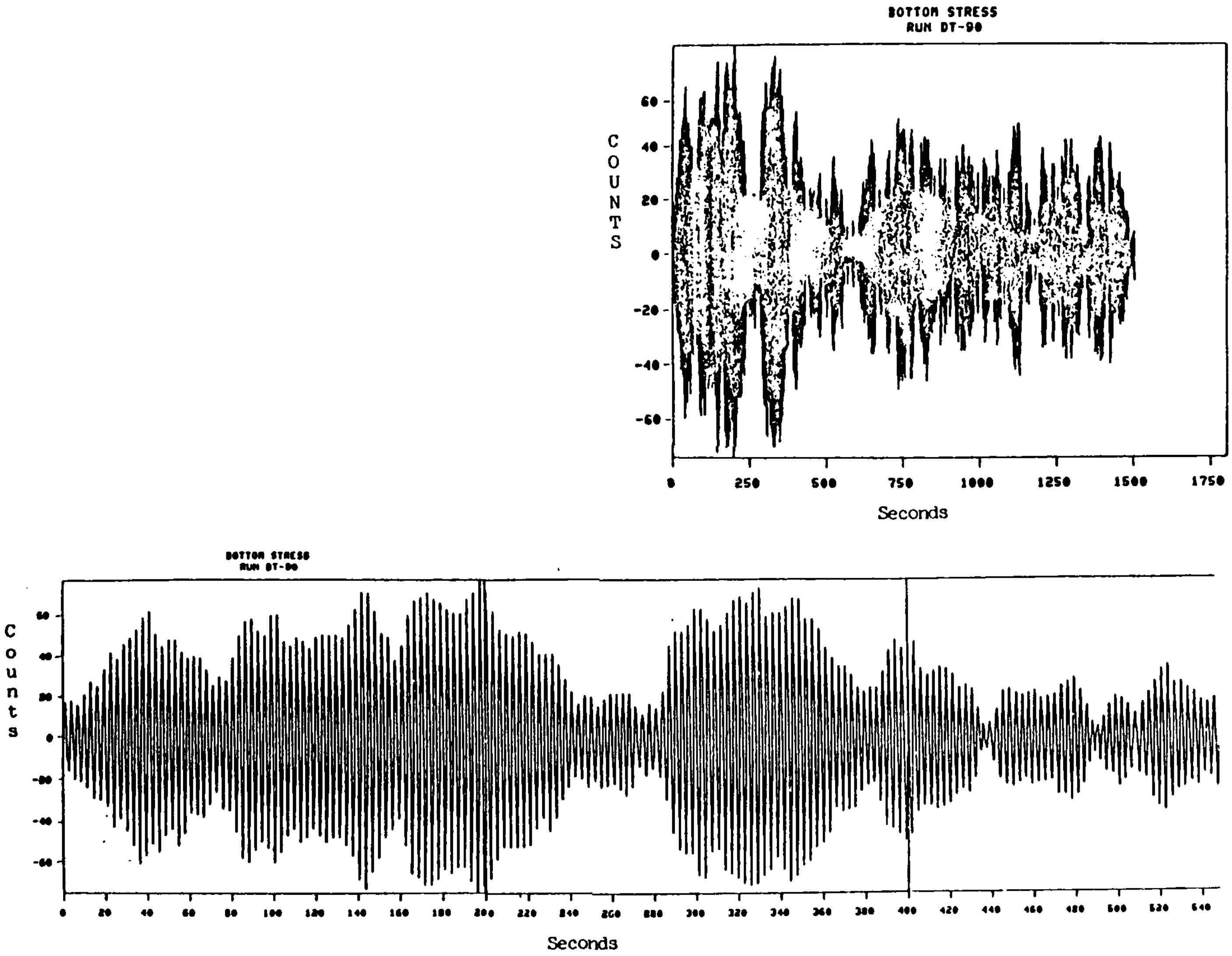
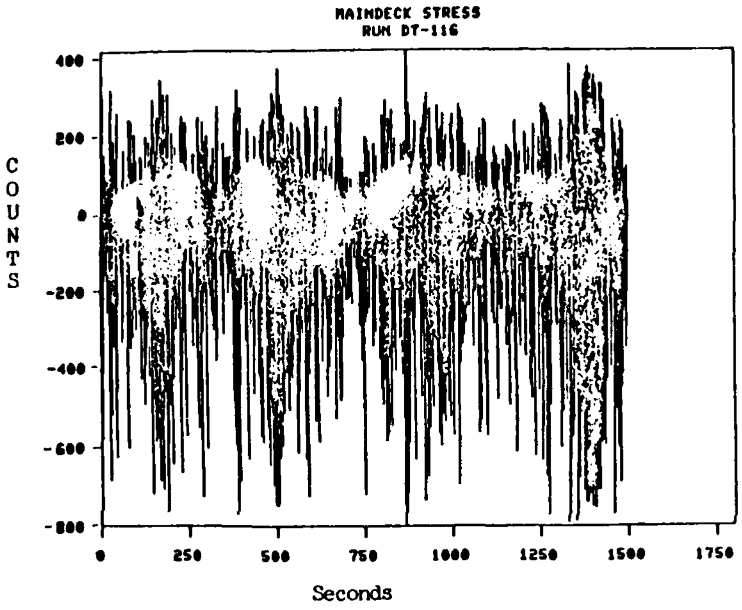


Figure A-17 Stress Time History Measured on the STEWART J. CORT

CONDITION 5

```
R/V S J CORT FALL TRIALS
          RUN            116          POINT          13
          DATE   09-DEC-79            TIME    13:42:01
          DURATION OF RUN IN MINUTES IS          25.000
          NORTH LATITUDE (DD MM)             87  7
          WEST LONGITUDE (DD MM)             44  8
          VESSEL'S SPEED (MPH - XX.X)      13.5
          VESSEL'S HEADING (DEGREES)        189
          VESSEL'S DRAFT (FEET)              27
          WIND DIRECTION (DEGREES)          247
          WIND SPEED (KNOTS)                 18
          WAVE DIRECTION (DEGREES)          212
          WAVE HEIGHT (FEET)                  4
REMARKS
MICHIGAN SNDNG, HEAD/BOW SEA, HEAD PRED
SEA DYING

End-of-run message
```



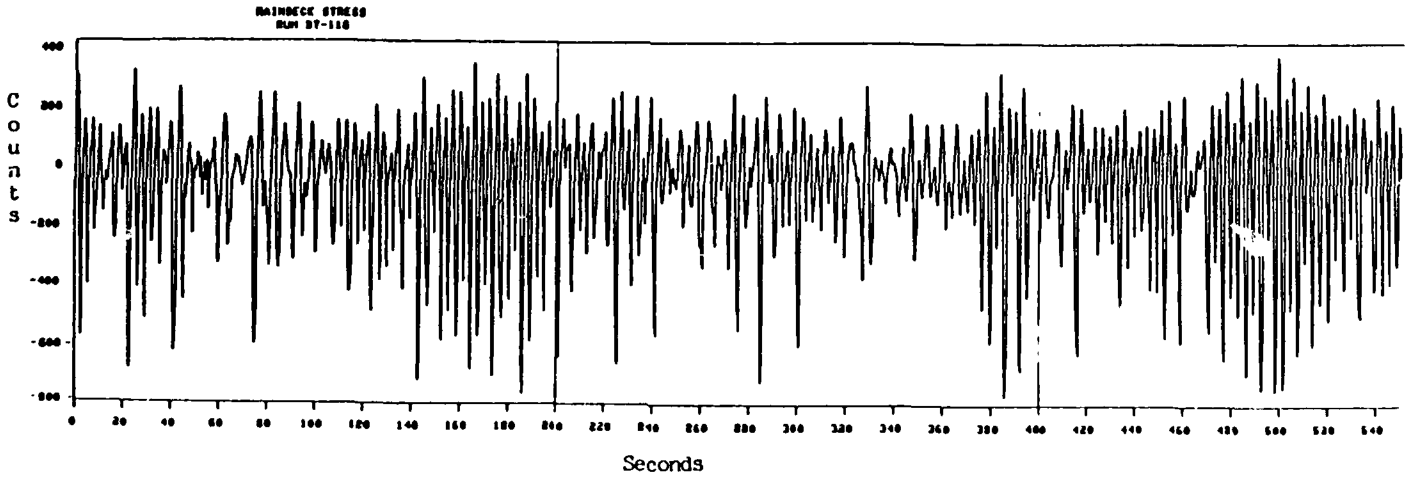
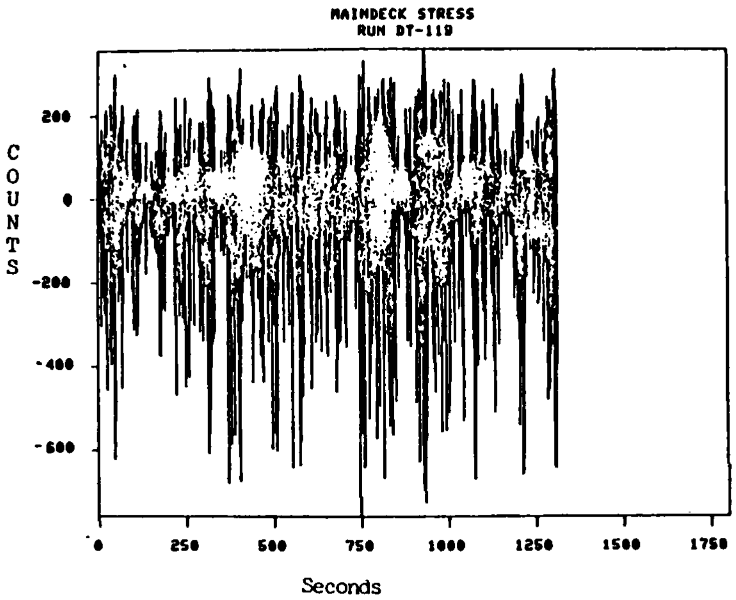


Figure A-18 Stress Time History Measured on the STEWART J. CORT

CONDITION 4

```
M/V S J CORT FALL TRIALS
          RUN          119          POINT        21
          DATE   09-DEC-79          TIME   13:50:07
          DURATION OF RUN IN MINUTES IS         25.000
          NORTH LATITUDE (DD MM)            86 52
          WEST LONGITUDE (DD MM)            43  9
          VESSEL'S SPEED (MPH - XX.X)      14.2
          VESSEL'S HEADING (DEGREES)        189
          VESSEL'S DRAFT (FEET)              27
          WIND DIRECTION (DEGREES)          209
          WIND SPEED (KNOTS)                 10
          WAVE DIRECTION (DEGREES)          190
          WAVE HEIGHT (FEET)                  3
REMARKS
MICHIGAN SBDNB,HEAD SEA
2-3 FT SWELL
```



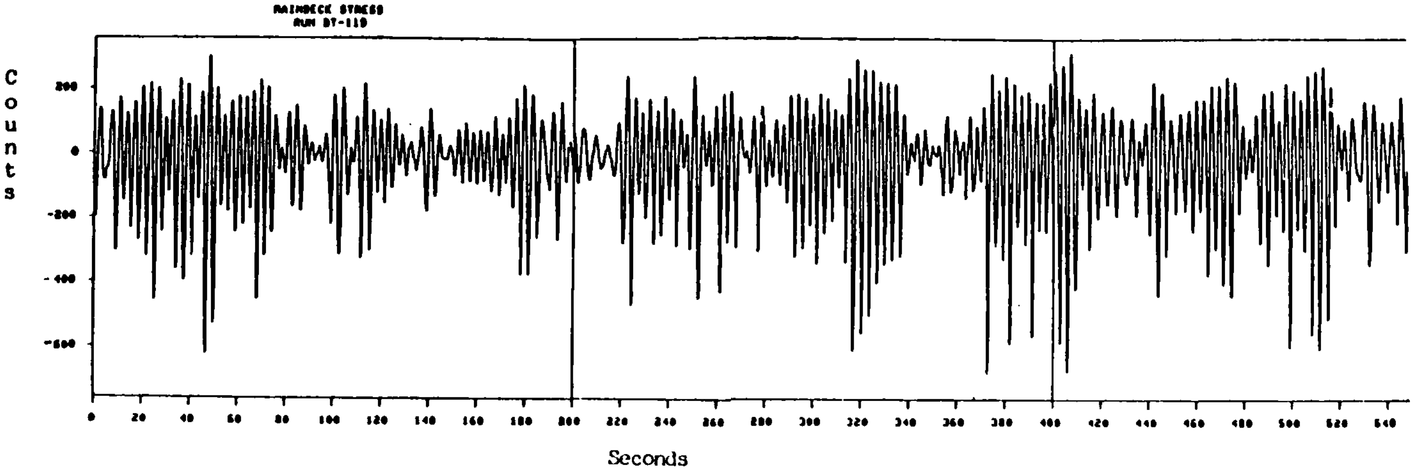
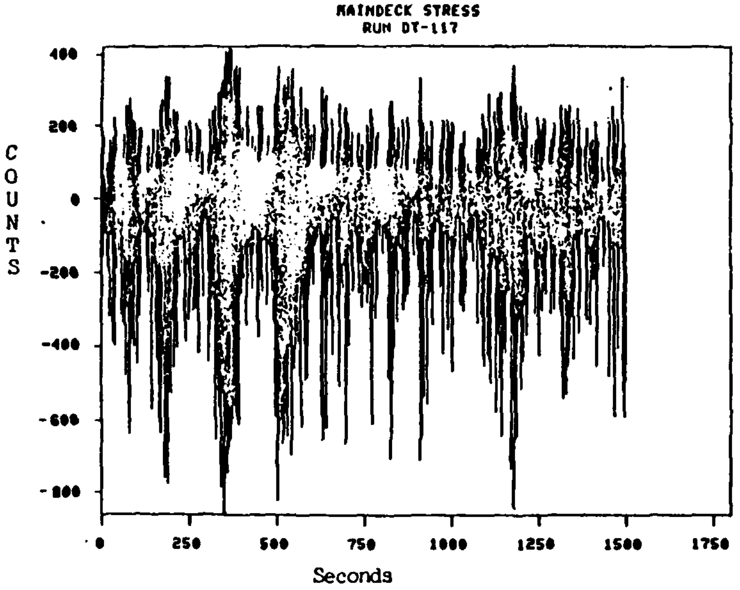


Figure A-19 Stress Time History Measured on the STEWART J. CORT

CONDITION 6

```
M/V S J CORT FALL TRIALS
          RUN            117          POINT          17
          DATE    09-DEC-79           TIME     15104156
          DURATION OF RUN IN MINUTES IS          25.000
          NORTH LATITUDE (DD MM)             87 13
          WEST LONGITUDE (DD MM)             43 20
          VESSEL'S SPEED (MPH - XX.X)      13.5
          VESSEL'S HEADING (DEGREES)       188
          VESSEL'S DRAFT (FEET)              27
          WIND DIRECTION (DEGREES)         263
          WIND SPEED (KNOTS)                 14
          WAVE DIRECTION (DEGREES)         190
          WAVE HEIGHT (FEET)                  3
REMARKS
MICHIGAN SOBND.HEAD SEA
2-3 FT SWELL

End-of-run message
```



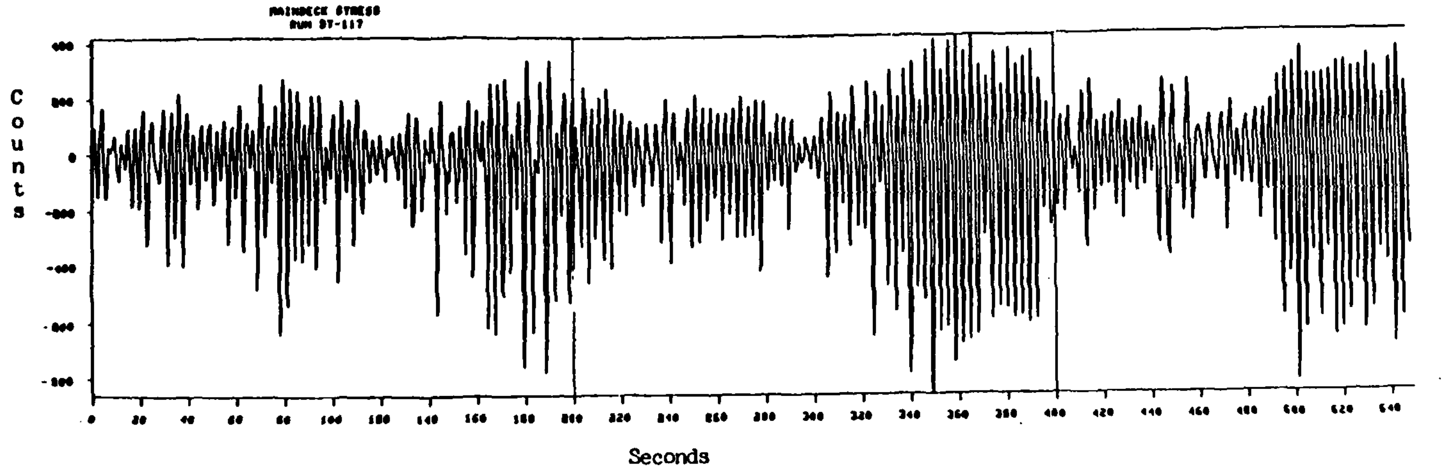


Figure A-20 Stress Time History Measured on the STEWART J. CORT

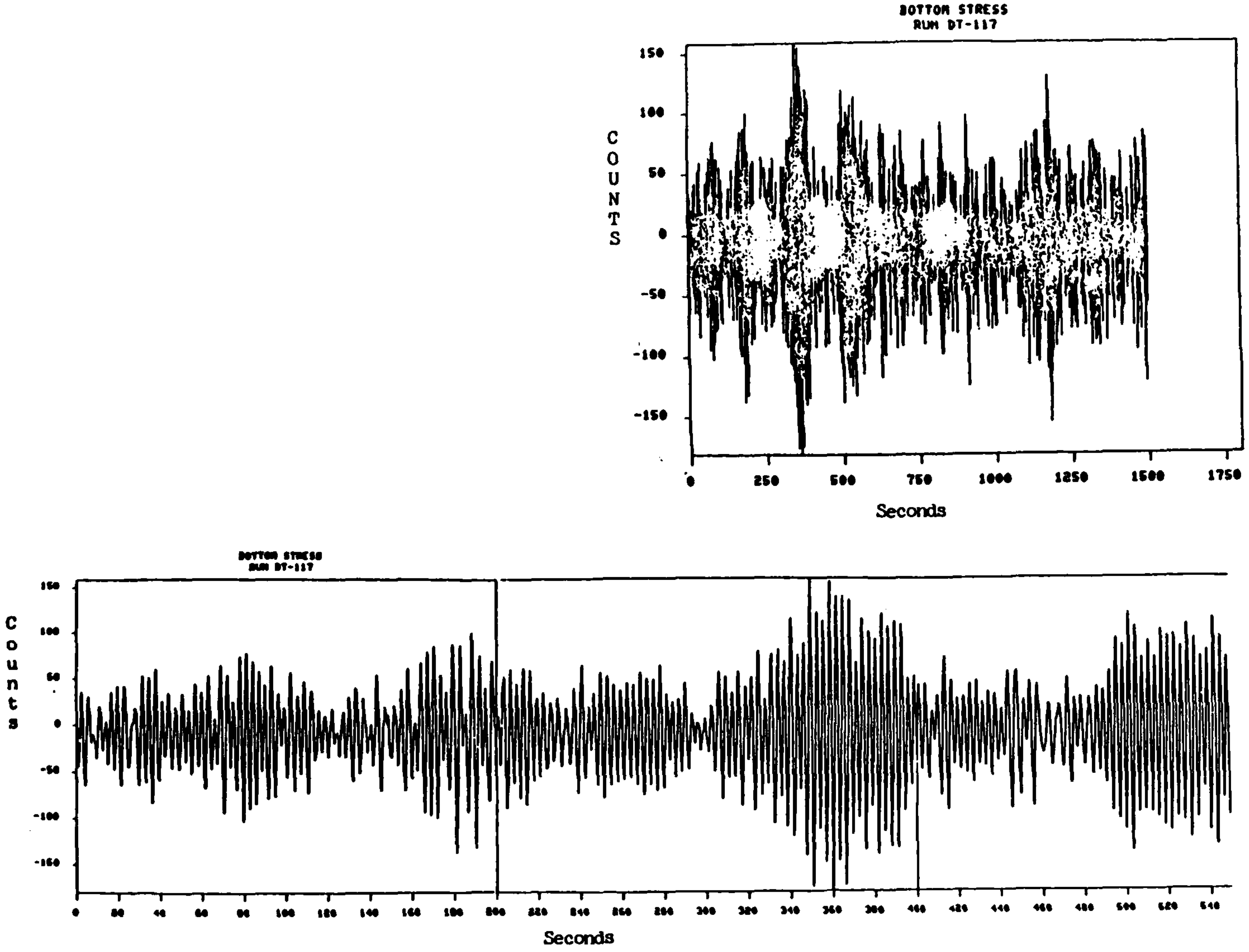
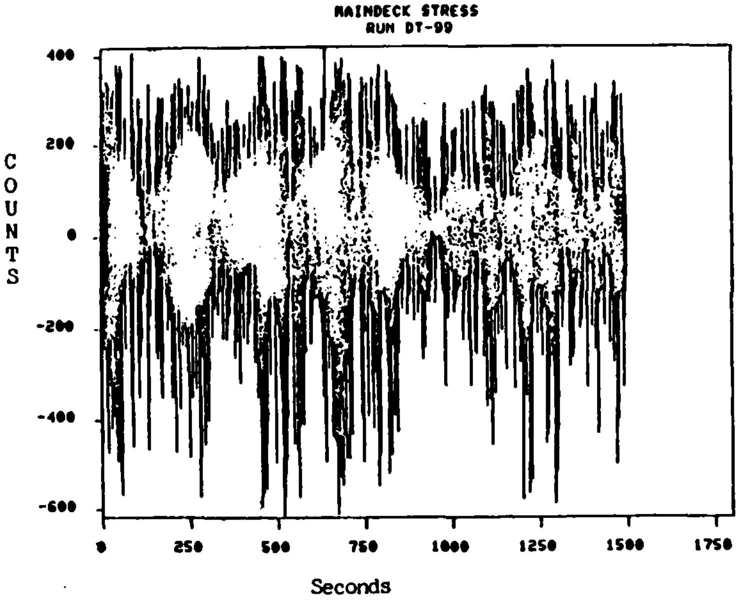


Figure A-21 Stress Time History Measured on the STEWART J. CORT

CONDITION 7

```
M/V S J CORT FALL TRIALS
          RUN              99          POINT          14
          DATE   05-DEC-79             TIME    14111119
          DURATION OF RUN IN MINUTES IS         25.000
          NORTH LATITUDE (DD MM)             88  0
          WEST LONGITUDE (DD MM)             47 35
          VESSEL'S SPEED (MPH - XX.X)       11.6
          VESSEL'S HEADING (DEGREES)         270
          VESSEL'S DRAFT (FEET)               10
          WIND DIRECTION (DEGREES)           270
          WIND SPEED (KNOTS)                  15
          WAVE DIRECTION (DEGREES)           270
          WAVE HEIGHT (FEET)                   5
REMARKS
SUPERIOR, UPBND., HEAD SEA, CODE 3
7 MI. OFF KEWEENAW PENINSULA , PT. OUTBD. ENGINE CLEARED

End-of-run message
```



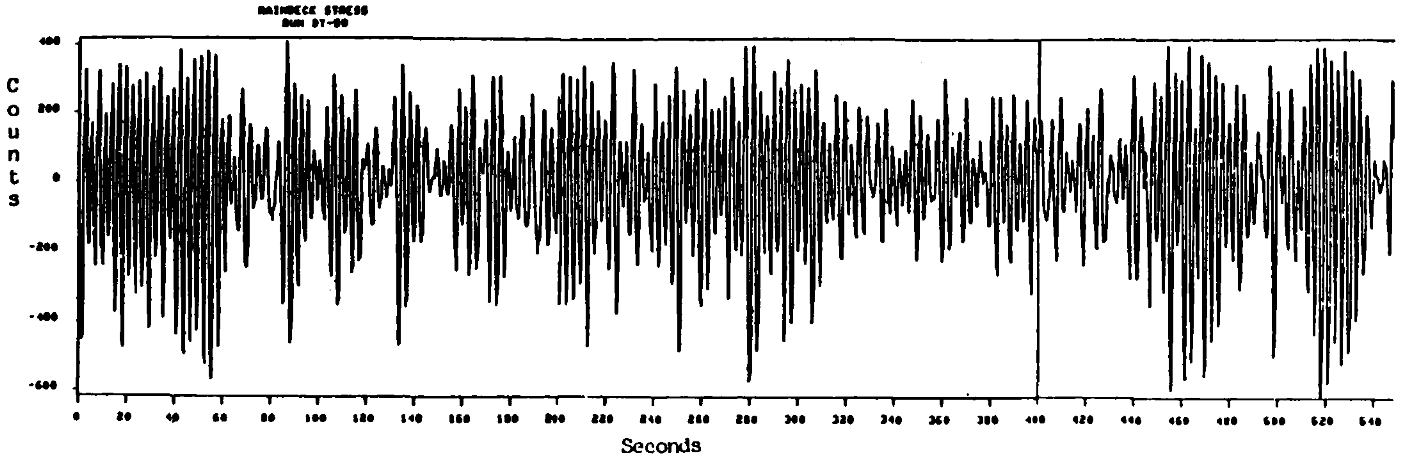
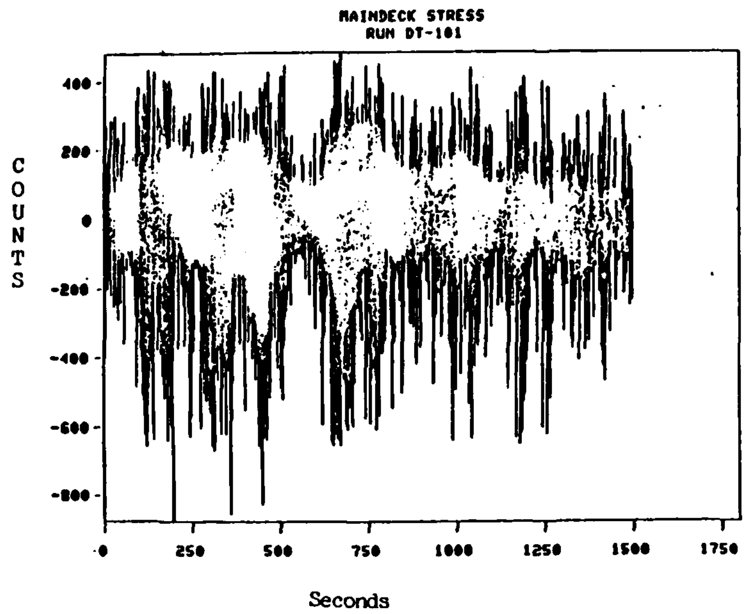


Figure A-22 Stress Time History Measured on the STEWART J. CORT

CONDITION 8

```
M/V S J CORT FALL TRIALS
          RUN             101          POINT          18
          DATE   05-DEC-79             TIME     14:53:38
          DURATION OF RUN IN MINUTES IS            25.000
          NORTH LATITUDE (DD MM)              88 20
          WEST LONGITUDE (DD MM.              47 30
          VESSEL'S SPEED (MPH - XX.X)        11.6
          VESSEL'S HEADING (DEGREES)          260
          VESSEL'S DRAFT (FEET)                19
          WIND DIRECTION (DEGREES)            350
          WIND SPEED (KNOTS)                   27
          WAVE DIRECTION (DEGREES)            240
          WAVE HEIGHT (FEET)                    8
REMARKS
SUPERIOR. UPBND., PORT BOW SEA CODE 3
OFF KEWEENAW PENINSULA

End-of-run message
PREDOMINANT SEA FROM PT BOW BEING KNOCKED DN BY STBD GALE
BECOMING CONFUSED
```



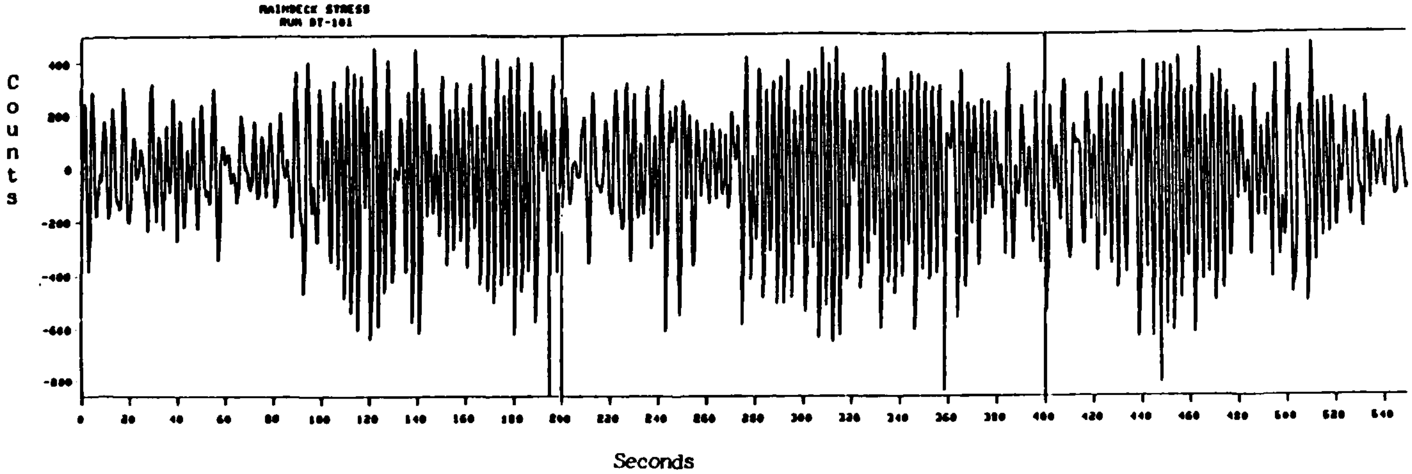


Figure A-23 Stress Time History Measured on the STEWART J. CORT

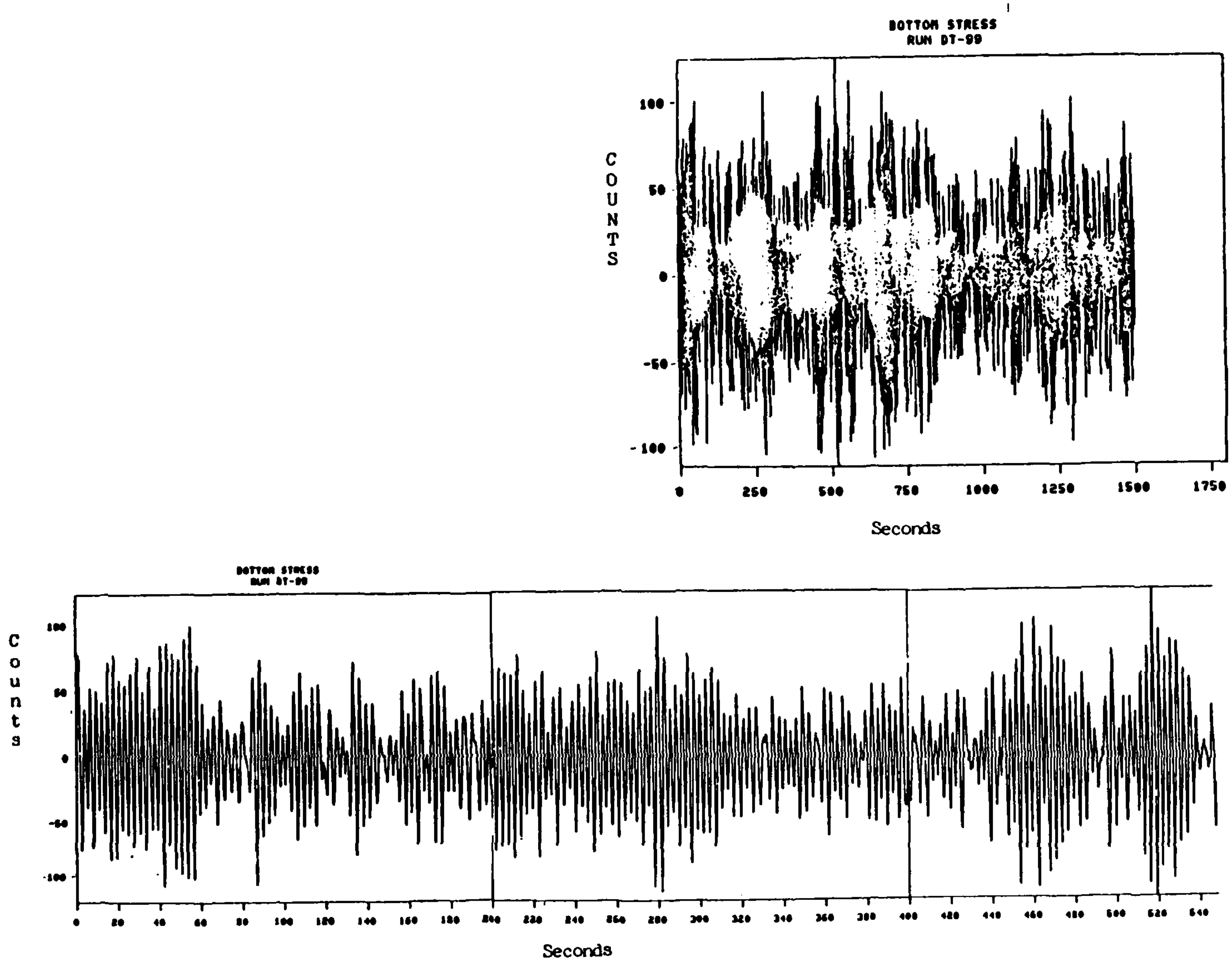


Figure A-24 Stress Time History Measured on the STEWART J. CORT

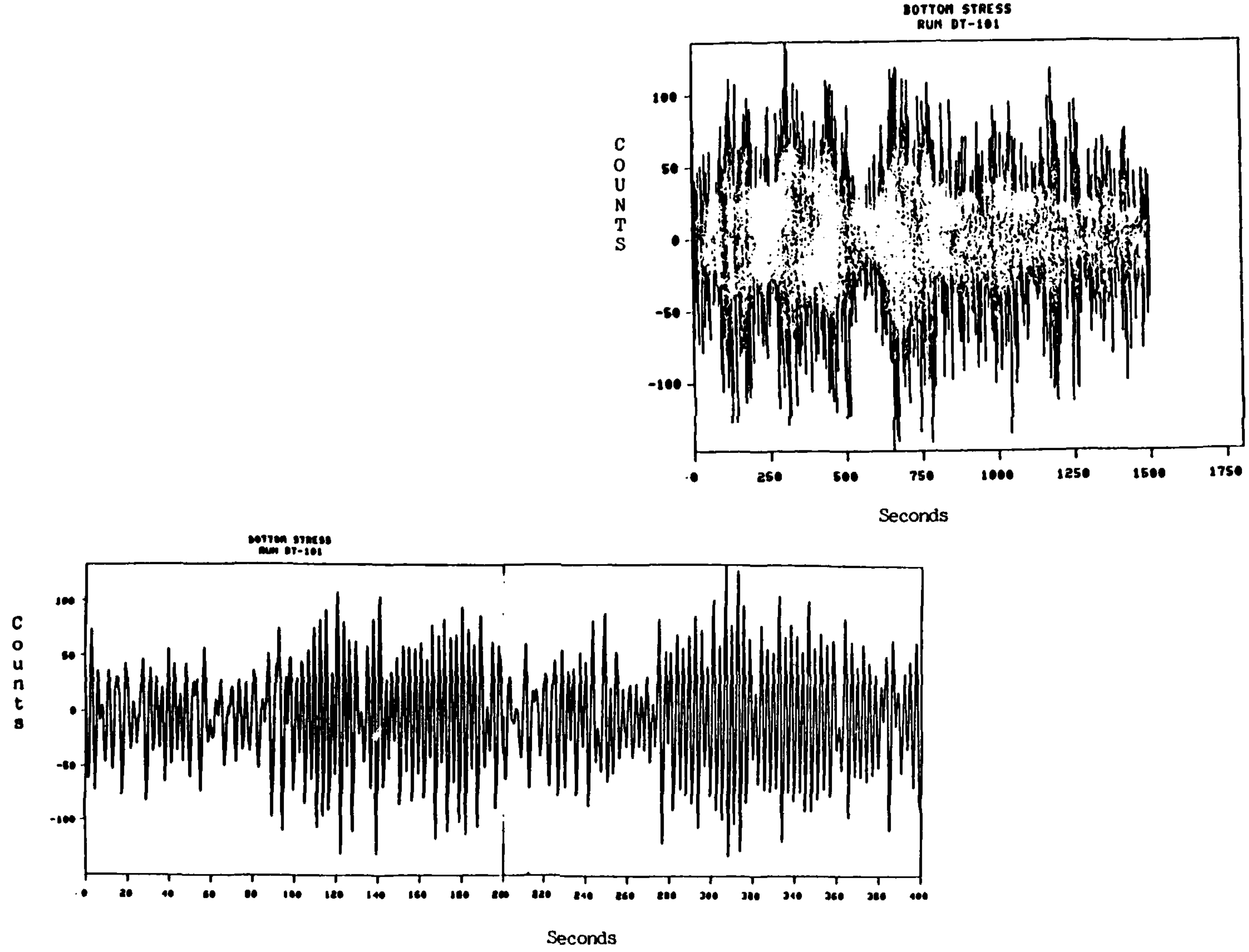
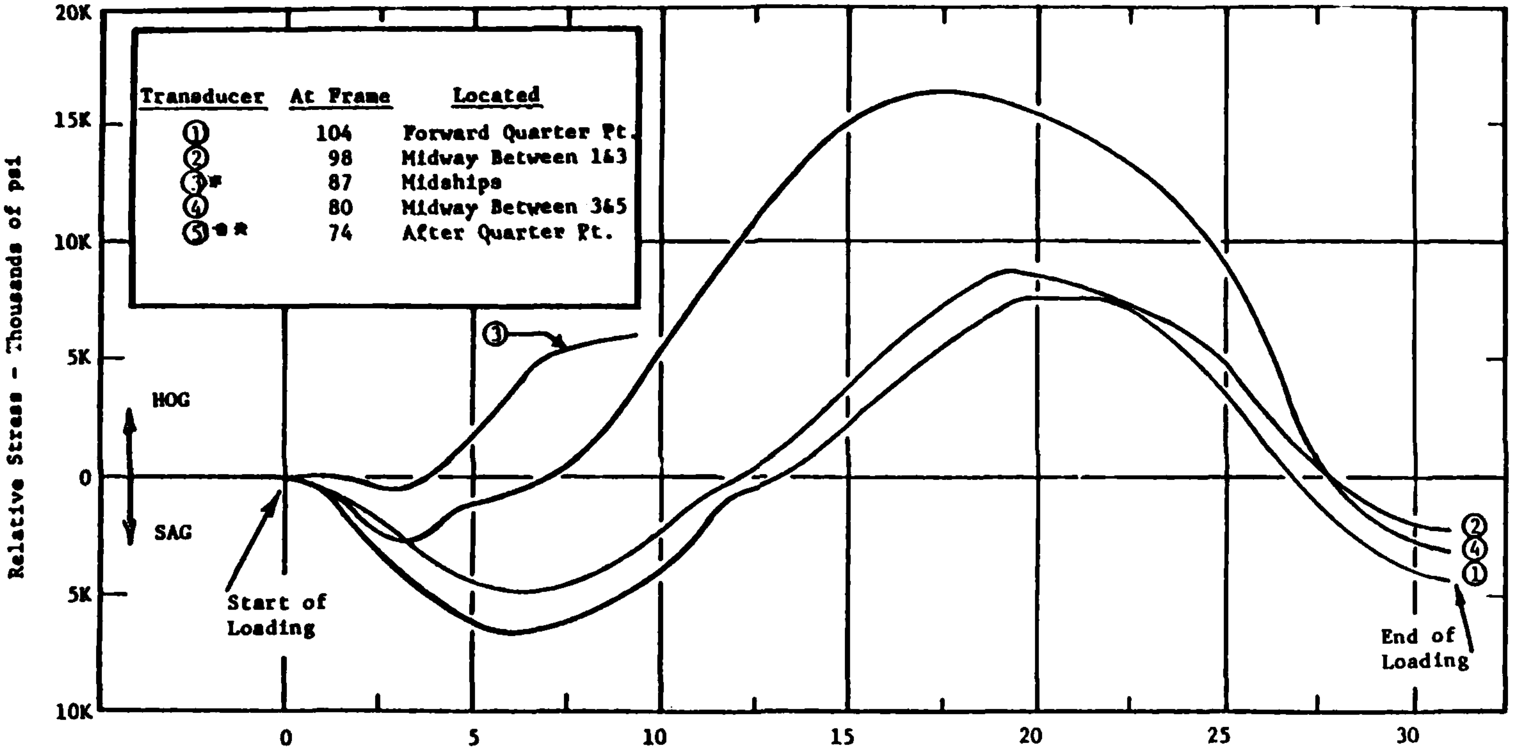


Figure A-25 Stress Time History Measured on the STEWART J. CORT



Elapsed Time-Hours

Figure A-26

SS UNIVERSE IRELAND

Loading Crude Oil at Mina Al Ahmadi, Kuwait

Mid-Voyage 5, August 16 & 17, 1969

(Ref. 6)

* failed 9 hours after start

** inoperative

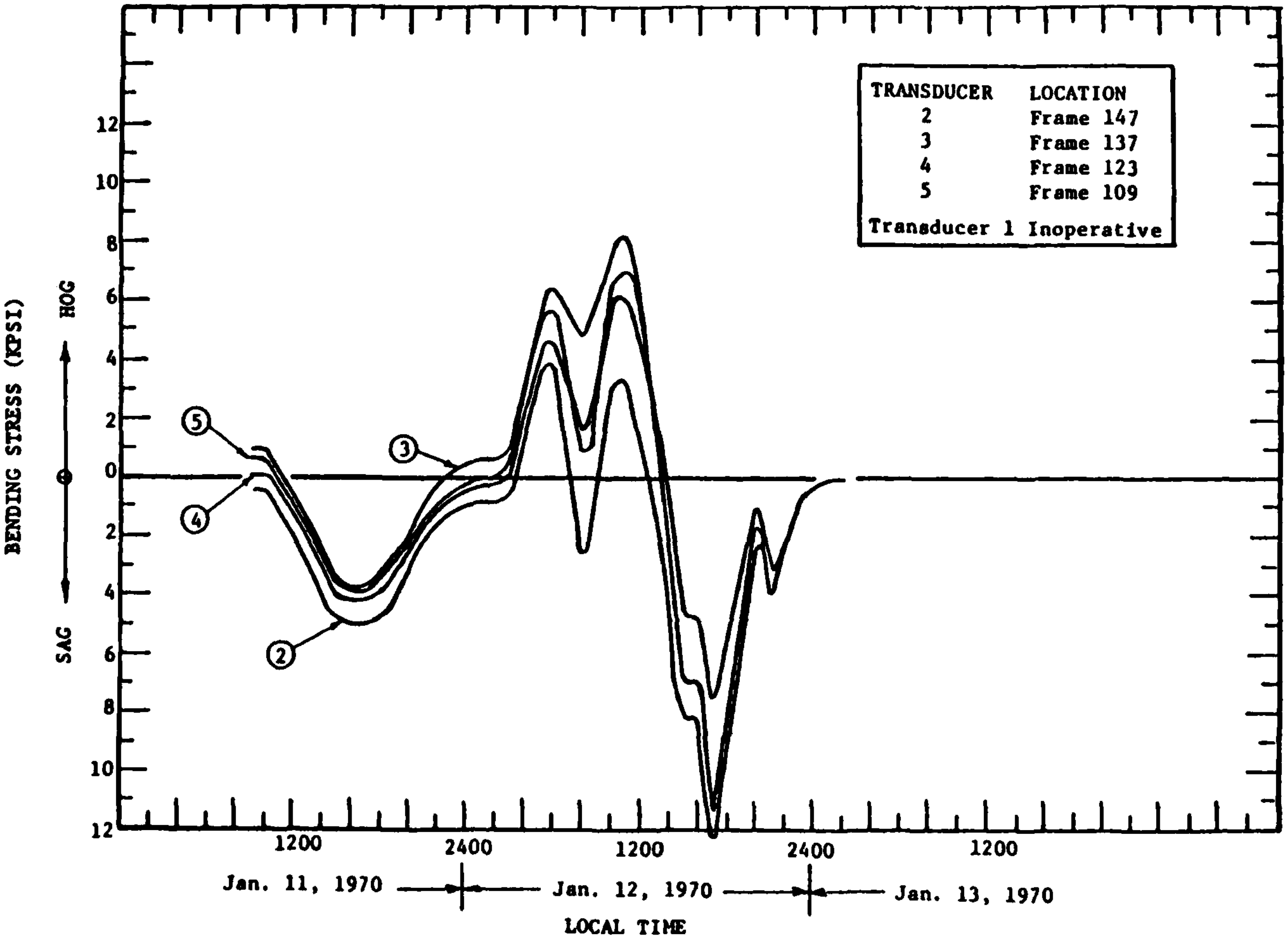


Figure A-27 Bending Stress vs. Time, MV FOTINI L Loading Iron Ore, San Nicolas, Peru; Mid-Voyage 15 (Ref. 5)

APPENDIX B

Tables of Strain Rates From Partial Data on the SL-7 SEA-LAND McLEAN and the STEWART J. CORT that was Presented in Appendix A

The strain rates have been presented along with collation information as discussed in Appendix A and the report.

TABLE B-1

Ship SL-7 SEA-LAND McLEAN, Maximum Strain Rate for 76-sec. Intervals

Strain Rates are Given in/in/sec

Tape Interval		Strain Rate Induced by High Frequency Transet Response $\dot{\varepsilon}$	Strain Rate Induced by Encounter of Waves $\dot{\varepsilon}$	Heading	Wave Height	Ship Speed
141	37	3.64×10^{-5}	26×10^{-5}	115P	10	27.7
141	41		1.73×10^{-5}	155S	10	27.7
141	45		1.26×10^{-5}	151S	10	27.7
141	49		2.18×10^{-5}	165P	8	27.5
173	13		7.13×10^{-5}	178P	4	32.1
173	17		2.83×10^{-5}	179P	3	32.3
173	25		1.19×10^{-5}	180P	2	32.3
175	29		1.796×10^{-5}	56P	2	32.1
175	33		1.64×10^{-5}	33P	3	32.4
175	37		4.9×10^{-5}	55P	3	31.9
175	41		3.86×10^{-5}	33P	3	32.1
175	49		2.06×10^{-5}	55P	3	32.3
175	53		1.39×10^{-5}	32P	2	32.3
139	37		1.37×10^{-5}	168P	5	21.1
139	45		2.09×10^{-5}	168P	10	21.4
139	49		1.496×10^{-5}	123P	15	21.3
139	53		2.36×10^{-5}	168P	18	21.1
139	57		4.04×10^{-5}	157P	20	21.0
139	61		2.33×10^{-5}	135P	20	21.9
141	1		4.04×10^{-5}	157P	20	20.8
141	5		3.807×10^{-5}	157P	12	21.0
141	9		1.833×10^{-5}	120P	10	21.4

TABLE B-1 (Cont'd)

Ship SL-7 SEA-LAND McLEAN, Maximum Strain Rate for 76-sec. Intervals

Strain Rates are Given in/in/sec

Tape Interval	Strain Rate Induced by High Frequency Transet Response $\dot{\epsilon}$	Strain Rate Induced by Encounter of Waves $\dot{\epsilon}$	Heading	Wave Height	Ship Speed
141 13		$1.77x10^{-5}$	120P	12	22.5
141 17		$2.89x10^{-5}$	157P	15	24.1
141 21		$2.075x10^{-5}$	157P	15	24.1
141 25		$2.64x10^{-5}$	130P	12	27.1
141 29		$1.764x10^{-5}$	115P	12	27.7
141 33		$2.49x10^{-5}$	115P	8	27.7
145 29	$2.69x10^{-4}$	$8.39x10^{-5}$	00	20	18.7
145 37		$1.286x10^{-5}$	91P	15	28.4
145 41	$1.57x10^{-4}$	$5.05x10^{-5}$	02S	25	32.5
145 50		$8.42x10^{-5}$	02S	25	28.1
145 53	$3.03x10^{-4}$	$8.45x10^{-5}$	02S	25	28.1
145 61		$1.62x10^{-5}$	47P	15	29.6
145 65	$1.64x10^{-4}$	$8.32x10^{-5}$	43S	25	32.6
147 7		$9.57x10^{-5}$	41S	15	31.9
147 12		$8.08x10^{-5}$	41S	15	31.9
147 13		$9.203x10^{-5}$	41S	4	32.8
139 13		$1.108x10^{-5}$	169P	3	32.7
139 17		$1.197x10^{-5}$	169P	6	32.7
139 21		$4.35x10^{-6}$	169P	5	32.7
139 33		$1.212x10^{-5}$	168P	5	32.6
143 9	$9.18x10^{-5}$	$3.37x10^{-5}$	35P	10	31.5
143 13		$4.28x10^{-5}$	35P	10	31.5

TABLE B-1 (Cont'd)

Ship SL-7 SEA-LAND McLEAN, Maximum Strain Rate for 76-sec. Intervals

Strain Rates are Given in/in/sec

Tape Interval	Strain Rate Induced by High Frequency Transet Response $\dot{\varepsilon}$	Strain Rate Induced by Encounter of Waves $\dot{\varepsilon}$	Heading	Wave Height	Ship Speed
143 36		5.66×10^{-5}	08P	15	32.6
143 40	3.03×10^{-4}	6.734×10^{-5}	30P	15	32.7
143 44		6.95×10^{-5}	64P	10	32.3
143 48		1.23×10^{-4}	41P	15	31.8
143 58		9.34×10^{-5}	02S	30	11.0
143 60		8.754×10^{-5}	02S	30	11.0
145 1		1.04×10^{-4}	20S	25	8.7
145 5		7.9×10^{-5}	02P	25	10.9
145 9		1.14×10^{-4}	37P	35	26.1
145 13		6.06×10^{-5}	15P	35	11.0
145 21		1.01×10^{-4}	45S	30	12.4
145 25		1.09×10^{-4}	45S	20	16.2
149 33		2.28×10^{-5}	123P	20	32.4
149 37		2.36×10^{-5}	122P	20	32.5
149 41		4.98×10^{-5}	122P	20	32.5
149 45		1.7×10^{-5}	144P	20	32.2
149 49		2.83×10^{-5}	144P	20	32.2
149 57		3.367×10^{-5}	145P	20	32.4
151 2		2.0875×10^{-5}	145P	12	32.5
151 5		2.83×10^{-5}	145P	8	32.4
151 9		1.089×10^{-5}	123P	8	32.5
151 13		1.53×10^{-5}	168P	4	32.6

TABLE B-1 (Cont'd)

Ship SL-7 SEA-LAND McLEAN, Maximum Strain Rate for 76-sec. Intervals

Strain Rates are Given in/in/sec

Tape Interval		Strain Rate Induced by High Frequency Transet Response $\dot{\varepsilon}$	Strain Rate Induced by Encounter of Waves $\dot{\varepsilon}$	Heading	Wave Height	Ship Speed
151	17	5.5x10^{-5}	1.811x10^{-5}	169P	4	32.4
151	21		1.86x10^{-5}	124P	4	32.7
151	25		1.2x10^{-5}	167P	4	32.7
151	29		4.04x10^{-5}	77P	6	32.0
151	33		8.4x10^{-6}	35S	6	32.3
151	37		4.9x10^{-6}	58S	6	32.9
155	13		4.04x10^{-5}	04S	1	32.4
155	17		2.02x10^{-5}	49S	2	32.3
155	21		4.39x10^{-6}	48S	2	33.1
155	25		2.02x10^{-5}	48S	[illegible]	32.4
155	29		9.38x10^{-6}	48S	1	32.4
155	37		4.32x10^{-6}	41P	6	32.2
155	41		7.07x10^{-5}	[illegible]	4	[illegible]
155	45		3.82x10^{-5}	[illegible]	[illegible]	[illegible]
155	49		6.18x10^{-5}	[illegible]	[illegible]	[illegible]
149	1		1.57x10^{-5}	[illegible]	[illegible]	[illegible]
149	5		4.55x10^{-5}	[illegible]	[illegible]	[illegible]
149	9		2.78x10^{-5}	[illegible]	[illegible]	[illegible]
149	13		4.4x10^{-5}	[illegible]	[illegible]	[illegible]
149	21		1.36x10^{-5}	[illegible]	[illegible]	[illegible]
149	25		3.37x10^{-5}	[illegible]	[illegible]	[illegible]
149	29		2.55x10^{-5}	[illegible]	[illegible]	[illegible]

TABLE B-1 (Cont'd)

Ship SL-7 SEA-LAND McLEAN, Maximum Strain Rate for 76-sec. Intervals

Strain Rates are Given in/in/sec

Tape Interval		Strain Rate Induced by High Frequency Transet Response $\dot{\varepsilon}$	Strain Rate Induced by Encounter of Waves $\dot{\varepsilon}$	Heading	Wave Height	Ship Speed
159	45		$1.178x10^{-5}$	154S	3	32.1
159	49		$3.82x10^{-6}$	154S	1	32.2
153	15		$6.73x10^{-5}$	02S	2	32.3
153	17		$7.35x10^{-5}$	25S	1	32.3
153	22		$4.21x10^{-5}$	23S	1	32.2
153	25		$3.57x10^{-5}$	12P	2	33.3
153	29		$3.46x10^{-5}$	10P	2	32.4
153	37	$1.3x10^{-4}$	$5.68x10^{-5}$	24S	3	31.9
153	37		$4.22x10^{-5}$	01S	5	32.1
153	41	$2.98x10^{-4}$	$3.6x10^{-5}$	21P	5	32.1
153	45		$8.08x10^{-5}$	05S	8	31.8
153	49	$2.53x10^{-4}$	$1.01x10^{-4}$	04S	8	31.8
153	53		$8.84x10^{-5}$	49S	12	31.8
153	61	$3.84x10^{-4}$	$1.68x10^{-4}$	26S	12	32.0
155	1		$1.1x10^{-4}$	04S	6	31.2
155	5		$3.85x10^{-5}$	04S	5	31.8
155	9		$6.3x10^{-5}$	26S	1	32.6
157	21		$1.52x10^{-5}$	00.0	2	32.3
157	26		$9.24x10^{-6}$	11S	2	32.1
157	33		$3.37x10^{-5}$	45S	2	32.1
157	37		$1.75x10^{-5}$	22S	2	31.9
157	41		$3.12x10^{-5}$	11S	2	32.2

TABLE B-1 (Cont'd)

Ship SL-7 SEA-LAND McLEAN, Maximum Strain Rate for 76-sec. Intervals

Strain Rates are Given in/in/sec

Tape Interval		Strain Rate Induced by High Frequency Transet Response $\dot{\varepsilon}$	Strain Rate Induced by Encounter of Waves $\dot{\varepsilon}$	Heading	Wave Height	Ship Speed
157	45		5.05×10^{-5}	11S	3	32.6
157	49		2.85×10^{-5}	95P	2	32.3
159	1		3.47×10^{-5}	50P	2	32.1
159	5		4.04×10^{-5}	95P	2	32.3
159	9		3.8×10^{-5}	95P	2	31.8
159	13		3.57×10^{-5}	118P	2	32.3
159	17		3.8×10^{-5}	117P	3	32.3
159	22		3.54×10^{-5}	151P	4	32.4
159	25		3.79×10^{-5}	117P	4	32.3
159	29		3.46×10^{-5}	175P	4	32.6
159	34		1.68×10^{-5}	161P	4	32.4
159	41		1.774×10^{-5}	64S	3	32.3
163	21		3.2×10^{-5}	47S	0	31.8
163	29		7.4×10^{-6}	92S	2	31.3
163	53		5.69×10^{-5}	75S	2	31.4
163	37		3.93×10^{-5}	159S	2	31.8
163	41		2.27×10^{-5}	137S	2	32.1
163	45	6.57×10^{-5}	1.65×10^{-5}	137S	2	32.1
165	5		1.14×10^{-5}	124P	2	32.4
165	9		1.94×10^{-5}	124P	3	32.3
165	13		1.25×10^{-5}	124P	3	32.4
165	17		4.55×10^{-5}	124P	3	32.3

TABLE B-1 (Cont'd)

Ship SL-7 SEA-LAND McLEAN, Maximum Strain Rate for 76-sec. Intervals

Strain Rates are Given in/in/sec

Tape Interval		Strain Rate Induced by High Frequency Transet Response $\dot{\varepsilon}$	Strain Rate Induced by Encounter of Waves $\dot{\varepsilon}$	Heading	Wave Height	Ship Speed
165	21		$3.7x10^{-5}$	124P	3	32.1
165	29		$1.59x10^{-5}$	135P	4	32.3
165	33		$8.08x10^{-5}$	169P	6	32.4
157	9		$1.12x10^{-5}$	172	1	32.3
157	13		$1.307x10^{-5}$	179	1	32.2
157	17		$2.27x10^{-5}$	19	1	32.3
171	10	$2.09x10^{-4}$	$5.69x10^{-5}$	22S	6	31.3
171	13	$1.89x10^{-4}$	$5.84x10^{-5}$	35S	6	25.3
			$7.2x10^{-5}$			
171	17	$2.45x10^{-4}$	$8.68x10^{-5}$	55S	4	20.2
171	21	$2.75x10^{-4}$	$1.38x10^{-4}$	36P	2	31.8
171	25		$6.96x10^{-6}$	81P	2	32.1
171	29	$1.75x10^{-4}$	$3.5x10^{-5}$	56P	5	32.0
171	43		$1.32x10^{-4}$	12S	25	10.0
171	47		$9.14x10^{-5}$	0	30	6.0
171	49		$9.29x10^{-5}$	56S	30	-
171	56	$2.7x10^{-4}$	$8.08x10^{-5}$	20S	15	10.0
173	1	$3.1x10^{-4}$	$9.95x10^{-5}$	11S	15	10.0
173	9	$1.39x10^{-4}$	$7.86x10^{-5}$	2S	6	32.0
173	13		$5.84x10^{-5}$	178S	4	32.1
167	5		$3.79x10^{-5}$	124P	6	32.2
167	13		$4.75x10^{-5}$	111P	10	31.9
167	17		$1.85x10^{-5}$	121P	20	31.9

TABLE B-1 (Cont'd)

Ship SL-7 SEA-LAND McLEAN, Maximum Strain Rate for 76-sec. Intervals

Strain Rates are Given in/in/sec

Tape Interval	Strain Rate Induced by High Frequency Transet Response $\dot{\varepsilon}$	Strain Rate Induced by Encounter of Waves $\dot{\varepsilon}$	Heading	Wave Height	Ship Speed
167 25		2.92×10^{-5}	125P	20	17.2
167 29		3.64×10^{-5}	120P	20	17.3
167 33		4.52×10^{-5}	97P	20	17.3
167 37		3.08×10^{-5}	97P	20	16.5
167 41		1.97×10^{-5}	97P	20	19.7
167 45		1.84×10^{-5}	97P	4	26.2
169 17		5.05×10^{-5}	7S	1	31.6
169 21		3.84×10^{-5}	7S	1	31.8
169 25		4.94×10^{-5}	38P	1	31.8
169 29		3.3×10^{-5}	36P	2	32.0
169 33	1.2×10^{-4}	5.25×10^{-5}	36P	3	31.4
169 41		8.08×10^{-5}	99S	3	31.9
169 45	1.16×10^{-4}	5.84×10^{-5}	171P	3	32.0
169 49		3.37×10^{-5}	103P	3	32.0
169 53	2.02×10^{-4}	7.58×10^{-5}	79P	6	31.8
171 5		1.17×10^{-4}	33S	6	31.3
161 9		1.3×10^{-5}	83P	1.0	32.3
161 17		7.68×10^{-5}	138S	5.0	31.9
161 28		6.4×10^{-5}	136S	5.0	30.8
161 30		7.27×10^{-5}	156P	4.0	31.3
161 33		3.8×10^{-5}	100P	2.0	31.6
161 37		4.78×10^{-5}	118P	2.0	31.6
161 41		6.14×10^{-5}	106P	3.0	31.6

TABLE B-1 (Cont'd)

Ship SL-7 SEA-LAND McLEAN, Maximum Strain Rate for 76-sec. Intervals

Strain Rates are Given in/in/sec

Tape Interval	Strain Rate Induced by High Frequency Transet Response $\dot{\varepsilon}$	Strain Rate Induced by Encounter of Waves $\dot{\varepsilon}$	Heading	Wave Height	Ship Speed
161 45		6.9×10^{-5}	103P	2.0	31.7
163 5		7.2×10^{-5}	018P	2.0	31.3
163 9	2.73×10^{-4}	1.04×10^{-4}	018P	2.0	31.3
163 17		4.85×10^{-5}	49S	5.0	31.4
173 17		2.41×10^{-5}	179P	3	32.3
175 25		1.59×10^{-5}	032P	2	32.3
175 29		2.02×10^{-5}	56P	2	32.1
175 33	5.5×10^{-5}	1.68×10^{-5}	33P	3	32.4
175 37		2.53×10^{-5}	55P	3	31.9
175 41		3.2×10^{-5}	33P	3	32.1
175 49		2.08×10^{-5}	55P	3	32.3
175 53		1.59×10^{-5}	32P	2	32.3
175 57		2.155×10^{-5}	32P	2	32.4
175 61		3.46×10^{-5}	32P	2	32.2
165 37		4.04×10^{-5}	169P	6	32.3
165 42		4.36×10^{-5}	146P	6	32.3
165 45		4.56×10^{-5}	124P	5	32.1
165 49		5.5×10^{-5}	146P	5	32.3
167 1		3.79×10^{-5}	124P	6	32.1

Table B-2 Strain Rates Calculated from Data Recorded on the STEWART J. CORT

IDENTIFICATION	STRUCTURAL LOCATION	*STRAIN RATE in/in/sec	WAVE HT	HEADING	SHIP SPEED (mph)
Cond. 1	Maindeck Bottom	3.5×10^{-4} 9.36×10^{-5}	6'	head seas	14.4
Cond. 2	Maindeck Bottom	4.27×10^{-4} 1.2×10^{-4}	6'	head seas	14.4
Cond. 3	Maindeck Bottom	2.43×10^{-4} 6.9×10^{-5}	3'	head seas	14.7
Cond. 4	Maindeck Bottom	4.4×10^{-4} 8.1×10^{-5}	3'	head seas	14.2
Cond. 5	Maindeck Bottom	4.65×10^{-4} 1.16×10^{-4}	4'	head seas	13.5
Cond. 6	Maindeck Bottom	5.12×10^{-4} 1.25×10^{-4}	3'	head seas	14
Cond. 7	Maindeck Bottom	4.2×10^{-4} 1.17×10^{-4}	5'	head seas	11.6
Cond. 8	Maindeck Bottom	5.1×10^{-4} 1.17×10^{-4}	5'	head seas	11.6

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* The strain rates presented in this table are for each respective recording interval.

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