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APPENDICES

1.0 EXECUTIVE SUMMARY

The Round Robin Test Program was undertaken to document the abilities of several non-destructive evaluation (NDE) techniques in monitoring the integrity of large, complex structures. The program was funded jointly by the Office of Naval Research and the Minerals Management Service, Branch of Technology Assessment and Research, of the Department of the Interior*.

The test program required advocates of various techniques to diagnose damages done to a scale model offshore oil platform. These diagnoses were based on data acquired by an independent test facility which carried out the specific instructions of the advocates in applying the techniques. In this way the advocates were blind to any information on the exact nature of the damages except for the data provided by their instrumentation.

Of the three NDE methods which completed the testing (two others dropped out during the program), the Random Decrement Technique and the Frequency Response Technique both showed the ability to determine whether or not structural damage had occurred and to estimate the severity of that damage. Beyond that, the Frequency Response Method performed best in locating the damage and the Random Decrement Method showed more confidence in identifying low levels of damage. In a separate test sequence, the Ultrasonic Technique demonstrated the ability to predict impending catastrophic failure in a scale model welded steel K-joint.

* What was formerly the Conservation Division of USGS is now the Minerals Management Service of the Department of the Interior due to a recent reorganization of DOI.

2.0 OVERVIEW

2.1 Main Program Objective:

The main objective of the Round Robin program was to evaluate the capabilities of several non-destructive evaluation (NDE) techniques which may be effective in the monitoring and inspection of complex structures and, particularly, of offshore oil platforms. The Minerals Management Service of the Department of the Interior has collaborated with the Structural Mechanics Division of the Office of Naval Research in supporting research into these techniques. The Round Robin program is a part of that ongoing, cooperative effort intended to aid in planning future research.

The Round Robin Test Program sought to verify the capabilities of several NDE techniques through an independent test agent, and to verify the performance of each technique in a "blind mode" series of tests.

2.2 Background:

Over the last two decades, there has been considerable activity in the development of NDE techniques to determine the vibration characteristics, functional life expectancy, and integrity of various types of structures subject to deterioration. ONR is interested in the application of these techniques to a broad range of complex structures. DOI is particularly interested in the application of these techniques to the problem of determining the structural integrity of offshore oil platforms. The capabilities of these techniques in general and in underwater applications need to be quantified and documented.

2.3 Organization:

Figure 2-1 is an organizational chart of the participants in the Round Robin program.

Dr. Nicholas Perrone and Dr. Nicholas Basdekas of ONR and Messrs. John Gregory and Charles Smith of DOI have been the representatives for the sponsoring agencies.

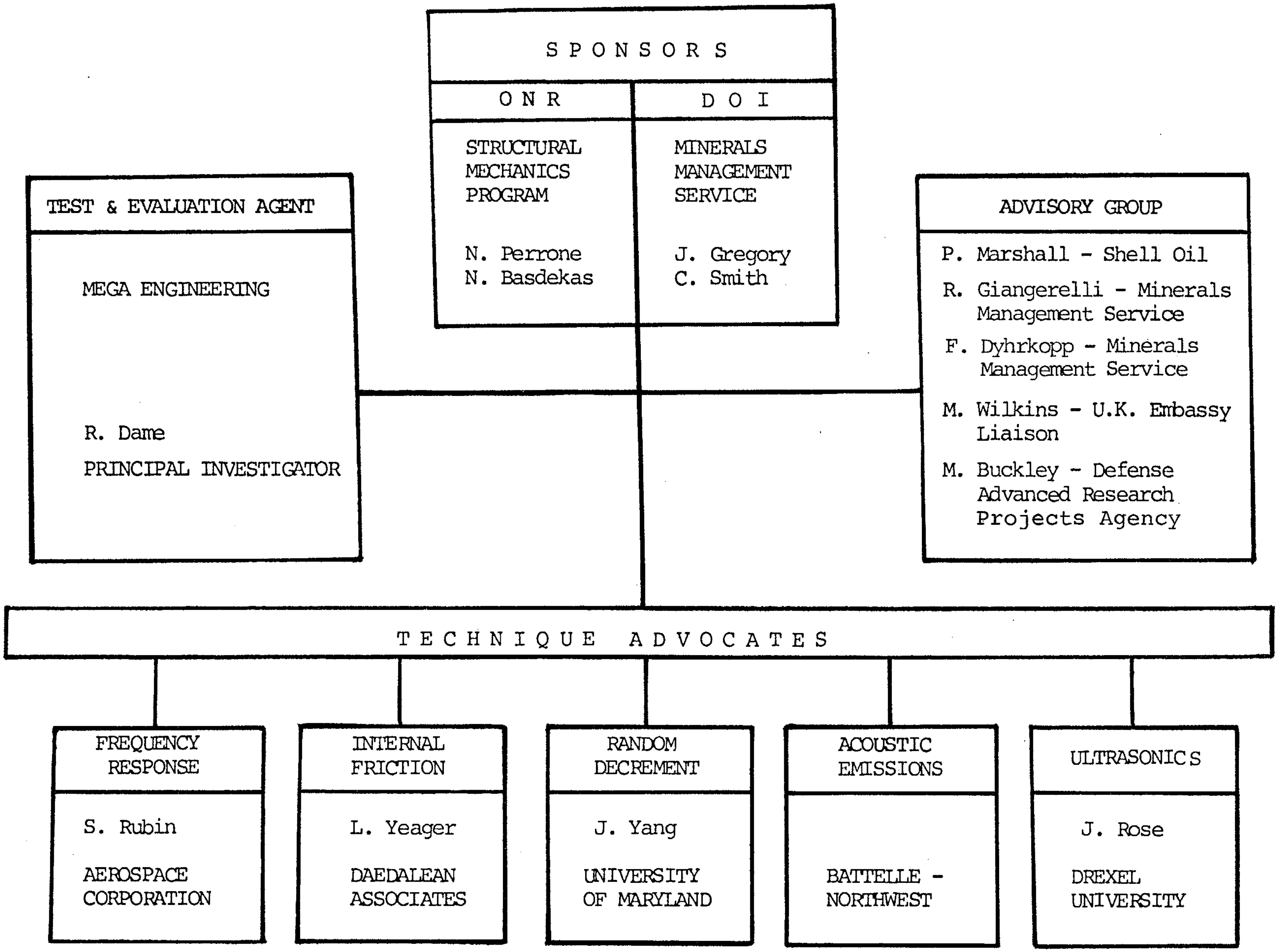
Dr. Richard Dame of Mega Engineering has been the testing principal investigator, serving as a neutral agent in the development of the test program and evaluation of the results.

The advocates and demonstrators of the various techniques include Dr. Jackson Yang of the University of Maryland, Dr. Sheldon Rubin of the Aerospace Corporation, Mr. Larry Yaeger of Daedalean Associates, Dr. Joseph Rose of Drexel University, and representatives of Battelle Labs for the Federal Highway Administration.

Test facilities were provided at NASA's Goddard Space Flight Center, and the fabrication of the test models was performed at the University of Maryland.

Staff to conduct the testing program was provided by GSFC, by Northrop Corp. as a sub-contractor, and also by Mega Engineering.

Other interested parties who advised in the development of the program included Shell Oil, the Department of Defense, and representatives from the United Kingdom.



NDE ROUND ROBIN ORGANIZATIONAL CHART

Figure 2.1

2.4 Program History

On Jan. 17, 1980 the first full meeting of NDE Round Robin participants, sponsors, and interested parties was held to discuss plans for the program. These plans were finalized and published in the Document "NDE Round Robin, the Evaluation of NDE Techniques for Determining Offshore Structures Integrity" in April 1980.

The scale models used in the program were then constructed and tested, and final details of the testing procedures were settled during the summer and fall of 1980. Testing began in Oct., 1980. The diagnoses of structural damages were presented to the test agent in May, 1981 for scoring and evaluation.

On Nov. 17, 1981 the program participants convened for the final presentation of results by the test advocates, evaluation by the test agent, and comments by all parties.

This report is the final report by the test agent, Mega Engineering, and it should be noted that final reports have also been generated by the technique advocates.

3.0 PARTICIPATING NDE TECHNIQUES

3.1 Methods Evaluated:

Originally, five NDE techniques were slated for evaluation. They included:

- The Random Decrement Method
- Frequency Response Monitoring Method
- Internal Friction Monitoring Method
- Acoustic Emissions Method
- Ultrasonic Testing Method

Of those five, the Random Decrement, Frequency Response, and Ultrasonic Techniques ultimately completed the test program. The Acoustic Emission Technique, advocated by The Federal Highway Administration, dropped out of the program at the beginning of its scheduled testing sequence due to shortages in the advocates' personnel. The Daedalean Associates Internal Friction Monitoring Technique was dropped from the program during its baseline testing sequence. This method was incompatible with test procedures and was judged by the sponsors of the Round Robin program to warrant no further consideration.

Of the remaining three techniques, the bulk of this report deals with the Random Decrement and Frequency Response Methods. These methods are similar in that they aim to assess the integrity of a complex structure taken as a whole, and testing for both was performed on the same test structure. A later section of this report deals with Ultrasonic Testing which individually analyzes specific areas of a structure.

3.2 General Principles for Global Methods:

The fundamental approach in both the Random Decrement and the Frequency Response Methods is to observe changes in the characteristics of structural vibrations over time and to infer from those changes their structural cause (e.g. major damage, minor damage, non-damage changes). The techniques differ in the particular type of vibrational data acquired and in the processing of the data selected for analysis.

Neither technique requires any unusual equipment. Standard sensors, dynamic test equipment, and computers are used by both.

3.3 Random Decrement Method:

This method is based on the analysis of a set of graphs called "Randomdec signatures" which present information on a structure's natural frequencies and damping characteristics. These signatures are generated from random response data, that is, from the vibrational response of a structure subjected to random excitations. Incipient structural failures can be detected by noting the changes their presence causes in these signatures.

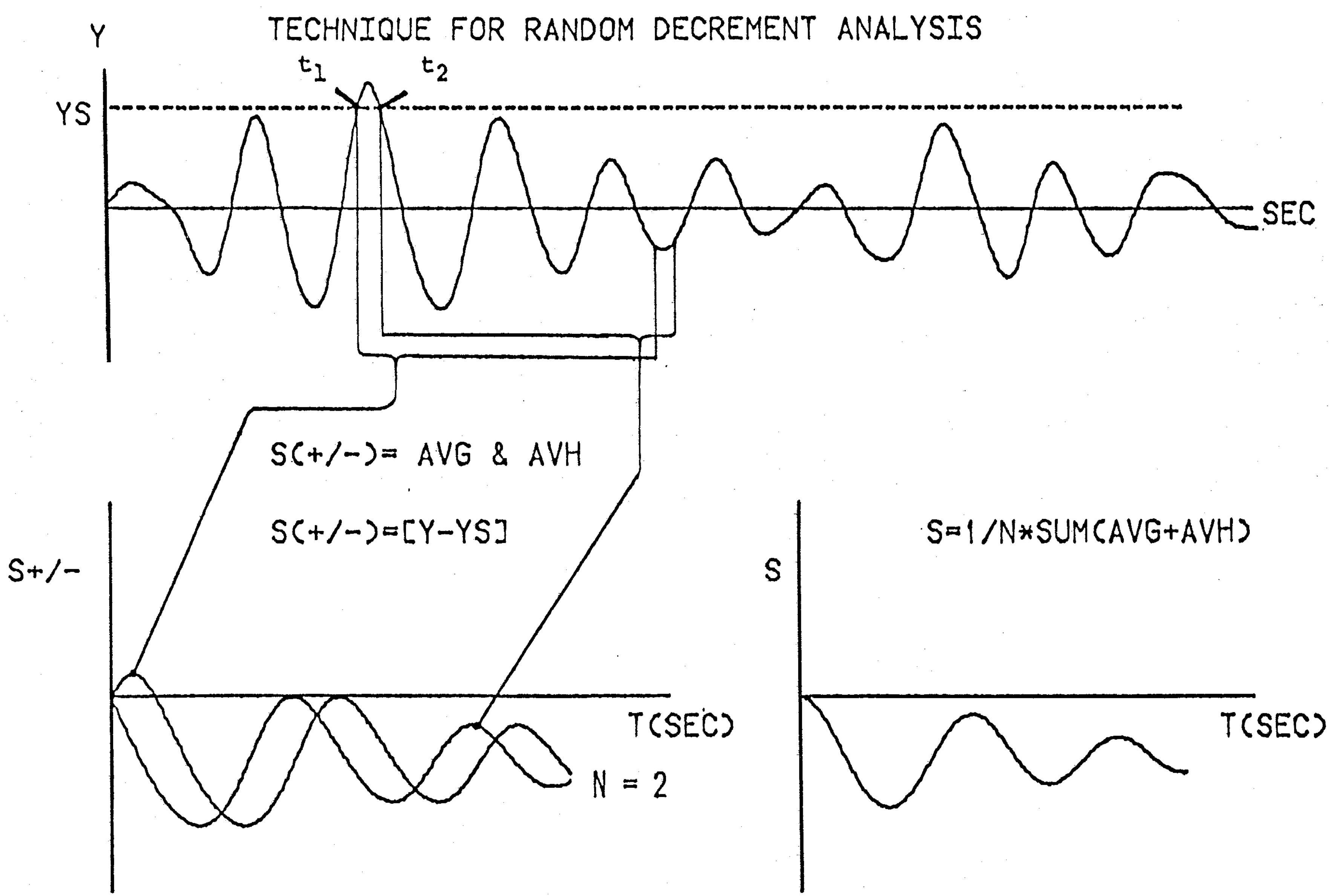
To date, methods have not been developed for specifically locating damage in complex structures using this technique.

To perform a Random Decrement analysis, several steps are involved:

- Development of baseline signatures which characterize the undamaged structure.
- Generation of test signatures as part of a monitoring process.
- Evaluation of the difference between the test signatures and the baseline signatures.
- Interpretation of any differences in terms of specific structural changes.

The principle behind generating the baseline or test Randomdec signatures is that the response of a system to random excitation is the sum of a random response and a characteristic system response. The Randomdec Method seeks to filter out the random response from the structure's overall vibrations and leave the characteristic response for analysis.

To do this, it chooses several intervals in an amplitude vs. time accelerometer output whose beginning points share a common characteristic (e.g. amplitude or slope). The vibrations of the system in these intervals are, therefore, responses to a common initial condition. If these intervals are laid on top of one another and summed, the random part of the response should average out to zero, and what remains must be a response curve with a frequency and damping characteristic of the system. This process is shown pictorially in Figure 3-1.



GRAPHIC REPRESENTATION OF THE RANDOM
DECREMENT ANALYSIS TECHNIQUE

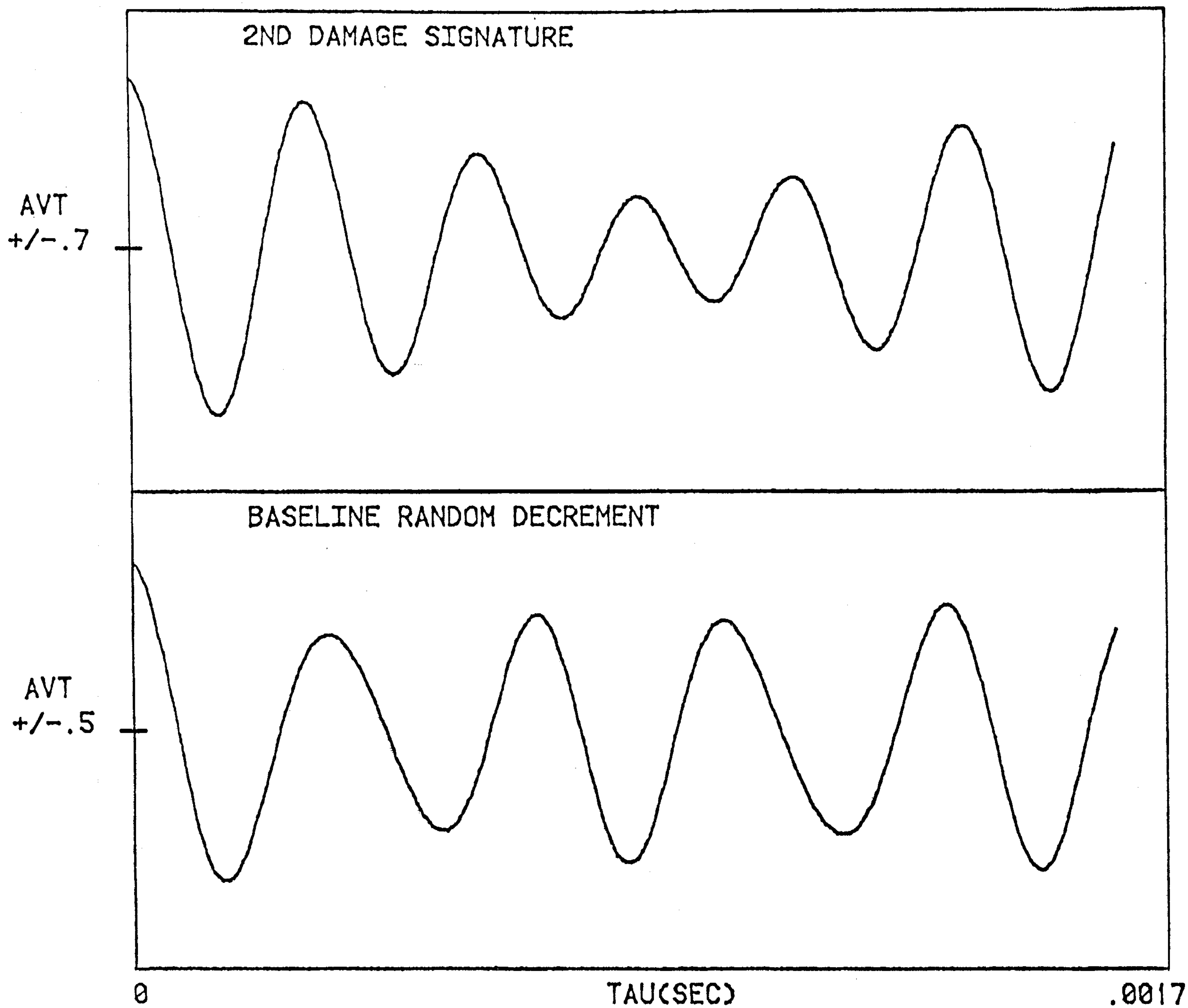
(Courtesy of Mr. Pete Alea)

Figure 3-1

Filtering of the amplitude vs. time data is performed to generate different signatures for different frequency ranges. Power spectra analysis is used to guide this filtering process in order to have the signatures dominated by important vibrational modes. Of particular interest are signatures from high frequency band widths since Random Decrement advocates hold that changes in these signatures are the earliest signs of structural damage.

To evaluate the differences between the baseline and the test signatures, various kinds of statistical analyses can be performed as well as less rigorous visual inspections. Figure 3-2 shows a typical damage signature relative to its baseline signature. The changes in frequency and damping are indications that failures are altering fundamental structural characteristics.

Interpreting the differences in the signatures in terms of specific structural changes or failures is not a very well defined process, as has been noted. If the outputs of several sensors are being monitored by the Randomdec method, it has been anticipated that locational information might be obtained by looking at the relative magnitude of the signature changes at different sensor locations. It should be noted, however, that the Randomdec Technique as it stands is not particularly suited to locating failures, but rather is aimed at early failure detection.



RANDOM DECREMENT SIGNATURES FOR THE 3RD DAMAGE MODEL (2400-3200 Hz)

(Courtest of Mr. Pete Alea)

Figure 3-2

There are questions as to the ability of this analysis method to distinguish between vibrational changes caused by failures and changes caused by other sources such as extraneous noise, marine growth, and system mass changes which would be likely to enter into the monitoring of large, complex structures. This is a problem for virtually all NDE methods. This problem area was not sufficiently explored during the test program due to the limited number of tests conducted.

The Random Decrement method's most notable characteristic is that a minimal number of sensors are required to globally monitor a structure. This is an advantage in locating instruments on offshore platforms since these few sensors can be located above the water line.

For more information on the Random Decrement Technique, refer to the articles listed in Appendix A.

3.4 Frequency Response Method:

The Aerospace Corp. uses up to three types of frequency response analyses in its Frequency Response Method. These include global mode monitoring, local mode monitoring, and flexibility monitoring (a new technique developed by Aerospace). Articles describing these three types of analysis in detail are listed in Appendix B.

Basically, global mode monitoring looks for shifts in low frequency vibrational peaks and for changes in mode shapes of the structure as a whole, which are indicative of structural damage. It relies on work with mathematical models of the structure to estimate the amount of frequency shift which signifies damage, and to define alterations in mode shapes characteristic of specific kinds of damage. For example, it has been found that frequency shifts of greater than 1% in low frequency modes are an indication of failure.

Local mode monitoring focuses attention on a particular structural member or small group of members in order to detect incipient failures. It uses the same type of frequency shift and mode shape analysis as global mode monitoring, but based on a more localized set of sensors.

As mentioned for the Random Decrement Method, the distinction between failures and non-failure changes such as in structural mass, is difficult when using either the global or local frequency response methods. To address this problem, flexibility monitoring was developed.

Flexibility monitoring observes the relative sizes of the deflections in various parts of the structure as indications of damage. It depends on very accurate relative amplitude measurements but theoretically has a very low sensitivity to non-damage structural changes. This method also purports to provide good locational information on failures.

Although the Frequency Response Method can operate to a large degree on the structure's excitation by random environmental forces, it is often augmented by the use of forced inputs. Since the technique relies on the accurate detection of shifts in major modal frequencies, excitation of the structure at these frequencies can aid in data resolution.

With regard to monitoring of offshore structures in particular, the various Frequency Response Methods can operate in any number of combinations. Global mode monitoring can be used alone based on sensors located only on the above water portions of the platform. This may be augmented with forced excitations. Additionally, a more extensive network of sensors extending below the water line on the legs of the platform may be used, allowing more detailed global mode monitoring as well as flexibility monitoring. If the location of these sensors is sufficiently dense, local mode monitoring may also be used.

3.5 Other techniques:

Originally, two other techniques were slated for evaluation in the Round Robin program. They will not be discussed further in this report but are described below in statements by the technique advocates excerpted from the original Round Robin program statement. More information is available in articles cited in the Appendices.

"Acoustic Emissions-

Acoustic Emission is a phenomena whereby transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material. Acoustic emission testing requires that an energy reservoir (i.e., strain energy) must be present. A propagating flaw in a structure then transduces minute amounts of strain energy to a transient elastic wave which propagates at the speed of sound in the structure. The spectral content of this signal is very broad and can be detected up to frequencies as high as 30 MHz. Most practical applications involve monitoring frequencies from 30 kHz to 1MHz.

Acoustic emission monitoring experiments have successfully demonstrated the ability of the technique to detect crack initiation and crack growth at very early stages, in laboratory simulations of the fatigue of typical offshore structural joints. This testing has been undertaken at various laboratories in the UK and at private laboratories in the U.S. Additional programs are underway to determine the viability of the technique to detect cracking in the marine environment.

Acoustic emission monitoring will fulfill several different roles in a structural integrity program for steel jacket structures:

a. Provide a statistical indication of overall platform integrity by monitoring selected nodes to detect crack initiation.

b. Conduct nodal monitoring to assess the integrity of all major nodes. With this approach, the system would be further expanded by the addition of transducers to monitor crack growth once detected at a specific node.

c. Monitor relatively long members, using few transducers, where the acoustic transmission path would encompass multiple nodes. This approach lends itself particularly well to platforms with flooded legs or 'tension leg' platforms."

"Internal Friction Monitoring

The internal friction monitoring method is based upon an understanding of the behavior which metals manifest when subject to stress. This behavior is a deviation from perfect elasticity and causes energy dissipation within a metal which is related to its granular structure. It has been known for more than a century that metals do not exhibit perfect elastic behavior even at very low levels of stress. Because of this 'anelasticity', part of the mechanical energy input to a metal is converted to heat, and the various mechanisms by which this process occurs are collectively termed internal damping. Increases in internal damping during the service life of a metal indicate progressive fatigue from which the remaining structural life can be determined.

Internal damping may be measured by subjecting a structure to a low-stress wave and recording the decrement. A simple beam can be excited by merely plucking it, or a complex structure can be driven by means of a vibration shaker. The decay response of the beam may only contain the fundamental frequency and its overtones, but complex structures will exhibit many decaying responses masked within a single envelope.

In a complex structure, once degradation is detected, the crack must be located. For a structure of welded columns, beams, braces, and so on, accelerometers can be placed at various locations, and by collectively analyzing their responses, structural deterioration or failure may be identified. Instruments can also be limited to key locations, as for example, where fatigue deterioration is most probable. Still unanswered, however, is the applicability of the technique to large structures, such as offshore platforms, which are subjected to complex fatigue regimes resulting from wind, wave, corrosion, ocean floor erosion, and changing deck loadings."

4.0 TESTING PROGRAM

4.1 General:

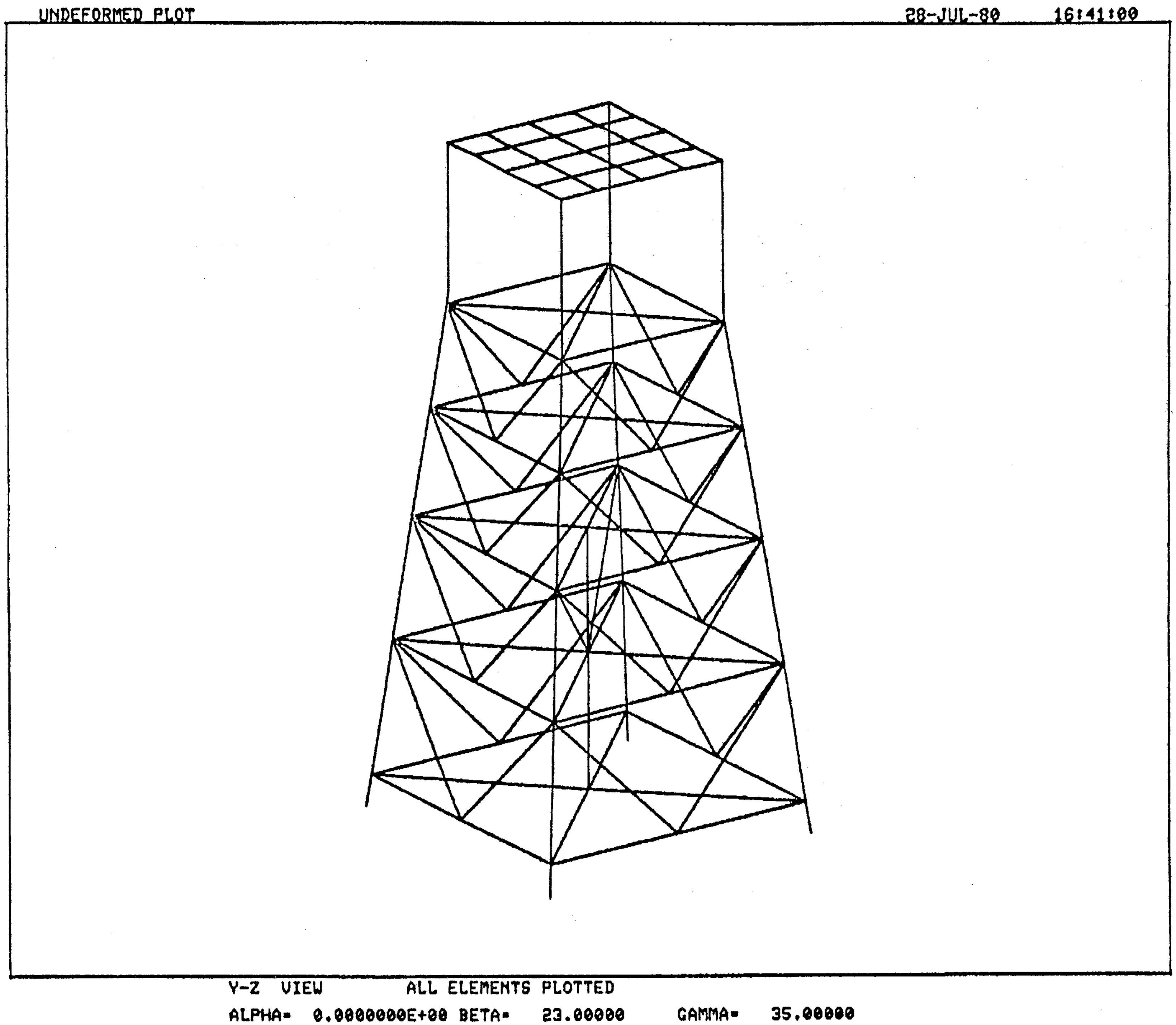
The method selected for evaluating the global NDE techniques was to have them diagnose structural damage on a scale model of an offshore oil platform. This specifically addressed the interest of DOI and provided a complex structure for the general evaluation of the techniques. The diagnoses would be performed in a blind mode, that is, data would be provided to the technique advocates by an independent test facility, thereby giving the advocates no prior knowledge of the specific nature of the damage being diagnosed. Specifically, each technique would attempt to:

- Determine whether or not a failure had occurred. NDE methods should not yield ambiguous results when no failures are present. For instance, the addition or removal of equipment from a platform or partial flooding of a jacket member can occur which will not affect platform integrity but which will alter its vibrational response. An NDE technique should not be fooled into diagnosing a failure when these types of structural changes have occurred.
- Determine the severity of the change if failures are diagnosed. If a failure is found, it is important to know whether or not it has significantly affected the structure's integrity.
- Determine as accurately as possible the location of any failures. This is required in order to guide more detailed inspection and repair, especially in larger structures.

The platform used for the test was a 13.8:1 scale model of a Gulf Oil platform in the Gulf of Mexico (Platform B, Block 48, South Marsh Island). A similar model had previously been constructed and tested at the University of Maryland and by Daedalean Associates. As shown in Figs. 4-1 through 4-5, the model consisted of a deck supported on four legs, with five levels of bracing and a variety of inter-level diagonal members. The design of this platform was based on dynamic similarity studies performed by the University of Maryland. Appendix E contains detailed data on dynamic testing and modelling, as well as other information on its construction.

The overall height of the model structure was approximately 12 ft., and it was 38 inches square at the deck level and 57 inches square at the base. The four vertical legs were made from 2" OD steel tube with .109" walls, and all other members were 3/4" OD steel tube with .065" walls. The deck was a honeycomb plate 1.5" thick and all four legs were supported on 1/2" thick, 4" x 4" plates. Material for all items was A-36 steel, and all parts were welded together.

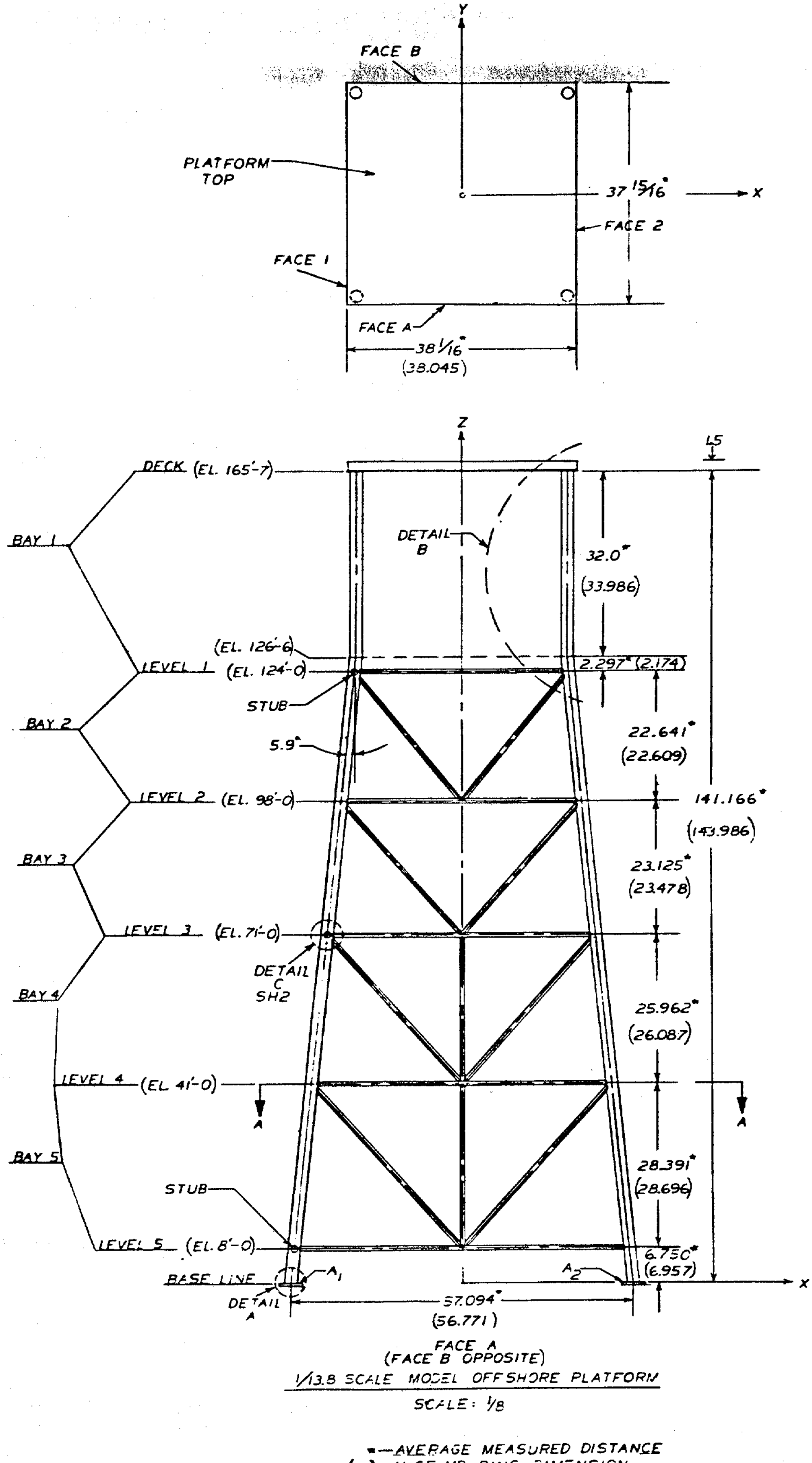
The platform was mathematically modelled by Mega Engineering using the NASTRAN and GIFTS programs to determine natural frequencies and mode shapes. Output from those programs and tables summarizing their results are included in Appendix E.



NASTRAN Plot of Tower Model Fig. 4-1

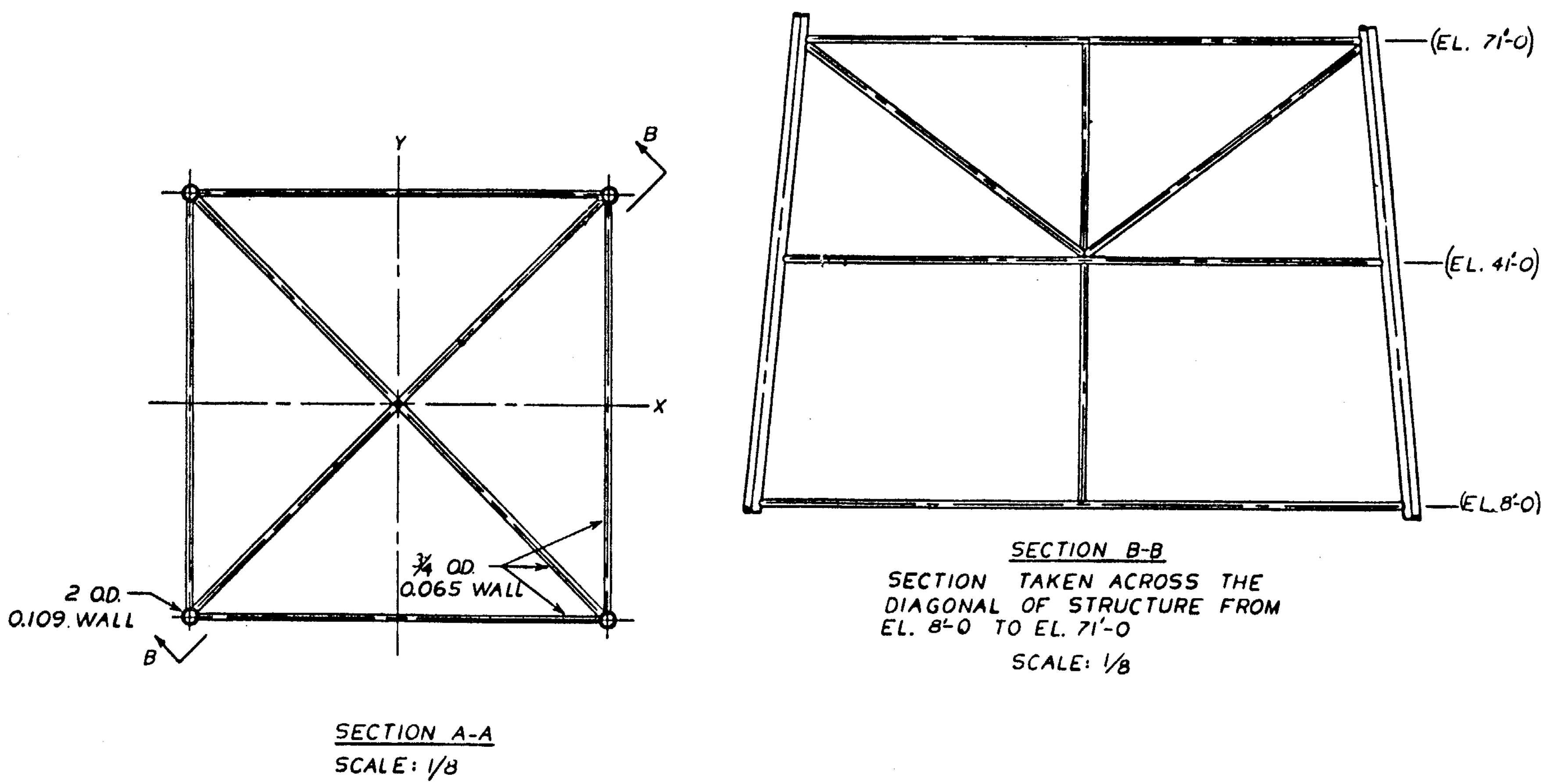
NASA -G- 80-6709

Fig. 4-2



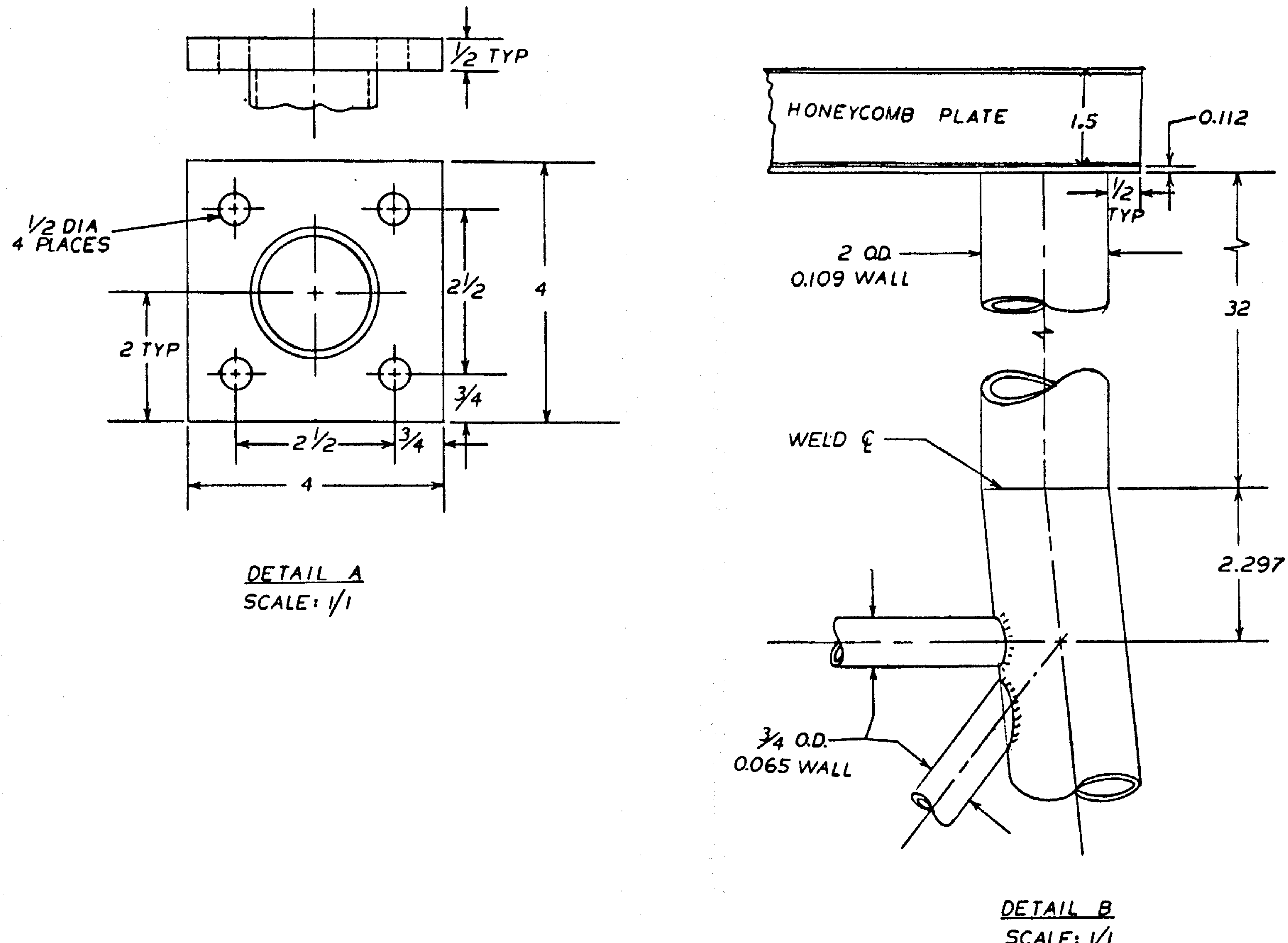
SCALE MODEL PLATFORM

Figure 4.3



SECTIONS, SCALE MODEL PLATFORM

Figure 4.4



DETAILS, SCALE MODEL PLATFORM

Figure 4.5

One significant structural change relative to the original University of Maryland design was made at the beginning of the test program, and that was the addition of a honeycomb plate as the deck of the platform. The suggestion for this change came from Dr. Sheldon Rubin of Aerospace Corporation and was intended to increase the deck's thin plate fundamental frequencies to a level removed from participation in other fundamental platform modes. The new deck had a natural frequency of about 90 Hz, which accomplished this purpose as the data in Appendix E shows.

The goal in using the scale model of the platform was, as mentioned, to make the testing as representative as possible of actual offshore monitoring conditions. There were, however, technical and programmatic limits to the similarity achievable between test and actual conditions. Some of the dissimilarities which bear noting are:

- Test data could only be taken periodically, after discrete changes were made in the platform. Normally, continuous monitoring of fatigue and failure processes would be possible.
- The model platform was not submerged in water which affects certain damping characteristics that could be important to the effectiveness of some techniques.
- The platform was bolted to the floor which is a configuration that is not dynamically similar to pile supports.

The importance of any of these issues to specific tests will be discussed in later sections of this report.

4.2 Development of Overall Program:

In developing the overall test program, Mega Engineering consulted with the sponsors and technique advocates.

Preliminary test information on the scale model platform was reviewed by all participants and recommendations for improving its design were considered. It was in this regard that the use of the honeycomb plate was incorporated at the suggestion of Dr. Rubin.

Test equipment specifications were also discussed including transducer selection and mounting methods, sensor location and number, recording instrumentation, and data processing equipment. The requirements of all technique advocates were accommodated where possible.

Advocates were also provided with a list of the possible damages they could be asked to diagnose. This list appears in Table 4-1. These scenarios were chosen in order to simulate realistic failures and to avoid biasing the tests towards the capabilites of any one NDE technique. They cover a range of possibilities including serious structural damage that would affect the platform's integrity, minor structural damage which would be an early sign of impending failure, and non-damage structural changes which would be sure to occur over time and would complicate NDE diagnoses.

Finally, the specific format for reporting diagnoses of the test results and the details of the final scoring procedure were also discussed. These items will be covered later in the report.

TABLE 4-1

POSSIBLE DAMAGE SCENARIOS

Major Damage

- Severed Diagonal Brace - One Face
- Two Severed Diagonals - Opposite Faces
- Severed Horizontal at Base
- Two Severed Horizontals at Base - Opposite Faces
- Changed Foundation Condition

Minor Damage

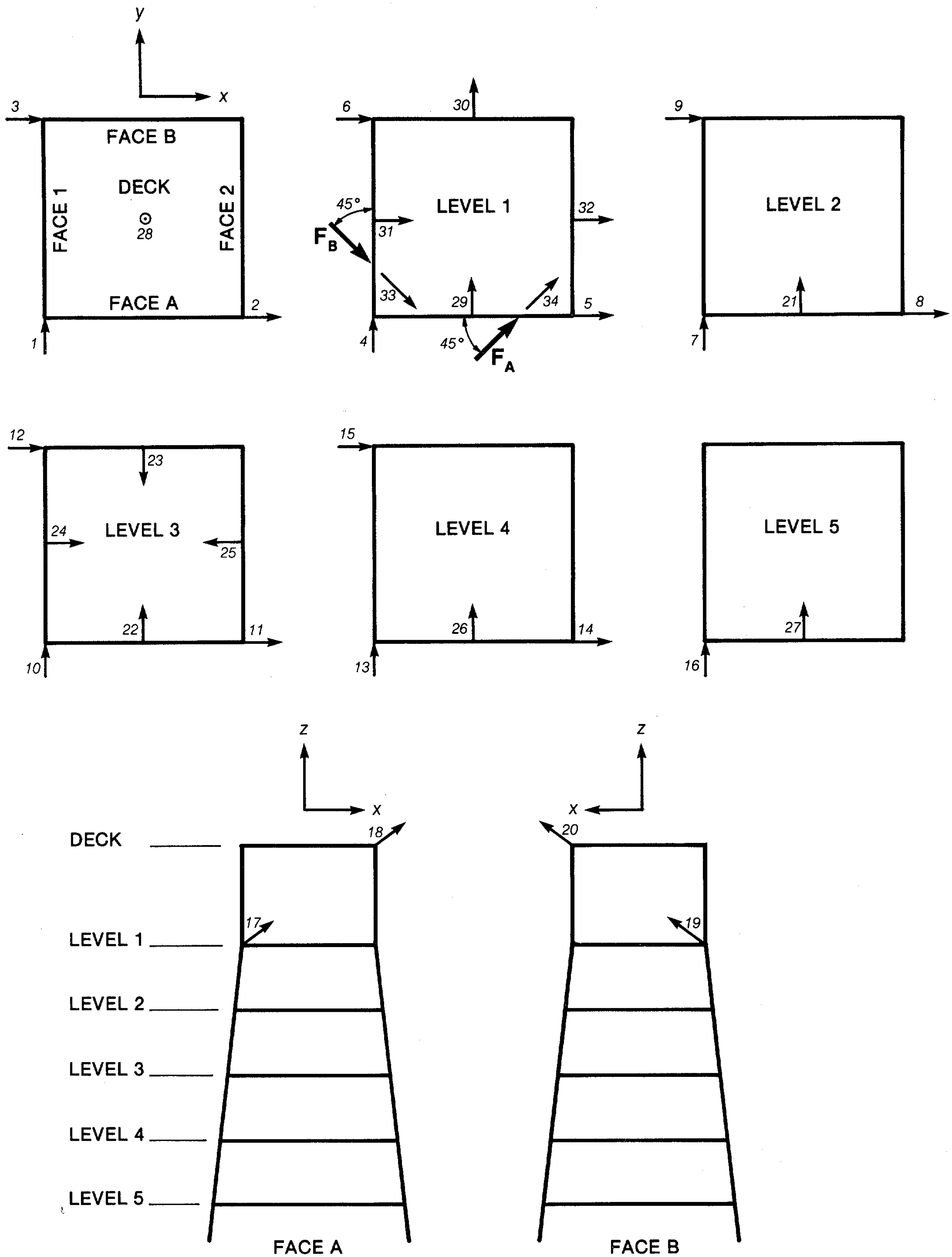
- Bent Diagonal in Upper Bay
- Change in Deck Mass
- Simulated Marine Growth
- Crack in One or Two Horizontal Members
- Progressive Cracking of Horizontal and Diagonal Members
- Installation of One or Two Riser Pipes

4.3 Specific Test Procedures:

Based on knowledge of the types of failures they would have to diagnose, each advocate developed a set of specific test procedures to be used in applying their particular technique, including:

- placement and orientation of electro-mechanical shakers which would input loads to the platform
- the specific series of inputs to apply through those shakers
- placement and orientation of accelerometers used to measure the platform's vibrational response
- instructions on what data to record from the accelerometers and what elementary data reduction to perform

A shaker with an output of 10 lbf was used at two locations by the Aerospace Corp. to input a broad based, low frequency (5 Hz to 500 Hz) random excitation. Although Aerospace originally requested that a series of sine dwell excitations at platform fundamental frequencies also be input, they ultimately decided not to run that sequence. They recorded raw data from 34 accelerometers and generated a variety of plots including autospectra, frequency response functions, and coherence plots. Figure 4-6 shows the location and orientation of their shaker positions and accelerometers on the structure.



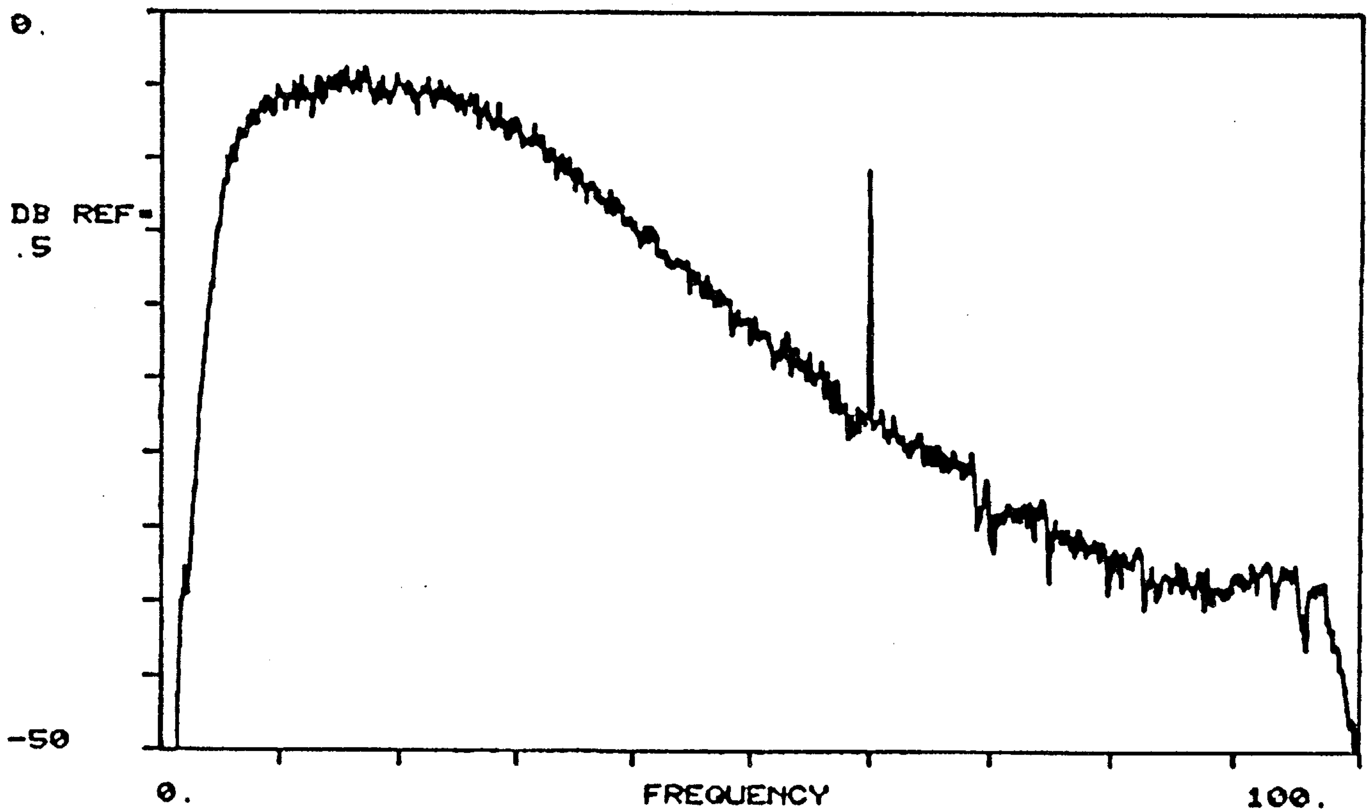
AEROSPACE CORPORATION
SHAKER AND ACCELEROMETER LOCATIONS

Figure 4-6

Figure 4-7 shows a typical autospectra or power spectral density plot of the random input introduced by the shaker. This particular one is for the 5 to 100 Hz input range. Note that the shaker was capable of higher power output at lower frequencies. The spike at 60 Hz is AC noise. Figure 4-8 shows the corresponding PSD plot for an accelerometer measuring the system response to the input in Figure 4-7. Figure 4-9 shows the frequency response function for the structure implied by the input and output. Figure 4-10 is a coherence plot which shows the statistical correlation between the output and the input. The ranges in which the coherence plot is close to unity or marked by distinct spikes are ranges where the PSD plot of the output and the frequency response function are reliably accurate. The high and very low frequency regions where coherence departs substantially from unity are areas of questionable output data. The data taken from all accelerometers was supplied to the Aerospace Corporation, although only subsets of that data were used for each analysis.

The University of Maryland used the same 10 lbf shaker at three locations to input low frequency (5 Hz to 200 Hz) and high frequency (200 Hz to 10 kHz) broad based, random excitation. Raw data was recorded from 17 accelerometers for 2 minute periods in the low frequency tests, and for 30 second periods in the high frequency tests. Shaker and accelerometer locations for the University of Maryland are shown in Figure 4-11. No data reduction was performed. The data from four of the 17 accelerometers was recorded on a University of Maryland FM recorder. At their request, only the data from six accelerometers in total was actually supplied to the University of Maryland team.

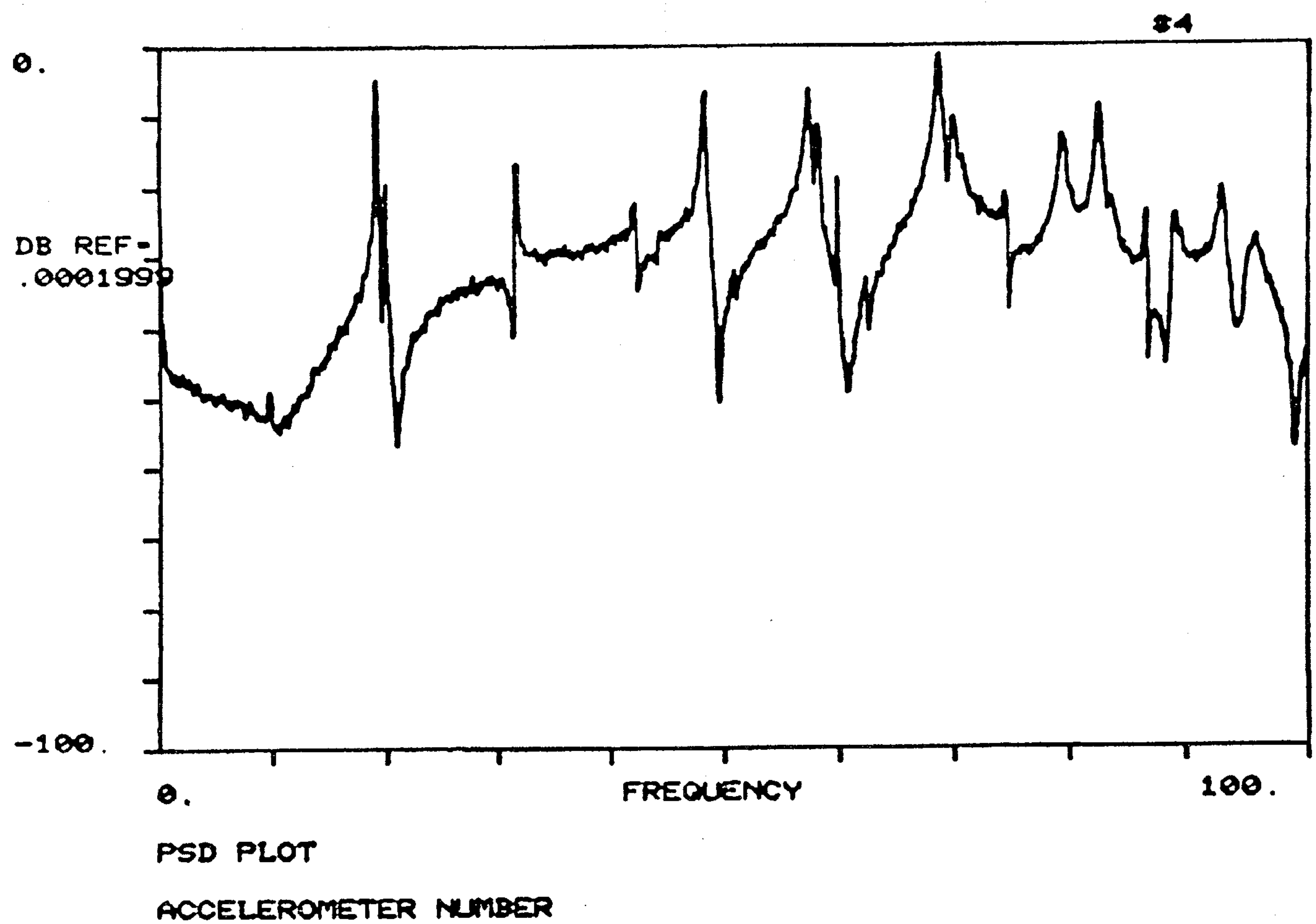
Appendix F contains further details on the specific test procedures.



RUN FA-7 AEROSPACE CORP 2ND DS

INPUT AUTOSPECTRA

FIGURE 4.7



#4
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DB REF=
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FREQUENCY
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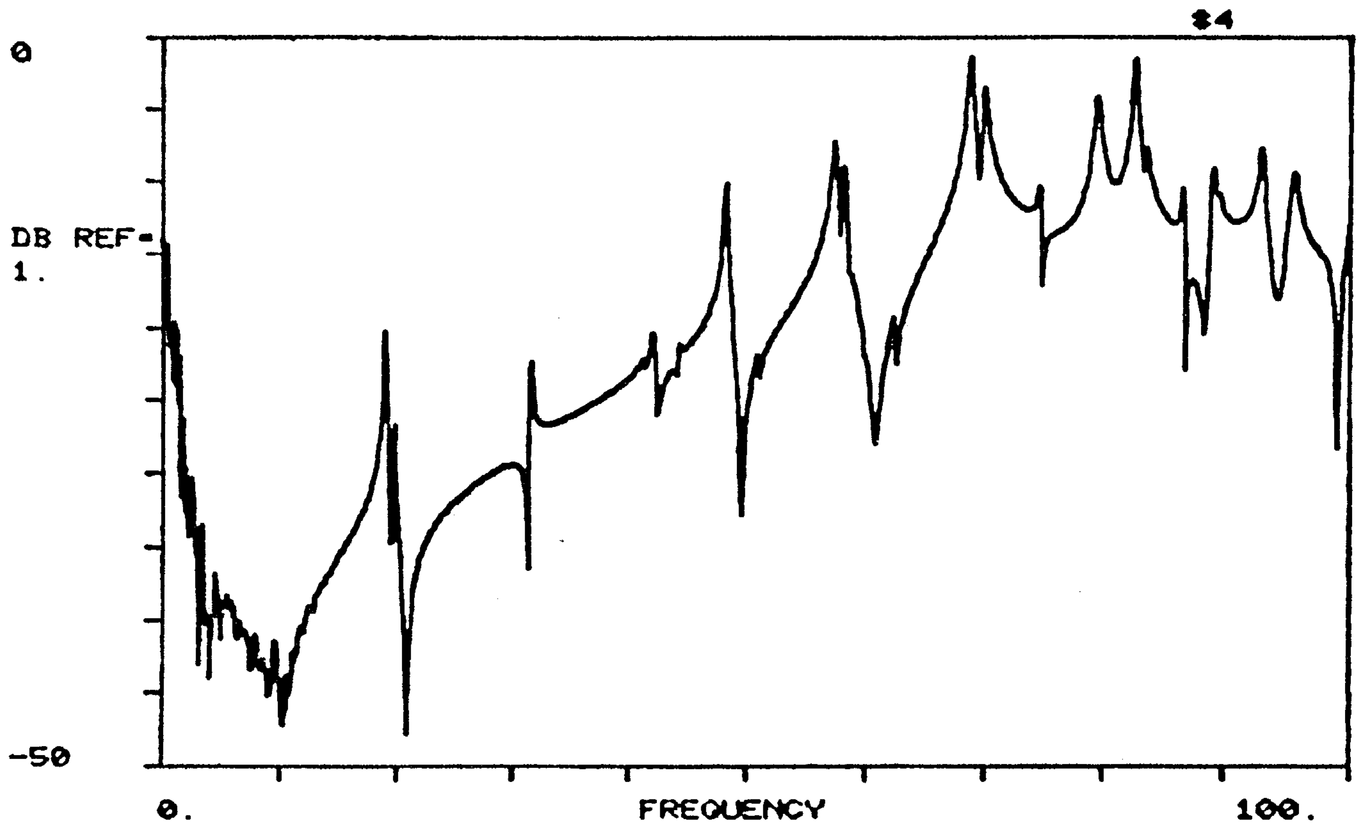
PSD PLOT
ACCELEROMETER NUMBER

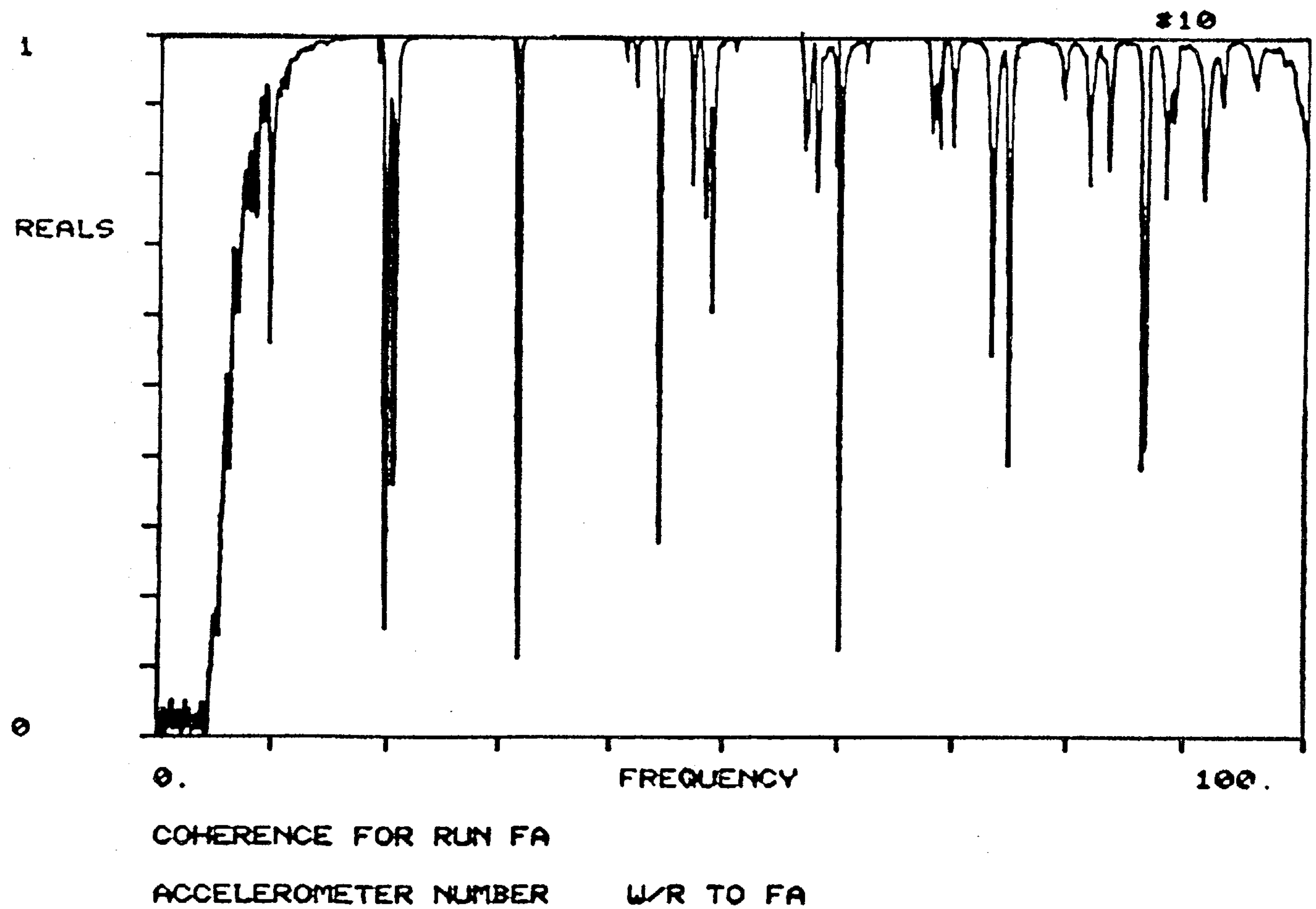
FIGURE 4-8



FREQUENCY RESPONSE FUNCTION

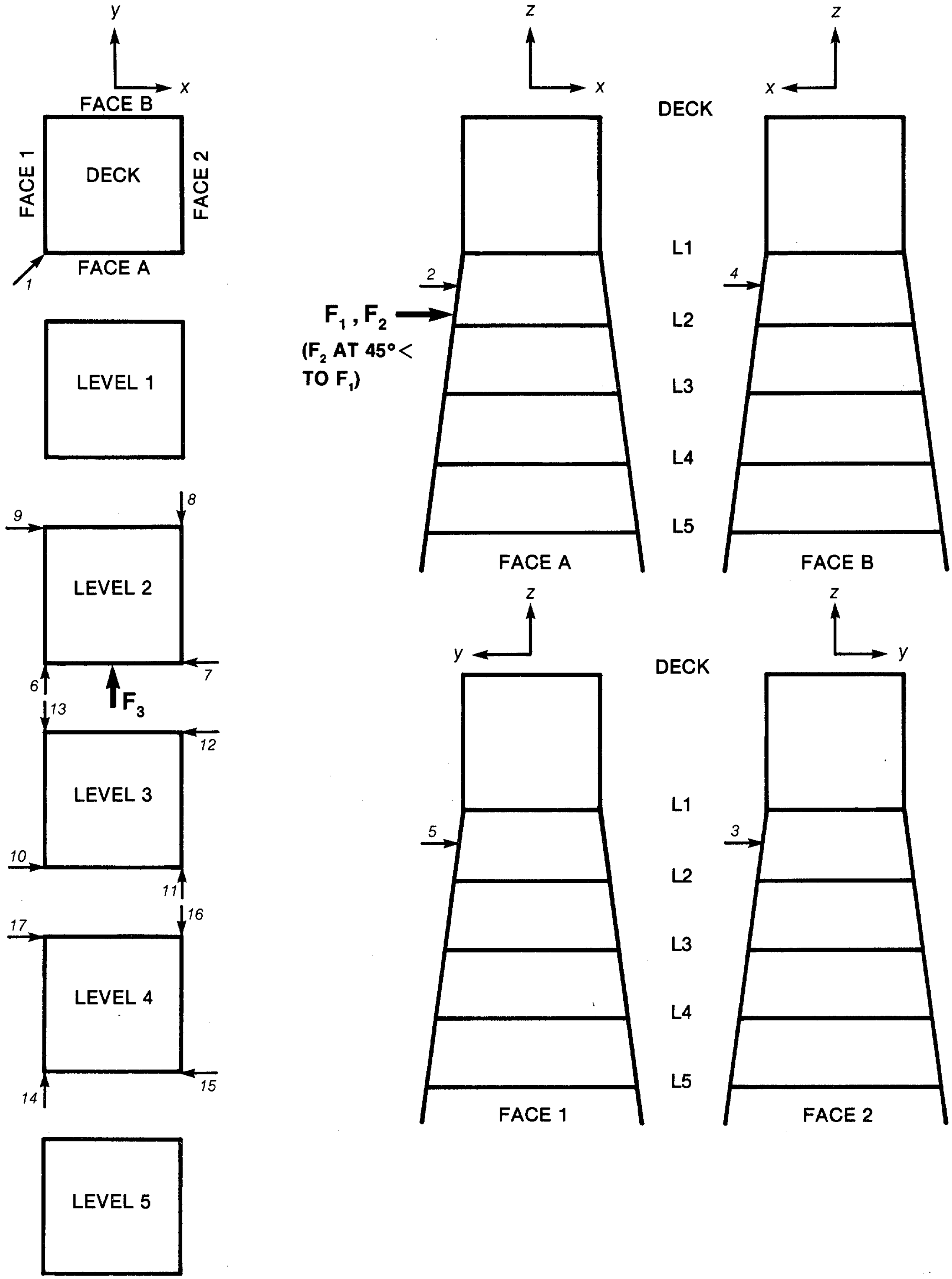
ACCELEROMETER NUMBER /FA FOR RUN FA

FIGURE 4-9



*10
1
REALS
0
0.
FREQUENCY
100.
COHERENCE FOR RUN FA
ACCELEROMETER NUMBER W/R TO FA

FIGURE 4-10



UNIVERSITY OF MARYLAND
SHAKER AND ACCELEROMETER LOCATIONS

Figure 4-11

4.4 Baseline Testing:

Using the specific procedures outlined by the test advocates, baseline data was obtained from the undamaged platform. GSFC, Northrop, and Mega personnel worked with the advocates in this phase to become familiar with the procedures. Advocates were not involved in the later test data acquisition so that the blind nature of the testing would be preserved.

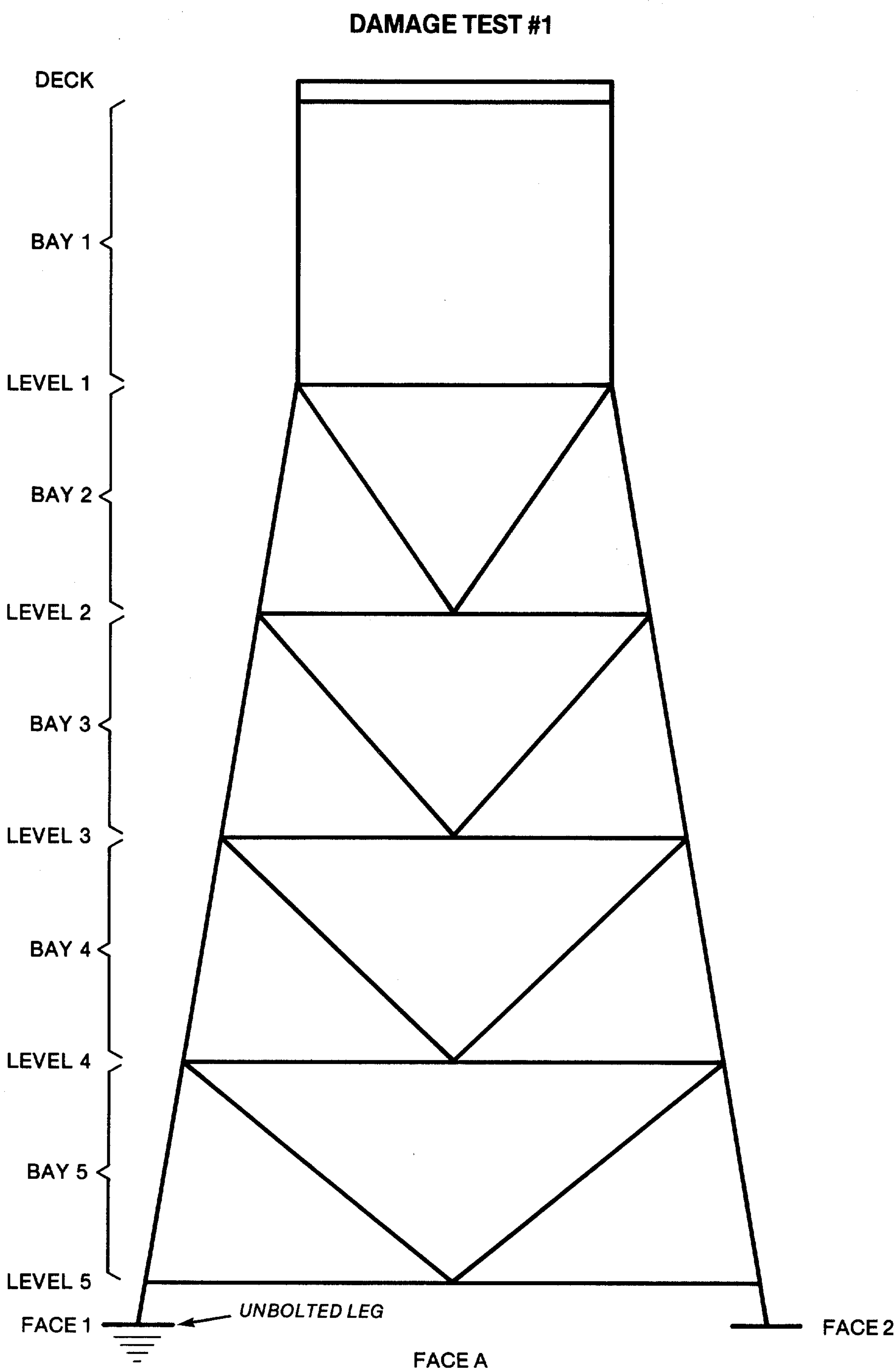
4.5 Damaged Platform Tests:

Mega Engineering then chose four damage scenarios from the list of possibilities as the final test cases. Two major damage cases were chosen, one minor damage case, and one non-damage case. Figs. 4-12 through 4-15 show these four scenarios.

Test #1 was a change in the platform foundation. The leg joining faces A and 1 was unbolted from the floor and levelling shims were removed. This was considered a major damage case.

Test #2 restored the unattached leg to the floor and partially cut through the horizontal member at level five on face B, near both its ends. Since these were only partial cuts, this was considered to be minor damage, but it would show a technique's ability to predict impending failure.

Test #3 was the total removal of the horizontal member damaged in Test #2 as well as the diagonal members attached to it. This was a major structural damage.



DAMAGE TEST #1
DECK
BAY 1
LEVEL 1
BAY 2
LEVEL 2
BAY 3
LEVEL 3
BAY 4
LEVEL 4
BAY 5
LEVEL 5
FACE 1
UNBOLTED LEG
FACE 2
FACE A

Figure 4-12

DAMAGE TEST #2

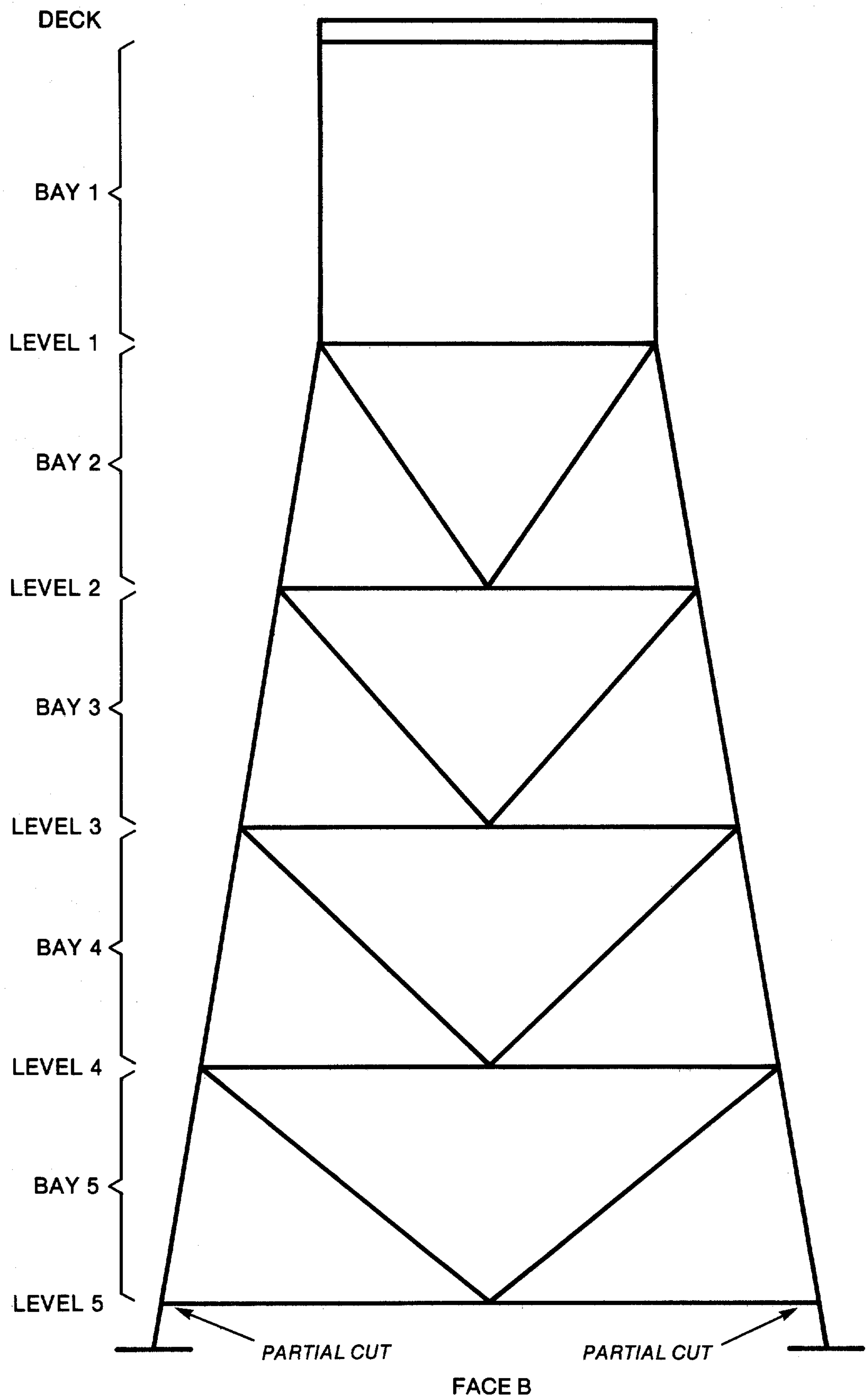


Figure 4-13

DAMAGE TEST #3

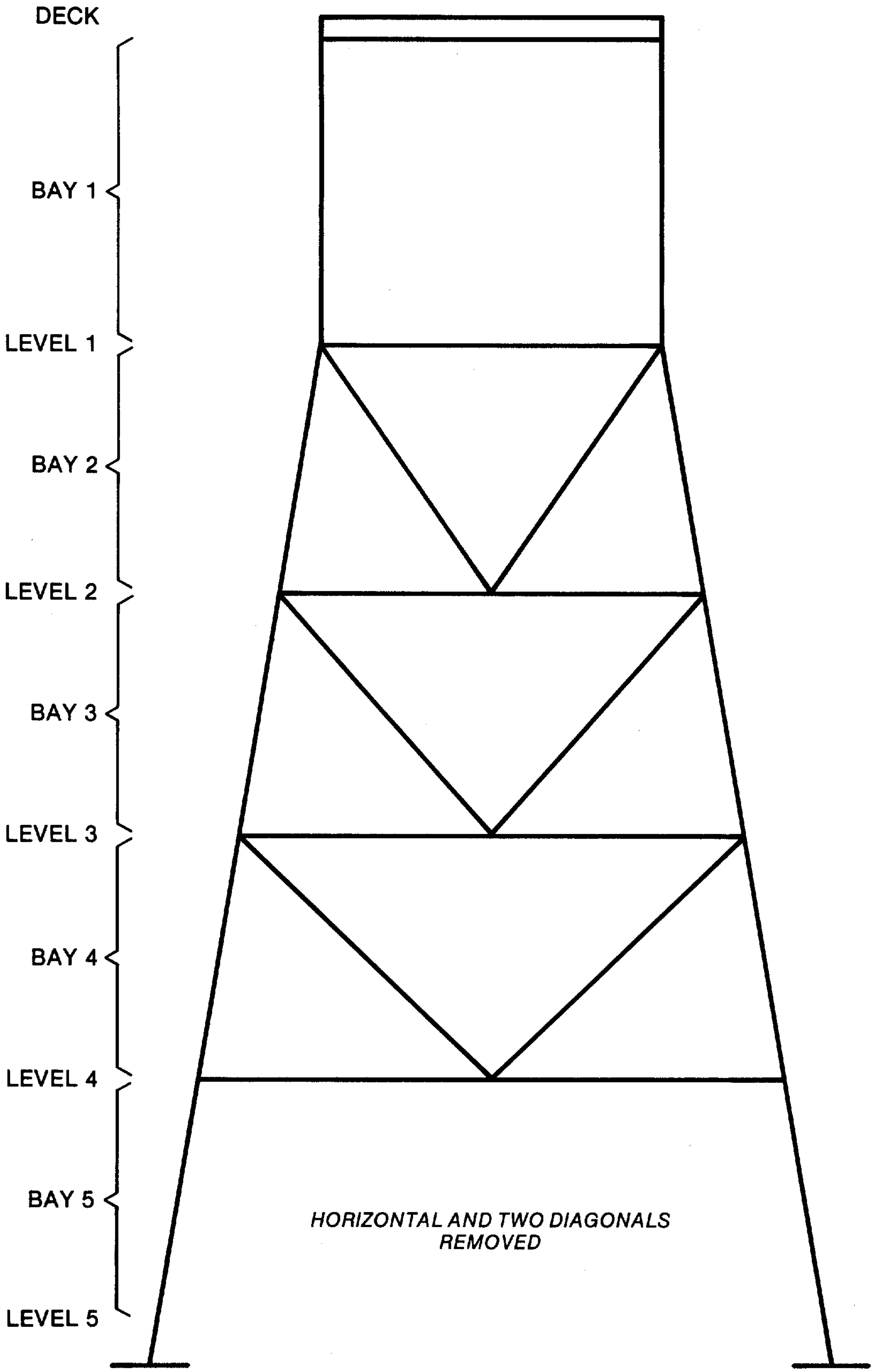
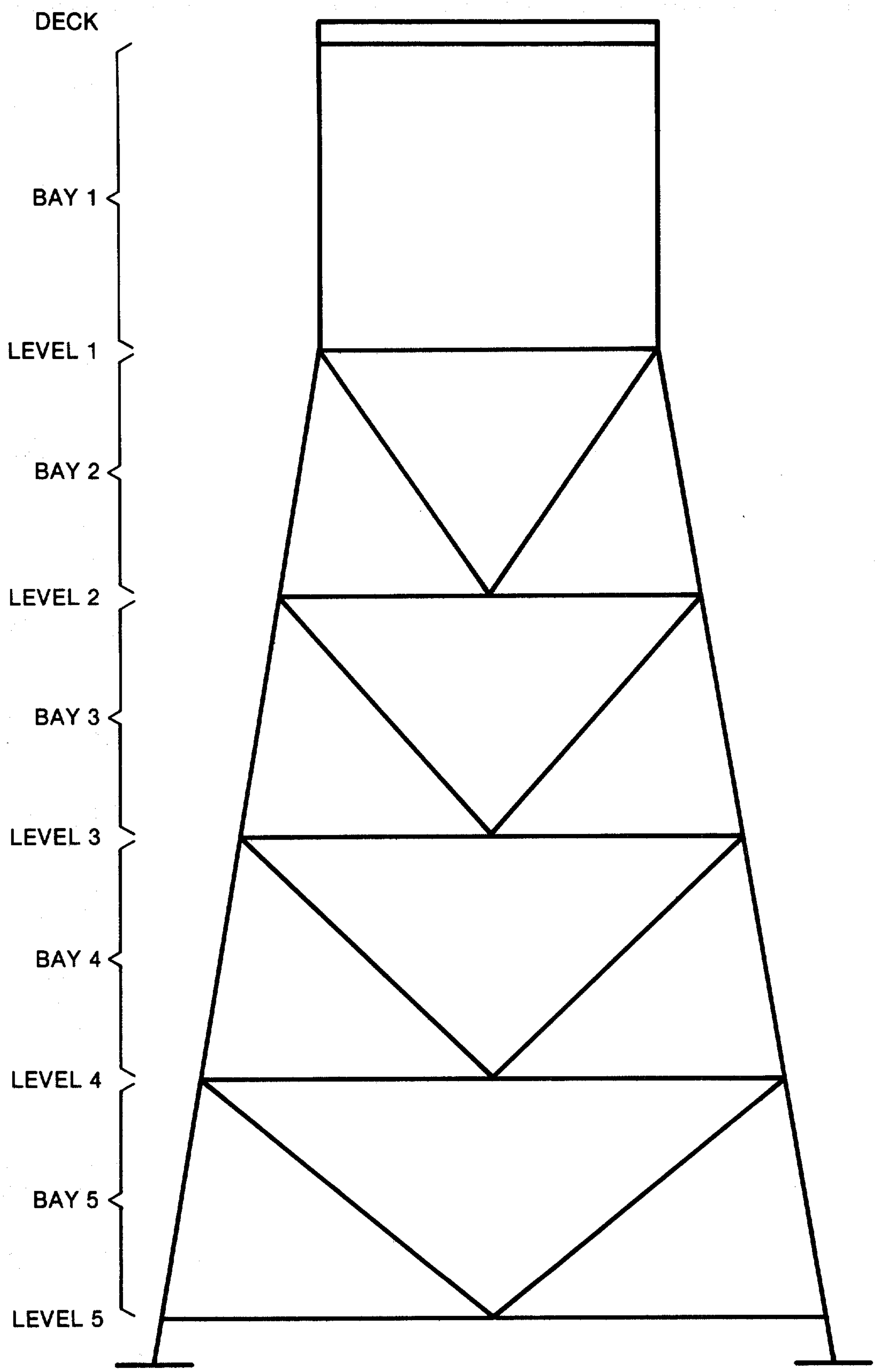


Figure 4-14

DAMAGE TEST #4



NO DAMAGE
EQUIVALENT TO BASELINE

Figure 4-15

Test #4 was originally scheduled to be a reassembly of the structure to its original form and a retest of the baseline. However, due to a shortage of funds at this point, the advocates were sent copies of the original baseline data. The purpose of this was to evaluate the repeatability of the NDE technique measurements.

All of these tests were carried out by GSFC, Northrop, and Mega Engineering personnel. Tapes, disks, and plots of the data were mailed to the advocates for failure diagnoses as they required.

4.6 Response Requested of Advocates:

The forms on which the advocates were asked to fill in their diagnoses are reproduced in Figure 4-16. First, the advocates were asked simply to determine whether or not a structural failure had occurred and also asked to give an estimate of their degree of confidence in that assessment. Second, the advocates were asked to locate the failure (if one had occurred) and to add comments about their analyses. Those comments could include estimates of the severity of the damage diagnosed, description of the particular data features which led to the diagnoses, as well as a list of any problems with the test data.

4.7 Problems Encountered:

Several problems arose in the development of the testing program and in the execution of the tests, none of which significantly impaired the evaluation process, but which do deserve mention.

Response Form for the
Round Robin NDE
of
Scale Model Tower Tests

Four tests have been conducted on a scale model of an off-shore tower structure.

Test data, as requested by each test advocate, has been sent under separate cover to each advocate.

To evaluate each technique it is requested that the following response be given to each of the four test scenarios after the baseline tests and not including the baseline tests.

1. Accuracy of Methods to Predict a Failure

The success or failure of your technique to predict a tower member failure (if one exists), or to predict that no failure has occurred (if none exists) should be recorded. The response expected is as follows:

For the test data series ________________, Test Scenario No. _______, there was:

(a) No failure ____; Confidence level * ____%
(b) A failure ____; Confidence level * ____%
(c) Cannot predict ____

* Your prediction confidence level should be given as a percentage, assigning a value 0% to 100% (where 100% would indicate a completely confident prediction).

2. Locating the Failure

If possible, locate the failure in the tower.

For the test data series ________________________

Test Scenario No. ______________, the:

(a) Tower level at which the failure occurred is: ____________________.
(b) The face on which the failure occurred is: ____________________.
(c) The location of the member is (x,y,z coordinates of member ends) ____________ ____________________________________.
(d) No failure occurred. ☐
(e) Cannot locate a failure. ☐

3. Comments

Figure 4-16

Sensor locations severely limited the types of damage allowed. With approximately 40 different sensor locations, there were a restricted number of damages which could be inflicted without leaving clear clues as to their specific nature on one of the sensors.

The order in which damage was inflicted on the structure was important. Some of the damage inflicted was irreversible in the sense that once members were partially cut or severed, the system could not be repaired without requiring a new set of baseline tests. Otherwise, discrete damage scenarios might also carry misleading evidence of altered baseline characteristics.

The complexity of the set up for each technique required that each method be tested separately, causing time problems. Due to limitations in test equipment, the number of test personnel available, and the conflicting requirements of the tests, techniques could not be tested simultaneously.

There were also problems with data collection and transmittal including problems with the University of Maryland FM tape recorder and missing data. Some of these problems are documented in Appendix G, the response sheets from the University of Maryland. It is important to note, however, that these data problems did not appear to significantly impair the ability of the advocates to make their diagnoses.

5.0 RESULTS OF TESTS

5.1 Damage Diagnoses:

The completed response sheets from the University of Maryland and from the Aerospace Corp. are included in Appendices G and H respectively. As figure 5-1 indicates, both techniques performed well in diagnosing the structural damage. Both methods correctly determined whether or not damage had occurred for all test cases and were able to assess the severity (minor or major) of that damage. Both methods were able to accurately describe the type of damage to the structure, and the Aerospace team was able to provide good locational data on the failures.

5.2 Overall Scoring:

The complete scoring system for evaluating the performance of these techniques is described in Figs. 5-2 through 5-6. In addition to being scored on the accuracy of the failure diagnoses, the techniques were graded on their testing procedure. Points were given and penalties assessed based on the instrumentation and data acquisition requirements, location of sensors, and changes made to procedures during the test period.

The purposes of the procedural scoring were many. The simplicity of a testing procedure in terms of the number of sensors required and the data analysis requirements was rewarded, as being a beneficial attribute of NDE techniques in general, and also as a way to help the program to remain within manpower and budgetary constraints. The scoring also rewarded features of the techniques which would be directly beneficial specifically in offshore analysis, such as minimization of underwater sensor locations.

SUMMARY OF DIAGNOSES SCORING

TEST NO.	DAMAGE TYPE *	U. OF MARYLAND, RANDOM DECREMENT				AEROSPACE CORP., FREQUENCY RESPONSE			
		A	B	C	D	A	B	C	D
1	MAJOR (5)	X	100%	X	O	X	100%	X	O
2	MINOR (9)	X	100%	X		X	50%	X	O
3	MAJOR (1)	X	100%	X		X	100%	X	X
4	NONE	X	100%	X	N/A	X	100%	X	N/A

* See Table 4.1

A - Identification of damage vs. no damage

B - Confidence in diagnosos

C - Severity of damage

D - Location of failure

X - Correct answer

O - Partially correct answer

Figure 5.1

Proposed Procedures for
Comparing Round Robin NDE Methods

The NDE methods used for the scale model tests will be evaluated in two parts. A separate score will be given for each part. First, the degree of difficulty in performing each procedure will be considered. Specifically, points will be awarded based on the following criteria:

1. Test instrumentation requirements
2. Location of accelerometers relative to water lines.
3. On-site analysis requirements.
4. Changes to NDE methods after baseline tests have been proposed.

Secondly, failure prediction capabilities will be scored. Specifically, for each series of tests after the baseline, points will be awarded for the following:

1. Accuracy of methods to predict a failure
2. Accuracy of methods to locate a failure

Each of these factors is explained below along with the proposed scheme for weighting each.

Fig. 5-2

Evaluation Part I: Difficulty in Performing Tests
(1 points possible)

1. Test Instrumentation - 4 points possible

The number of data channels for each forcing function for each test will be computed for each advocate. A data channel will be interpreted to include any discrete measurement made by GSFC. This number will be called N for each advocate and the average of the three values will be called N_{avg}.

$$\text{No. points} = 2 \text{ pts } (1 - \frac{N - N_{avg}}{N_{avg}})$$

For example, if 3 advocates use 60 channels, $\bar{N} = 20$; and if one of the advocates uses 4 channels,

$$\text{No. points} = 2 \ (1 - \frac{4 - 20}{20}) = +3.6 \text{ pts.}$$

Note: The point total will be bracketed at ±4 points.

2. Location of Accelerometers Relative to Waterline

The number of accelerometers below level I will be computed for each advocate. This number will be called NBW and the average value of this number for the three advocates or NBW avg. Points will be awarded as follows:

$$\text{No. points} = 2 \text{ pts } (1 - \frac{NBW - NBW\ avg}{NBW\ avg})$$

Note: The point total will be bracketed at $\pm$ 4 points.

Fig. 5-3

3. Test Analysis - 4 points possible

The number of analysis steps on each data channel for each forcing function for each test will be computed for each advocate. Analysis steps will include such things as computing PSD plots, transferring data from disk to tape, etc. This number will be called NA and the average of this number for the three advocates will be called NA_{avg}. Points will be awarded as follows:

$$\text{No. points} = 2 \text{ pts. } \left(1 - \frac{NA - NA_{avg}}{NA_{avg}}\right)$$

Note: The Point total will be bracketed at $\pm$ 4 points.

4. Changes to NDE methods after baseline tests have been proposed - 2 points.

If the test procedure is significantly reduced in scope (e.g., several accelerometers removed, forcing functions eliminated, etc.), a maximum of +2 points will be given.

If the test procedure is significantly changed (e.g., accelerometers relocated, forcing function changed, etc.), a maximum of 3 points will be assessed.

Fig. 5-4

1. Accuracy of Methods to Predict a Failure

The success or failure of each technique to predict a tower member failure (if one exists), or no failure (if none exists) will be recorded. The response expected from each advocate is as follows.

For the test data series ______________________________ there is:

(a) no failure ___
(b) failure ___
(c) cannot predict ___

A failure may be reflected by a cut or complete removal of a member or by fatigue failure of a member.

A point score of +5 points will be given for a correct prediction of (a) or (b) and 0 points will be given for (c). A -5 point score will be given for an incorrect prediction for (a) or (b).

2. Locating Failure

Locating a failure by an NDE method will be evaluated by:

	points
(a) level of failure	1
(b) face of failure	1
(c) location of member (x,y,z coordinates)	3
(d) no failure	1
(e) cannot locate failure	0

Fig. 5-5

For each <u>incorrect</u> location description, i.e., (a) or (b), -1 point will be assigned. For an incorrect member selection, -3 points will be assigned.

Fig. 5-6

OVERALL TECHNIQUE SCORING AND COMPARISON

1)<u>Test Instrumentation</u>

Randomdec	17 accelerometers
	3 shakers
	20 pieces of data
Frequency Response	34 accelerometers
	2 shakers
	36 pieces of data

Scoring points = 2(1-(N-Navg)/Navg)

Randomdec	+2.6 points
Frequency Response	+1.4 points

Note: same for all test scenarios

2)<u>Location of Accelerometers Relative to Waterline</u>

"Below Waterline" means below Level #1

Randomdec	16 accelerometers below level #1
Frequency Response	17 accelerometers below level #1

Scoring points = 2(1-(N-Navg)/Navg)

Randomdec	+2.1 points
Frequency Response	+1.9 points

Note: same for all test scenarios

3) Number of Analysis Steps

Randomdec - used only raw data (1 step)

Frequency Response - generated 2 PSD, 1 Frequency Response, and 1 Coherence Plot, plus raw data (5 steps)

Scoring points = 2(1-(N-Navg)/Navg)

Randomdec +3.3

Frequency Response +0.7

Note: same for all test scenarios

4) Changes in Test Procedure

Neither test procedure changed in terms of the amount of data acquired.

Randomdec +0.0

Frequency Response +0.0

Note: same for all test scenarios

5) Accuracy to Predict a Failure

	Randomdec	Frequency Response
Test #1	+5	+5
Test #2	+5	+5 *
Test #3	+5	+5
Test #4	+5	+5

* 50% confidence

Notes: all predictions with 100% confidence except where noted; all predictions gave correct level of damage (i.e. major vs. minor)

6) Locating and Identifying Failure

	Randomdec	Frequency Response
Test #1	+1 leg failure	+1 leg failure
	+1 correct face	+1 narrowed to 1 of 2 legs
	-3 wrong leg	
Test #2	+1 minor damage	+1 minor damage (50% confident of 5th level horizontal failure)
Test #3	+1 major damage	+1 major damage
		+1 correct face (B)
		+3 diagonals severed, lowest bay
Test #4	+1 no damage	+1 identical to baseline
Total	+2	+9

5.3 Conclusions and Comments:

5.3.1 General:

The general conclusion to be drawn from the results is that both methods completing the test program proved capable of detecting structural failure in a blind mode in the laboratory test program. Further, they were both able to assess the seriousness of those failures.

Beyond this, the Frequency Response Method performed better in locating failures and the Random Decrement Method was most confident in diagnosing low levels of damage.

5.3.2 Sensor Network:

The Random Decrement method showed the ability to determine the existence of a failure using a very minimal sensor network. Although the University of Maryland asked for seventeen sensors to be located on the structure initially, they asked only to be supplied with the data from six of those sensors which were located high on the platform (above level #2 of the structure and, therefore, above the presumed water line). They claim that their diagnoses were made on the basis of only four of these sensors, and in general, their diagnoses were correct.

It is not clear why the University of Maryland team wished to have 17 sensors located but only receive some of that data. It might be presumed, however, that the large network was necessary to cover the full range of damages that could have occurred, and to provide a reserve of data if the limited data requested proved to be insufficient.

The Aerospace Corporation asked for 34 accelerometers to be located on the structure. They did not request to receive only a subset of the data, and so, data from all of these sensors was provided to them. In their final report they said that they only used the data from a total of 19 of those sensors, numbers 1-15 and 29 to 32 in their diagnoses. They noted that these 19 accelerometers were located either "above water" or on the main legs of the platform where, for some structures, instrument chutes will be available. In the final report by the Aerospace Corporation, the specific sensors used in each piece of diagnosis are enumerated. Data from the other 15 accelerometers was used for verification of the modal parameters in the Aerospace finite element model, and would also have been necessary had local monitoring techniques been employed by Aerospace in their diagnoses.

5.3.3 Details of Diagnoses:

The following section summarizes the information contained in the final reports of the two technique advocates relating to how they performed their diagnoses. For further details, the reader is referred to those final reports.

Frequency Response Method-

In their diagnoses, The Aerospace Corporation used three methods of analyzing the frequency response data:

- Global mode monitoring using data from above water sensors to observe changes in three fundamental platform modes.
- Flexibility monitoring using above water sensors and sensors mounted on the platform legs to perform this new type of anaylsis.
- Brace mode monitoring using above water sensors to observe changes in a number of higher frequency modes associated with certain restricted areas of the platform.

In addition to the above methods, Aerospace could have used local mode monitoring using below water sensors to monitor specific structural members. However, they indicated they did not use this method in this program.

The basis for interpreting the frequency response data in terms of specific structural changes was by comparison to data generated by a NASTRAN finite element model. A model was generated to represent the baseline structure and modal parameters were verified in the baseline testing sequence. Aerospace then simulated with their model the failure modes which had been pre-defined as possibilities in the Round Robin program, cataloging the significant changes in modal parameters.

Damage Case 1:

For this damage scenario, global mode monitoring from above water accelerometers provided a clear indication of the nature of the failure. A large change in the frequency of a fundamental platform mode matched up with predictions from the NASTRAN model for this type of damage.

Flexibility monitoring supported the conclusion of global mode monitoring by showing uniform increases in flexibility across all bays.

Although the Aerospace team was not able to pick the leg which had been damaged, they were able to narrow it down to one of two legs which included the damaged one. Further, they note in their report that missing data from an above water accelerometer would have provided verification of the correct leg.

Brace mode monitoring was not necessary in verifying the type of damage in this scenario once the problem was diagnosed with the other two methods.

Damage Case 2:

In this damage case the only evidence of damage that could be detected were small changes in brace modes based on data from above water accelerometers. The specific nature of the brace mode changes allowed the Aerospace team to narrow the structural change to the lowest bay.

The Aerospace diagnosis was only given a confidence level of 50%, however, because they had no way of telling whether the change was damage or a non-damage change such as simulated marine growth or member flooding.

Damage Case 3:

Analysis of platform fundamental mode shapes provided a clear indication of brace damage and narrowed the damage down to the lower portion of the correct side of the structure.

Flexibility monitoring further narrowed the damage down to the correct bay.

Damage Case 4:

Anaylsis made clear that this data was identical to the baseline data.

Random Decrement Method-

In their diagnosis, the University of Maryland team used a few types of analysis:

- Two types of measures were used to quantify the differences between the damage scenario signatures and the baseline signatures. Threshold levels of change were established to diagnose the existence of damage and severity of damage.

- There was apparently analysis of other characteristics of the signatures such as damping changes. The specifics, however, were not addressed in the report.

The basis for interpreting the signatures in terms of specific damages that had occurred appeared to incorporate a few methods:

- The report indicates that the primary method of interpretation is comparison of each damage signature to the baseline. In addition, the damage to baseline differences for each run were compared to the differences in other runs. This aided in selecting each damage from the list of possibilities.
- There also appeared to be some experience related intuition about what signature changes signify what types of damage for these structures.

Damage Case 1:

The Randomdec signatures for this scenario showed large changes in the low frequency filtered signatures and small changes in the higher frequency signatures, especially relative to other damage scenario signatures. This led to a diagnosis of bottom leg failure out of the possible options.

The Maryland team attempted to diagnose which leg had failed but chose the wrong one. The basis for the choice was the accelerometer with the largest magnitude of signature change, but apparently this was misleading.

Damage Case 2:

The diagnosis of this failure was based on the fact that the magnitude of change in the signatures indicated that the damage was much less serious than the damage in either scenario #1 or #3. Further, the signatures were qualitatively like the signatures from scenario #3, indicating that they were a lower level damage of the same type.

Although the Maryland report does not indicate how this small damage was differentiated from a small no-damage change, they were 100% confident in their diagnosis.

Damage Case 3:

The relatively large changes in the higher frequency signatures along with relatively small changes in the low frequency signatures suggested that this was a brace failure damage. The uniformly high deviations across all signatures relative to the baseline indicated that the damage was significant.

The report also mentions that analysis of the signatures' damping characteristics suggested a cross member severance, however, no quantitative analysis explaining this comment is given.

Damage Case 4:

For this case the damage signatures were sufficiently similar to the baseline data to indicate that there was no change in the structure.

5.3.4 Questions, Comments, and Criticisms of the Methods:

Random Decrement Method-

A major criticism of the Random Decrement Method is that it is not capable of locating failures in a complex structure. The existing literature on Random Decrement methods has not offered any systematic procedures for failure location. This criticism was substantiated by the Round Robin test program. As the results presented in this report indicate, the University of Maryland team did not offer detailed response on the specific location of the failures, and where they did try to make an estimate, the technique was incorrect.

In the University of Maryland report the analysis of data seemed to be largely based on comparing various damage scenarios in light of the anticipated failure modes. It is not clear if this would hinder its diagnostic performance in a real time analysis of structural changes.

The ability of the Random Decrement method to distinguish between damage and non-damage structural changes in real platform environments has also been questioned. Unfortunately the Round Robin test series did not attempt to simulate in the lab some of the potentially confusing circumstances. This question remains to be resolved in future testing either in the laboratory or in the field.

It must be said for the Random Decrement Method that the Round Robin program was not set up to show off the technique at its best. The Random Decrement method is primarily aimed at early failure detection by global monitoring of high frequency vibrational data. In the Round Robin program, data was taken at discrete intervals in damage instead of continuously, and most of the damage tended to manifest itself by substantial shifts in low frequency modal parameters. It should be noted that in Damage Case 2, the Randomdec method showed clear evidence of damage by virtue of high frequency response data.

Frequency Response Technique-

The first question about The Frequency Response Method regards its ability to function strictly on random response data. In their final report Aerospace states that the global mode monitoring can certainly be used with pure random output data, flexibility monitoring can probably be used with random response data, and that brace mode analysis would probably require forced excitation to make results clear.

From the test program and the final report of Aerospace, it is not clear that these questions have been resolved. Aerospace was provided with reduced data that not only showed the structure's response to the input shakers but the response relative to the inputs.

Another question regards brace mode monitoring based on above water sensors. Aerospace stated that extraneous noise from equipment on a real platform could mask the response changes in this frequency range.

Mass changes of certain types also can create diagnostic problems. Based on their NASTRAN model, Aerospace noted that there were certain types of mass change which they were prepared to diagnose, however, in Damage Case 2 of the Round Robin they specifically could not rule out a lower member mass change as the cause of frequency response change.

The Aerospace report made brief mention of another point that deserves mention. They stated that in performing the global mode monitoring, they could not work with higher order global mode data because, in the scale model, these modes occurred at unrealistically high frequencies. This leaves the question as to whether more detailed diagnosis based on global mode monitoring alone could be made in a real platform where this data is available.

Aerospace was eager to show the capabilities of the flexibility monitoring technique and in the tests, the technique appeared to perform quite well. Although this technique requires below water sensors it should be noted that they are necessary only on the legs which is a plus for platforms equipped with instrument chutes.

5.3.5 Summary Comments By Test Agent:

Although the Round Robin Test Program was set up in the form of competition between NDE techniques to diagnose the same set of test conditions, the broader, underlying purpose of the Round Robin was, of course, to explore as fully as possible the capabilities of each technique. In this regard, the information presented in this report and the information contained in the final reports of the technique advocates provides a complete and detailed account of test design, test execution, analysis performed, comments on all phases, and implications of the testing. It should be pointed out that only a full review of this information gives a fair review to the techniques evaluated.

After reviewing the Round Robin program in total, it has become apparent that the two techniques evaluated cannot be fairly compared strictly on a point-for-point competitive basis. Both techniques have their particular strengths and weaknesses, and certain types of monitoring tasks for which they are particularly well suited. On the whole, the Random Decrement Method substantiated its ability to identify the occurance of damage to the test structure, but did not show the ability to specifically locate the failure within the structure. Using a more detailed type of analysis based on a larger number of accelerometer inputs, the Frequency Response Method was able to generate fairly accurate locational data on the failures in addition to establishing their existence.

6.0 ULTRASONIC TESTING

In addition to the study of the two global monitoring techniques, an Ultrasonic Method for assessing damage to a complex, but local, structural element was evaluated. The advocates for this procedure were a team from Drexel University headed by Dr. Joseph Rose.

6.1 General Principles:

The general principle of this technique is to observe changes in the transmission of ultrasonic waves through a member which indicate that a crack has developed. The joint effectively acts as a filter for an input ultrasonic beam, and the change in the filtering characteristics as damage occurs, are the indications of failure.

An ultrasonic pulser is attached to the joint as well as one or more receiving transducers. The location and orientation of these items depends on several technical judgments including assessments of likely areas for failures to initiate and consideration of ultrasonic wave propagation theory. The pulser inputs a specific frequency of ultrasonic waves to the joint and a power spectrum density plot is generated at each of the receiving transducers. The plot from an undamaged joint serves as a "template" against which future test data is compared.

Destructive tests of sample members (scale models for large structures) are then conducted and power spectrum density plots are generated for various sizes and types of cracks and failures. Comparison of this data with the original template, using statistical techniques, establishes threshold levels of mismatch indicative of serious damage.

More detailed information on this method is given in the articles listed in Appendix I.

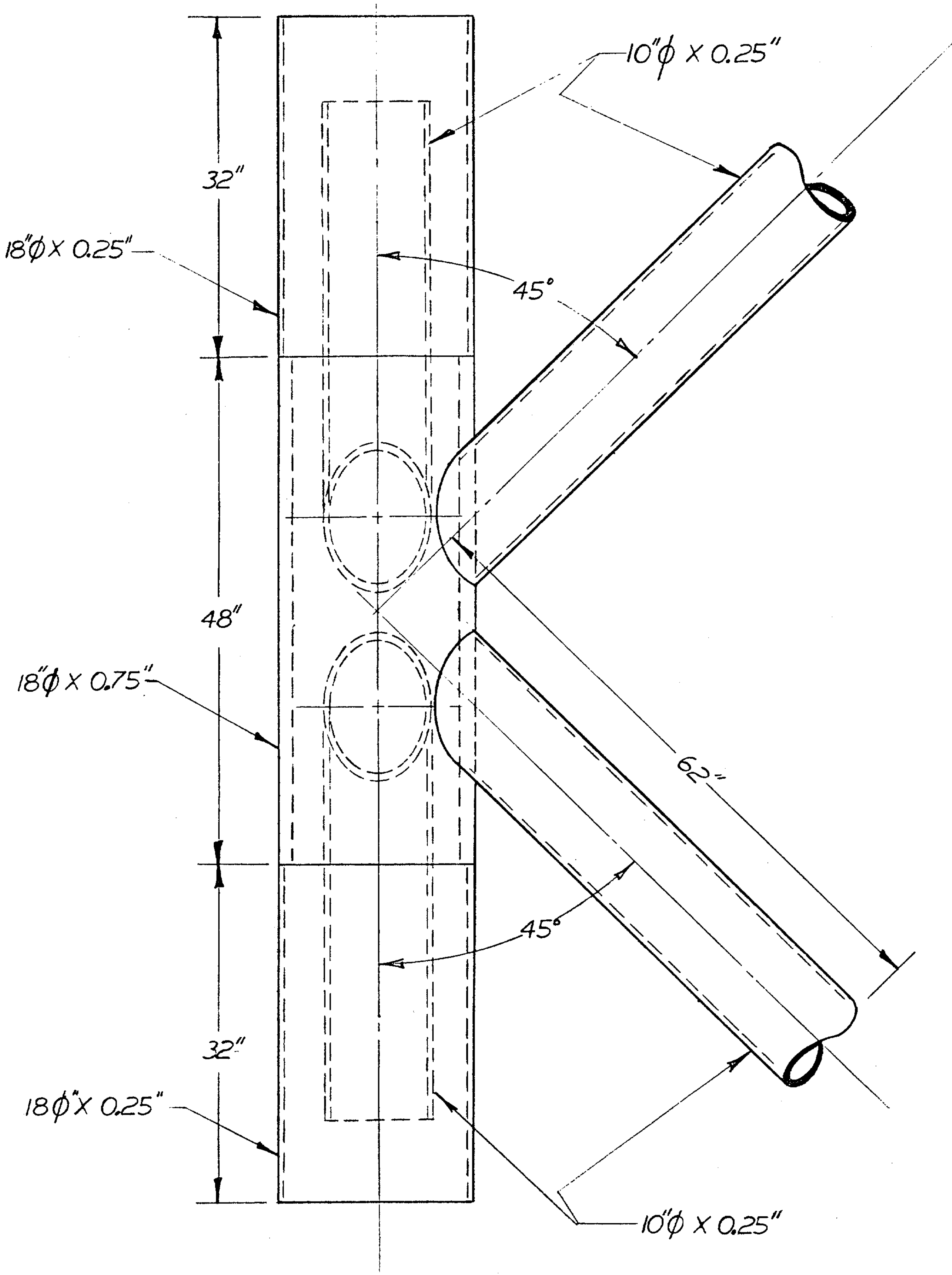
6.2 Test Program:

The test program chosen for evaluating this technique was a destructive fatigue test of a scale model K-joint. The K-joint is a typical jacket platform element. The Drexel team was asked to anticipate failure based on the output data from their equipment as the test was in progress. Figure 6-3 shows a schematic of the experimental set-up*.

The K-joint used in the testing was a 3:1 model constructed for the Round Robin program at the University of Maryland under the supervision of Dr. Jackson Yang (see Figs. 6-1 and 6.2). The joint weighed about 1800 lbs. and was constructed of A-36 steel. Appendix J includes details of its construction and of preliminary testing of the model.

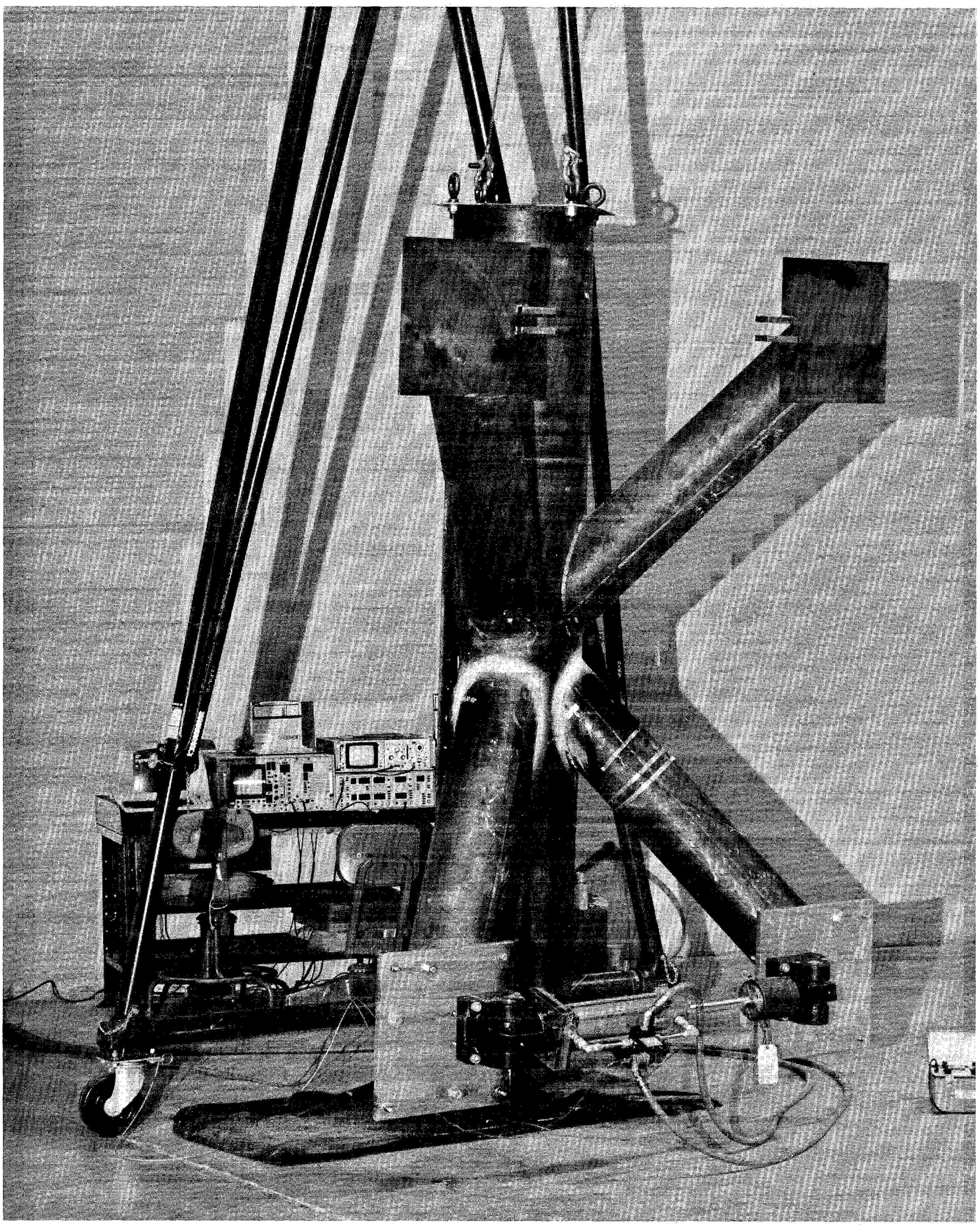
The joint was tested prior to the destructive test series to determine its approximate fatigue life. This data, which is included in Appendix J, was used to choose a loading pattern which would keep the duration of the fatigue test within reasonable time bounds.

*It might be noted here that the Acoustic Emission technique was to be tested on this fixture at the same time as the Drexel tests.



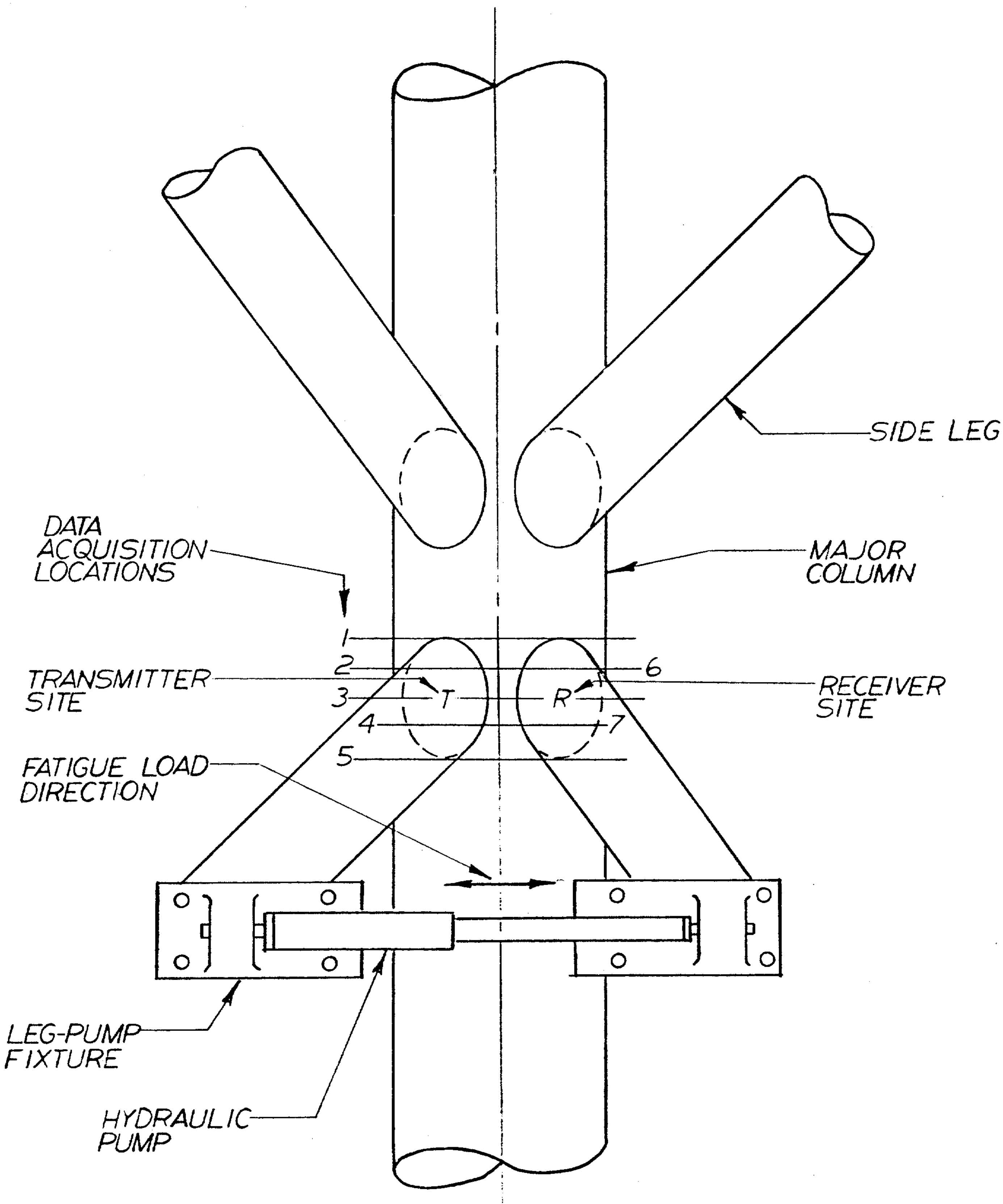
SCALE MODEL K-JOINT

Figure 6-1



NASA-G- 80-7934

Fig. 6-2



ULTRASONICS INSTRUMENTATION

Figure 6-3

Prior to the test sequence, Drexel performed destructive testing on smaller scale model K-joints (19:1 and 11:1) in order to establish the template mismatch thresholds indicative of incipient failure in this type of joint.
Table 6-1 shows the loads applied and the duration of the fatigue test. The frequency of the cycling was 2 Hz at low loads and was later dropped to 1 Hz for higher loads due to the limits of the hydraulic cylinder used to stress the K-joint. Notice that loads were increased substantially over the course of the test. This was done in order to keep the overall time of the test to a reasonable level.

Ultrasonic data was taken every 7200 cycles. Visual inspection was performed every 3600 cycles for reference, and at times, dye penetrants were used to assure accurate visual identification of the onset of failure. The first visible crack appeared shortly before cumulative cycle #33,000. Total failure did not occur until 10,000 cycles later, after the loads were increased substantially (see Table 6-1).

6.3 Results:

An imminent failure was first predicted on the basis of ultrasonic measurement at cycle #41,400 when a crack 6-3/4" long had formed at the joint (approximately 17% of the weld length). Template mismatches for some frequency bands of the transducer output became sufficiently large at this time to indicate damage. Figure 6-4 shows the time history of the template similarity coefficient for these locations.

TABLE 6-1

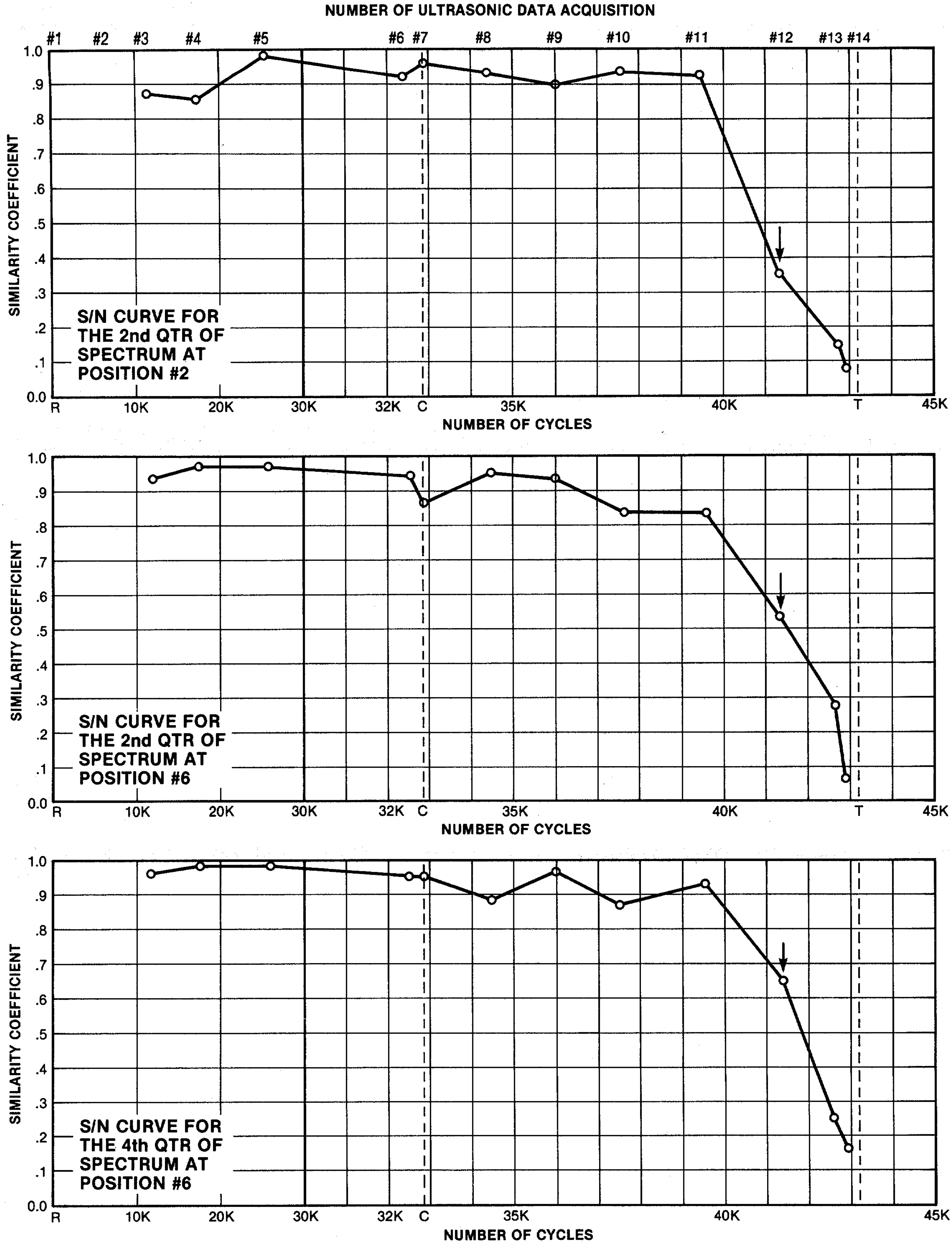
Summary of Test Cycling Sequence on K-Joint

Cycle Sequence	±Load (lbs)	Cycles	Cumulative Cycles
1	4000	3600	3600
2	4000	2200	5800
3	4000	1400	7200
4	5000	3600	10800
5	5000	3600	14400
6	5000	3600	18000
7	6000	3600	21600
8	6000	3600	25200
9	7000	1800	27000
10	7000	1800	28800
11	8000	3600	32400
12*	9000	573	32973
13	7000	1227	34200
14	7000	1800	36000
15	8000	1800	37800
16	9000	1800	39600
17	10000	1800	41400
18**	12000	600	42000
	13000	200	42200
	14000	200	42400
	15000	200	42600
	16000	184	42784
19		203	42987
20		205	43192

Total Failure in K-Joint

* First visible crack appeared

** Plastic deformation in this region



NOTE: ↓ THE POINT OF DAMAGE DETECTION BY ULTRASONICS

TYPICAL S/N CURVES (THE THREE BEST RESULTS)

Based on the cumulative number of cycles at the time of failure prediction (41,400) and the cumulative number of cycles at ultimate failure (43,192), it can be concluded that the detection was made with 4.2% of the structural life remaining. However, this is a low estimate since the cyclic load was increased greatly after the 41,400 cycle point which shortened the joint's life.

6.4 Conclusions:

Generally, the results of the test program should be considered very good. The technique showed its ability to predict an impending failure at a point where remedial action could still be taken.

However, it would appear that this technique requires a very large amount of analysis before any monitoring program can be initiated since the placement of transmitters and sensors and the determination of template mismatches is unique to many specific cases. It also appears that this technique can only give information on a the set of particular locations it is set up to monitor. Although judicious selection of the most likely sites for failure may make this a satisfactory monitoring technique, for large structures a very large numbers of transmitters and sensors may be required.

6.5 Recommendations:

At the conclusion of the testing program, four recommendations were made by the Drexel team:

- A test with constant fatigue load should be undertaken to better assess the remaining lifetime at which failure is predicted.
- Tests in water should be conducted. The attenuation of the ultrasonic pulse within the steel is a function of the steel's interface with its environment.
- Transducers should be permanently mounted for improved sensitivity.
- A study on the implementation of this technique in the field (i.e. in offshore structures) should be made.