TANK LEVEL DETECTION DEVICES

FOR THE CARRIAGE OF OIL

OIL POLLUTION ACT OF 1990,

SECTION 4110

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1 Executive Summary

This study was conducted to assess the technical feasibility of satisfying the requirements of Section 4110 of the Oil Pollution Act of 1990 (OPA 90), which calls for minimum regulatory standards tank level monitoring devices in the cargo tanks of tank vessels.

1.1 Technology survey The survey found that a wide variety of liquid level sensing systems are available, for both marine and shoreside applications. Their capabilities have improved in recent years as a result of the need for better accountability for most liquid commodities. This has been, primarily, for reasons of custody transfer in the oil tanker industry, and, in many shoreside industries, for environmental protection as well.

The legislative history of Section 4110 includes discussion of the need for cargo tank leak detection. This implies either the development of new technology or physical and operational enhancements of existing marine oil cargo sensors. Substantial upgrades of systems now used shoreside would be required for use on vessels; many possibilities exist for such adaptations.

1.2 Operating environment A marine oil cargo tank represents a severe operating environment in which many factors of measurement uncertainty (noise) are manifest (the use herein of the term "environment(al)" denoted the operational conditions of the vessel or the sensing device, unless otherwise noted). Some sources of noise, such as cargo stratification and deformation of tank boundaries will degrade the performance of any liquid level detection system employed, while the impact of others will vary depending on the type of sensor.

1.3 Sensor performance Sensor performance is a measure which includes the performance of the sensors under ideal conditions and the uncertainty due to environmental noise. Although manufacturers may claim accuracy as fine as 0.1%, such claims are not always supported by testing and must be viewed skeptically until proven. Environmental noise can substantially degrade performance further and give rise to false positive and false negative leak indications. The "attainable accuracy", defined as the limit outside of which false leak indications may be ruled out, is expected to be 1.0-2.0%, depending on the system used and assuming realistic additive noise effects for several different sets of operating conditions.

This study assumes that an alert operator will, in the absence of other evidence, respond to a suspected leak only when the sensor indicates a level change exceeding its attainable accuracy, which he has learned from experience. This number was figured conservatively at 1.0%, assuming a mix of benign and severe conditions and conscientious, knowledgeable operation by the crew. Table 1-1 gives minimum level changes and outflows which occur before this threshold is reached, for several typical tank vessels.

Tank Vessel	Cargo Tank Size [LxWxD] (ft)	Threshold Level Change (mm)	Outflow (gal.)
400,000 DWT VLCC	110.2x45.9x95.2	290.4	36,075
77,000 DWT tanker	75.0x90.4x58.4	178.1	29,660
25,000 bbl barge	47.9x20.0x17.2	52.5	1,239
130,000 bbl barge	60.0x34.4x29.3	89.4	4,535

Table 1-1
Minimum Detectable Outflows

The ability to detect slow leaks from very small hull breaches such as slowly forming cracks in the plating is quite limited and will depend upon the ability of the sensor and the crew to identify an appreciable level change which occurs over a long period of time. Many possible scenarios were developed where combinations of tank loading and draft resulted in zero hydrostatic outflow. A more serious outflow, such as the barge failure in the Chesapeake Bay which is part of the legislative history of Section 4110, would be detected very quickly by a continuously operating sensor being monitored by the watchstander.

Several system enhancements are suggested which could mitigate the uncertainties of cargo oil level detection, and improve leak detection performance. An alarm system integrated with the level indicator and other suggested environmental data collection is one approach to effective leak response.

1.4 Fleet baseline The study did not include any concerted effort to determine the baseline of existing tank level detection systems in the affected tank vessel fleet. Our limited inquiries have however shown that many large tanker operators, particularly in the crude trade, are using the most modern marine liquid level detection equipment available, for reasons of reliability, maintainability, and accurate accounting for custody transfer. Other fleet sectors, especially barges, only comply with existing U.S. Coast Guard requirements for tank sounding.

Compliance with Section 4110 might therefore be a matter of system modifications only or acquisition of whole systems by others.

1.5 Conclusions The intent of OPA 90 Section 4110 is to provide for the quick and reliable detection of small cargo leaks from tank vessels by modern sensing devices. While this goal is somewhat limited by available technology, implementation of the law could have the following results:

- Continuous monitoring of cargo tanks will be routine, and watchstanding duties increased.

- The ability of tanker and tank barge tugboat crews to monitor continuously the liquid levels in cargo tanks will result, in many cases, in more timely response to a polluting leak, particularly when a large leak occurs.

- In the case of a serious grounding casualty, the extent of damage can be more quickly ascertained, including tanks with large and small breaches, and response by crew and shore personnel much improved.

- The detection of inflow as well as outflow situations will also result. If, for example, a crack develops when the vessel is in ballasted condition, its detection will lead to corrective action which will be preventative rather than remedial. Pollution by oil may thus in many cases be prevented altogether by an effective tank level indicating system.

- Type approval and testing standards could be upgraded to improve the design, installation, and operation of tank level sensors aboard the many types of tank vessels for which they may be required.

- Alternative approaches to leak detection and alarming may be expected due to the cost of installing a modern tank level sensor system. The need may therefore arise for an equivalency standard which combines elements of good measurement principles and sound marine engineering practice.

2 Introduction and Background

The Oil Pollution Act of 1990 (OPA 90), Section 4110, calls for the Secretary of Transportation to establish, by regulation, minimum standards for the monitoring of cargo tanks on oil tank ships and barges, in particular for the detection of leakage from cargo tanks [25]. The U.S. Coast Guard Office of Marine Safety, Security, and Environmental Protection (G-M) has sponsored this study in order to acquire technical documentation and analysis with which to approach the rulemaking process for the statute.

The grounding of the EXXON VALDEZ in Prince William Sound and the subsequent release of 35,000 tons of crude oil into Alaskan coastal waters in March 1989 was the event which caused Congress to pass OPA 90. The ability to detect leakage of cargo oil products from tank vessels is the requirement of Section 4110.

The inclusion of Section 4110 stems from an incident on the Chesapeake Bay in which a towed barge (TANK BARGE 565) developed a hull crack and leaked cargo; the tugboat operators were unaware of the problem until they were informed by a passing vessel. Precise, real time cargo tank monitoring is expected to improve the operators' ability to take corrective action when a cargo tank is breached and to minimize the resultant damage to the environment.

2.1 About this report

The report consists of seven sections following, which are described below:

Section 3 Identifies and describes all types of liquid level detection now applicable to tank vessels and those which may be adapted to this service.

Section 4 Defines the operating environment and limitations for the previously described liquid level sensors, as well as the various uncertainty factors inherent in that environment.

Section 5 Evaluates the performance of the identified sensors in the tank environment in a non-ruptured scenario and discusses potential false leak indications.

Section 6 Develops hull failure and leak scenarios for the evaluation of the sensing systems.

Section 7 Evaluates the performance of the identified systems for the given leak scenarios and suggests an approach to developing a type approval standard.

Conclusions appear at the end of each section.

3 Liquid Level Detection System Survey

This survey includes equipment currently available for marine cargo oil tank level measurement and other technologies offering potential application to the problem. Representative commercial products are chosen and compared with respect to key performance factors such as accuracy, maintenance, reliability, and cost in 1991. Level measurement systems of all types for both marine and shore-based operations were examined. Similar principles of operation were found for both.

Some systems used strictly for shoreside industries were culled from the survey as inherently unsuitable for tanker and tank barge operations. These include threaded sight glasses inserted into the tank wall for visual inspection and nuclear radiation level sensors. Point level sensing products, which function as alarm devices or on-off switches, are widely available but do not qualify for this survey. A laser system employed in the glass-making industry gives excellent resolution and accuracy, but only over a small range on a smooth, reflective surface [30]. Together, the complexity and fragility of the equipment also exclude this system from reasoned consideration.

Twelve types of tank level detection systems potentially suitable or already in service for marine cargo oil tank applications have been identified. Brief descriptions of the systems and their operating principles follow, accompanied by a comparison matrix which identifies particular makes and models, their costs of acquisition and installation, and their performance with respect to several key aspects of shipboard performance.

A brief description of liquid level measurement science and terminology is first given.

3.1 Measurement science

The identification and correction of uncertainties caused by the measurement device are the purpose of this discipline. They are briefly described below.

• Accuracy Accuracy is the closeness of approach to the value of the quantity measured. This is evaluated during calibration of the instrument, when it is compared to an instrument whose accuracy is verified by an accepted standard, one from the National Bureau of Standards for example.

Accuracy is usually expressed as "+/-" an absolute number, such as 3 millimeters (mm), or a +/- percentage. In the first instance, the measured value is within that delta value of the real value. The deviation implied by a +/- percentage is that percentage of what the real value is at that time or place, and therefore increases with increasing size, distance, or whatever quantity is being measured.

The term "full scale accuracy" indicates a less precise instrument, since the percentage applies to the full scale of the indicator rather than the measured value.

• Conformance If the presence of the measuring instrument alters the value of the measurement being performed, it is said to have poor conformance. The placement of a measuring device in a cargo tank holding thousands of tons of oil will most probably not result in poor conformance.

• Drift This is the tendency of an instrument to move away from its calibrated output values over time. It can be a function of repeated hysteresis.

• Error This term is the deviation between real and measured values, and is mathematically equal to accuracy. The types and causes of errors, and their remedies, are shown in Table 3-1 [8].

• Hysteresis Hysteresis is the measure of deviation caused by the measurement of cyclic events, such as loading and unloading.

• Linearity An instrument is said to be linear when its indicated measured values are directly proportional to the quantity being measured. Limitations of the instrument often mean that the calibration curve deviates from the linear relationship. The maximum gap on a graph of actual versus measured value between the calibration curve and a straight line is the instrument's linearity. A linearity of 1% full scale means that the maximum error incurred by assuming a linear calibration factor will be 1% of the full scale reading.

• Noise Noise describes the various random measurement variations caused by external factors, resulting in degradation of precision and accuracy.

• Precision This term describes the closeness of approach of each of a number of measurements to the arithmetic mean, and may otherwise be described as repeatability. Precision does not imply accuracy since a device may make systematic errors with great precision. Precision is the most important attribute of measurement. As long as an instrument can reliably repeat the same reading for the same condition, accuracy problems can be solved by correct calibration of the instrument.

• Resolution Resolution is the smallest division on the instrument readout or display and is equal to one digit of change in the last digit.

3.1.1 Notes for this study The following notes are pertinent to the results of the technology study:

- The accuracies referred to in the technology survey are percentages claimed by the manufacturer or determined in a documented test procedure. When expressed as +/- an absolute number, it is done so for a specific measured range, i.e., the maximum distance being measured in a 75 foot deep tank.

• Accuracy usually degrades with increasing quantities as a flat percentage of the value being measured. The result is better accuracy near the top or the bottom of the tank, depending on the arrangement of the system.

• Most manufacturers do not publish data on the precision or linearity of their instruments. Manufacturers' published sensor performance data may not reflect true performance as measured by controlled unbiased testing [29].

• Environmental and random errors, those due to noise and other external factors, are discussed in Section 4, as well as sampling error, which results from variability in the measured parameter. Gross, systematic, and observational errors arise from human interaction; elimination of these errors cannot be effected by design of the measurement devices.

Type of Error	Causes	Remedies
Gross Error	Inexperience Misreading Misrecording Computational error	Care Training Duplicate readings Dual observers Checking against previous readings
Systematic Error	Improper calibration Loss of calibration Hysteresis Nonlinearity	Use of correct calibration Recalibration Use of standards Use of consistent reading procedures
Conformance Error	Inappropriate installation details Instrument design limitations	Select appropriate instrument Modify installation procedure Improve instrument design
Environmental Error	Weather Temperature Vibration Corrosion	Record environmental changes and apply corrections Make correct choice of instrument materials
Observational Error	Variation between observers	Training Use of automatic data acquisition systems
Sampling Error	Variability in the measured parameter Incorrect sampling techniques	Install sufficient # of instruments at representative locations
Random Error	Noise Friction Environmental effects	Correct choice of instrument Temporary elimination of noise Multiple readings Statistical analysis

Table 3-1
Measurement Uncertainty

3.2 Hydrostatic Tank Gauges

This device detects liquid loading levels by reading hydrostatic pressure at the bottom of the tank and adding data from two other sensors in the tank (see Figure 3-1). The system determines the density of the liquid by subtracting the pressure at an intermediate level gauge (P2) from that at the bottom (P1). The liquid level is found by the equation:

$$H = (g_c/g)P1/density$$

where g is the magnitude of gravity, and
g_c is a unit conversion factor (unity for SI units)

A third pressure sensor is required at the top of the tank in order to account for ullage air pressure in subsequent calculations. Temperature sensors also permit calculation of the density and volume of the cargo by use of appropriate material constants.

The pressure sensor reads the hydrostatic head on a diaphragm which in turn works upon a bonded strain gauge pressure transducer. The transducer's electrical signal output crosses a bridge circuit and is transmitted to a microcomputer, which calculates the liquid mass, density, and volume, standard density at 60 degrees F, and standard volume. Sensor redundancy allows automatic signal cross-checking capability, an enhancement of the reliability of the system. The microcomputer allows central access to all sensor data and may be networked with other shipboard equipment.

Versions are available for use on tankers which have corrosion resistant sensors that withstand the rigors of crude oil washing (COW) and which transmit their data to remotely located repeaters.

Several advantages are claimed for hydrostatic tank gauges. Most notable is the fact that they measure tank levels from the bottom up, rather than the top down, thus avoiding errors due to surface movement. This indicates excellent applicability for tankers and tank barges. Multiple pods of sensors at various locations in a tank whose outputs are time-averaged and combined might mitigate or nullify the effects of vessel attitude and motion. This is not, however, common practice. In addition, their specified location at the aft end of the tank allows for good dry tank detection because a ballasted vessel is usually trimmed by the stern.

Accuracy of +/- (4mm + H/1000) is typically claimed for these gauges throughout the depth of the tank, amounting to a maximum of +/- 34 mm for the largest tanks on oceangoing tankers. Inaccuracies of level measurement may arise because of thermal or density stratification of the liquid in the tank. Accuracy of liquid mass values, however, would not degrade and extra pressure

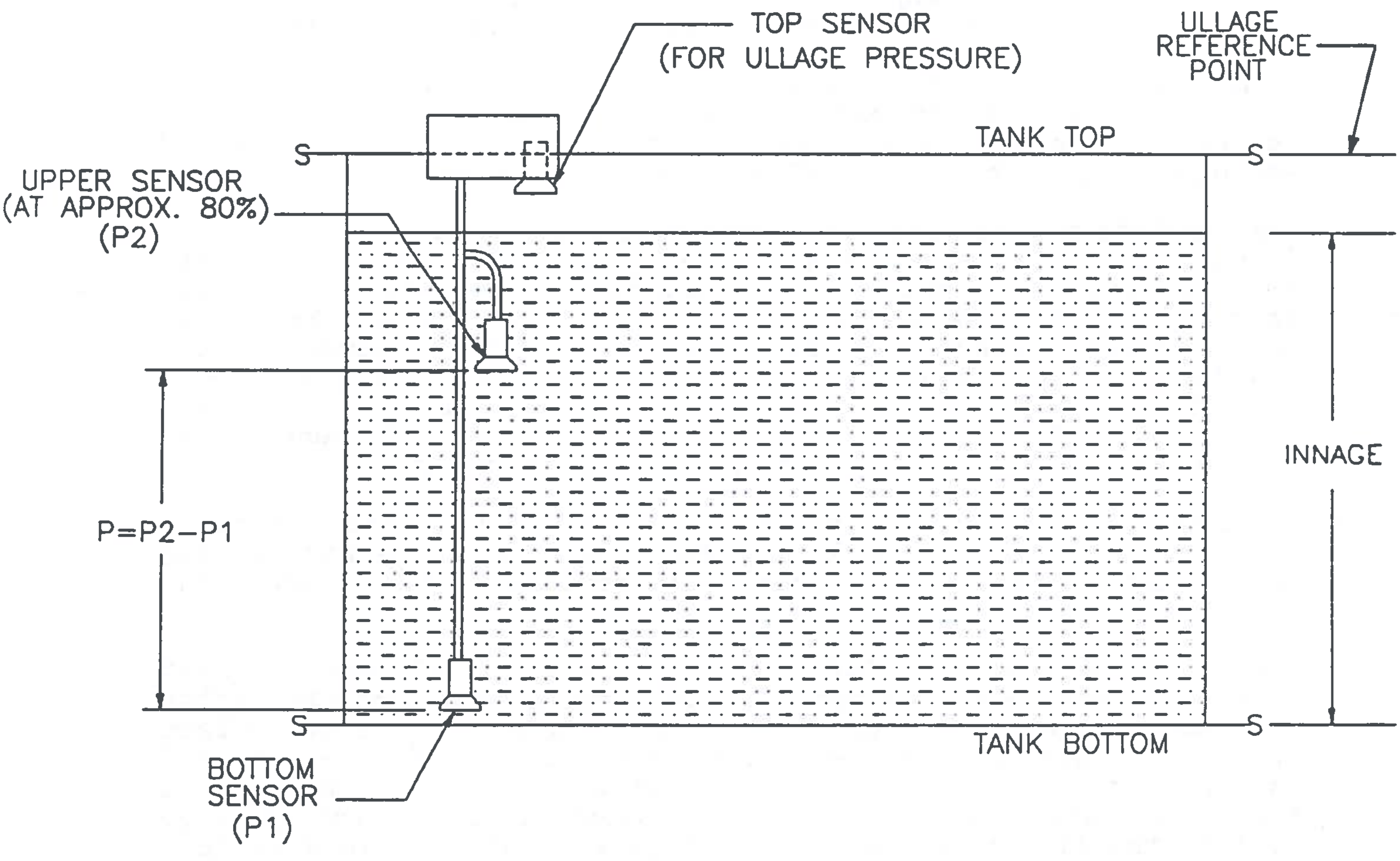


Figure 3-1
Hydrostatic Sensor Arrangement

and temperature gauges could be employed to eliminate the stratification factor. These gauges will operate at maximum accuracy when tank levels are in the vicinity of the intermediate gauge. Where stratification is present, the error is the greatest when the tank is full [3].

A leading manufacturer of hydrostatic sensors claims excellent characteristics of linearity, hysteresis, and repeatability (precision), all less than 0.1% at full range output.

Low levels of maintenance are indicated by the simplicity of gauge construction. A leading manufacturer of marine hydrostatic pressure gauges claims that only 10 of more than 20,000 in service have required replacement. It is also claimed that long term "drift" of the transducers is a minimal problem. Most transducers, however, are stressed units such as Wheatstone Bridges whose components may incur residual strain from hysteresis after many load cycles.

3.3 Radar Gauging

Radar gauging measures ullage from the top of the tank and is used both in tankers and shoreside tanks [31]. A microwave signal is transmitted from the top of the tank and is reflected from the liquid surface to a receiver, yielding a measurement of the ullage (see Figure 3-2). Reliable, low voltage equipment is safe for use in oil tanks; radar has therefore been given approval by the Coast Guard and several classification societies for use on tankers.

Radar systems may include integrated alarms and cargo temperature and pressure measurement by independent sensors in the tanks. Microprocessors convert the data output from the radar units.

The accuracy is stated, for one system, to be +/-(5mm +(0.05% x ullage)), or +/- 5-20mm for a 30 meter deep tank [26]. Tank levels can be accurately assessed at lists and trims (as well as pitch and roll) of up to 4 degrees, beyond which the beam reflection may not return in sufficient strength to the receiver. Radar may miss substantial amounts of residue cargo during tank stripping when the ship is in a ballasted and trimmed condition because it is typically mounted above the center of the tank.

The effect of varied compositions of ullage gas at various pressures on the tank level readings is usually negligible, but can amount to 0.02% of the measured ullage in the presence of very high petroleum vapor concentrations [31]. Beam scatter due to a disturbed (sloshing) liquid surface or foam on the surface is a potential difficulty if regular service from the detection system during a voyage will be expected. The installation of a stilling well may be required so that consistent results are obtained (see discussion of stilling wells, para. 3.12).

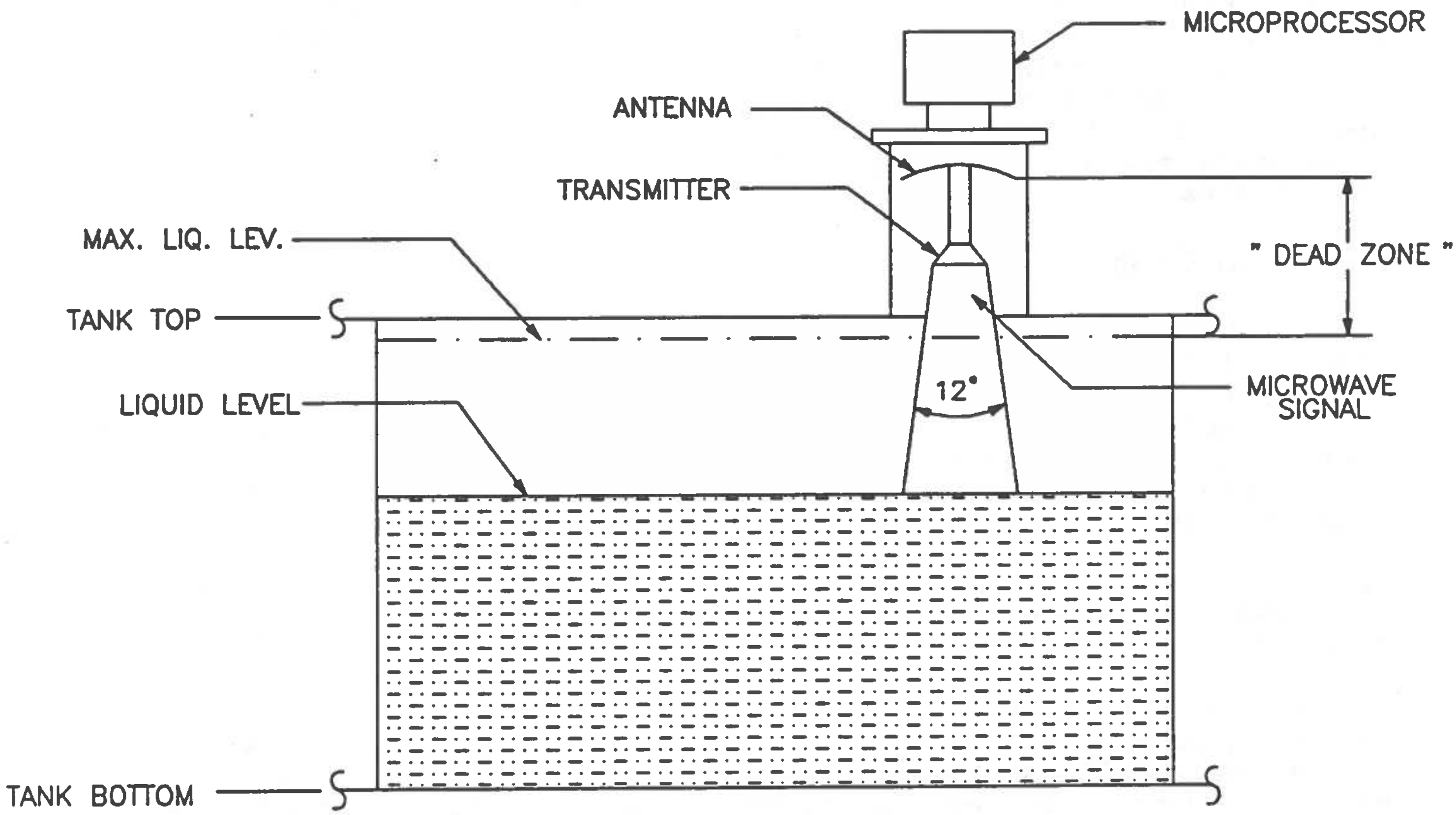


Figure 3-2
Radar Gauging System

The absence of moving parts and of any essential components in the tank is a significant advantage of radar gauges. In tanks having internal bottom stiffeners, radar wave deflectors on top of the beams may be necessary in order to prevent false reflections , particularly when cargo levels are low.

Installation of the base system requires no tank staging, although tank entry is required if wave deflectors are necessary. The radar unit is mounted atop a pedestal foundation over an opening in the deck. The beam transmitter and receiver look into the tank from within the top plate of the pedestal. The height negates the radar's "dead zone", the area immediately proximate to the transmitter where echo distortion can degrade accuracy.

Maintenance is low and can usually be performed without tank entry. Hand held self-checking diagnostic units are available with the commercially available products surveyed. The unit's intrusion into the tank is minimal and those components are quite rugged. COW does not adversely affect the radar.

Radar may on occasion give false empty readings with up to 18" of cargo in the tank. This occurs where the bottom of the tank is a smooth reflective surface, i.e. a double bottom tank top with no exposed longitudinal stiffeners. The problem can be solved by placement of a signal scattering medium, such as flatbar gridwork on the plate. The radar will then detect the echo from the liquid surface.

A potential drawback for radar, as well as other "look-down" systems, is the fact that its application for level detection in the ship's fuel bunkers, slop tanks, or double hull tanks may be difficult due to limitations of physical arrangement, i.e., lack of space above the tank or narrow tank dimensions which may cause unwanted reflections of the radar beam. An operator may desire one system which provides for all tank level detection needs on the vessel.

As well, single failure in the central electronic circuitry can affect all the gauges on the ship. The system has shown good reliability, however, in nearly ten years of service.

3.4 Resistance Tape

The sensor is a simple electrical circuit consisting of a helical wire connected to a parallel base strip, both within an oiltight sheath which runs vertically from the top of the tank to the bottom (Figure 3-3). A low level electrical current passes through the wire and base strip . In the presence of hydrostatic pressure, the sheath compresses and causes the helical wire within to contact the base strip, shortening the length of the circuit. In the absence of liquid pressure, the sheath expands and the wires separate,

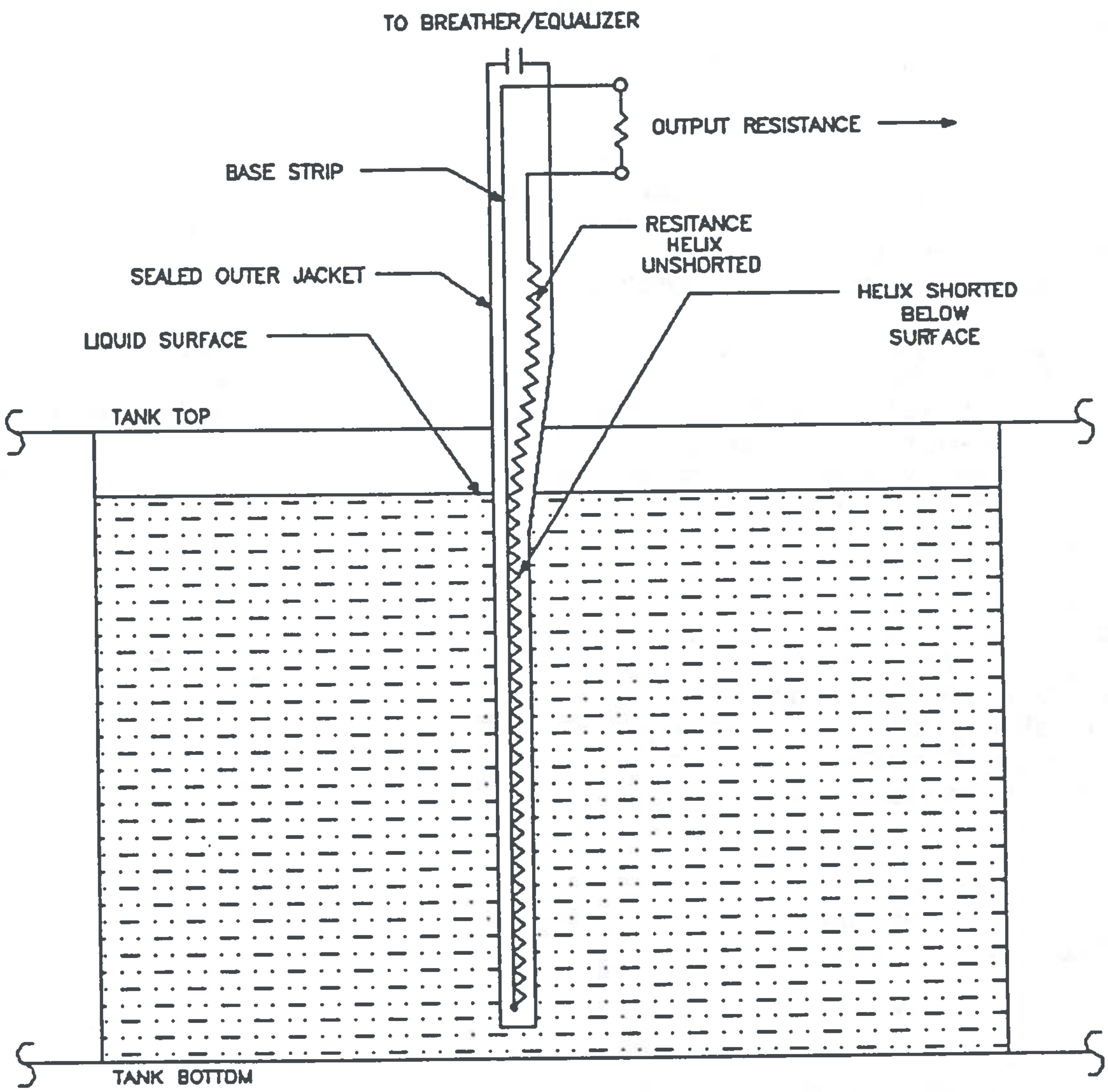


Figure 3-3
Resistance Tape

restoring current to the circuit.

The liquid level in the tank therefore determines the length of the electrical circuit and its resistance. The resistance is precisely calibrated in a proportional relationship to the unshorted length of the circuit, i.e., 1 ohm = 1 millimeter. Data is displayed on instrumentation located on the deck or remotely at a central control point. Claimed accuracy is +/- 3mm.

The sheath is connected to a breather/equalizer assembly above the deck which provides pressure inside the sheath equal to the ambient pressure in the tank's ullage space. The tape may be arranged such that it extends into a sump. This allows level sensing below the bottom of the tank and facilitates stripping operations. Temperature sensors at up to three depths are available. An optional computer system is capable of mass, density, and standard volume calculations and corrections for ship list and trim.

According to manufacturer claims, the system may be installed, maintained, and replaced without tank entry. The tape has no moving parts and low levels of maintenance are also claimed.

The tape may be positioned in the tank within a vertical still pipe which affords protection from external disturbances, such as COW [18].

3.5 Float Gauging Systems

Float gauges have dominated in the tanker industry for quite some time, but are now giving way to other forms of tank measurement. The operating principle is that of a light density float which rides the surface of the tank's liquid contents on a vertical guide and transmits the tank level data by mechanical or electronic means to the operator (see Figure 3-4).

There are many variations of the basic concept, including the style of the float, the construction of the vertical guide(s), the transmission of the level information, and combinations of varied density floats which can measure the heights of different liquids combined in the same tank (e.g. oil and water).

Float gauges provide reasonable accuracy for load/unload operations, although some are not suitable for topping off. Their construction of moving mechanical parts in a highly corrosive and dynamic environment translates to low reliability and intensive maintenance and calibration requirements. Cold weather freezing has also been reported in some instances. The frequent repair and maintenance needed for these systems results in considerable expense since human entry into the tank is usually required.

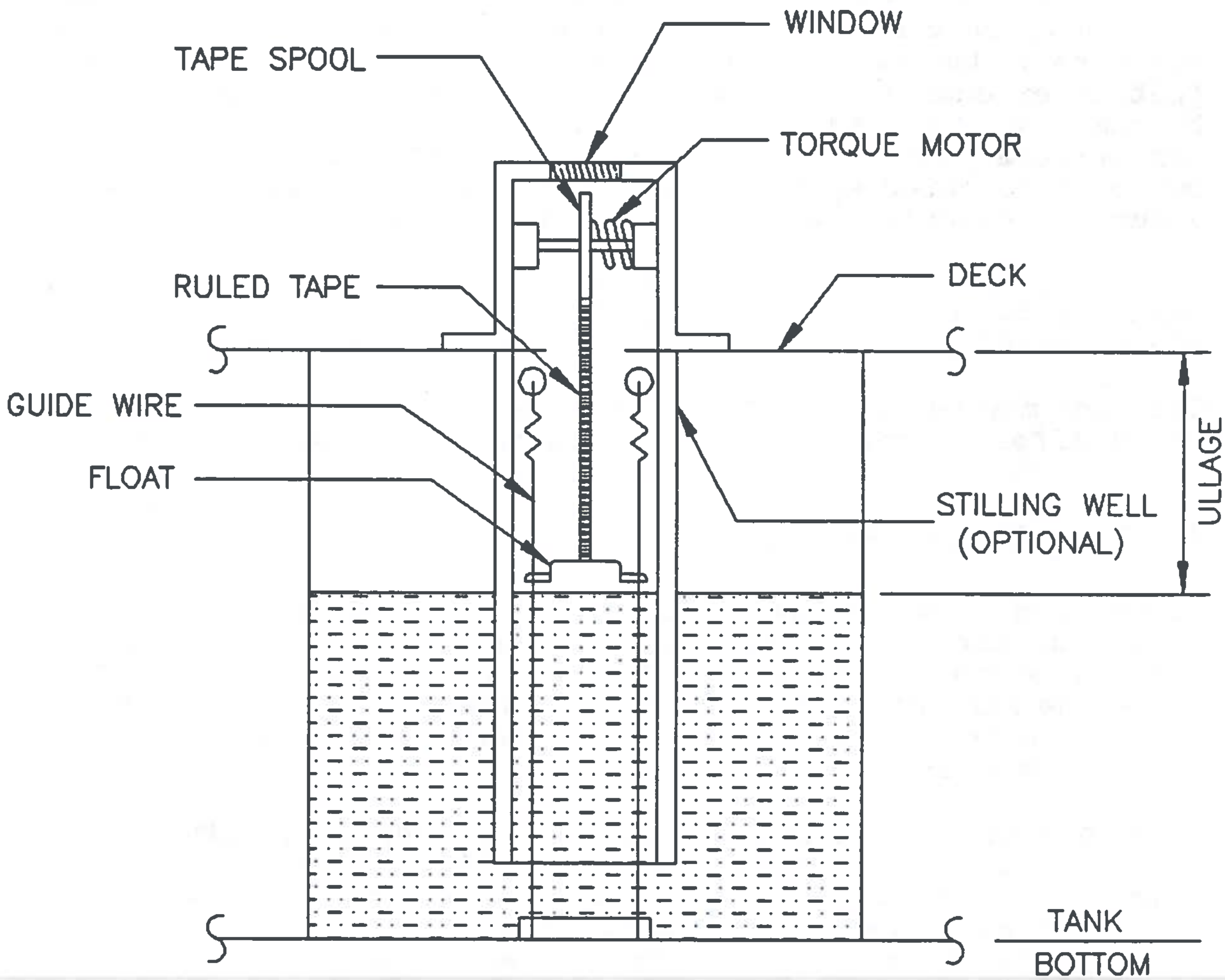


Figure 3-4
Float Gauging

The reported accuracy of float gauges is worse by a degree of magnitude than more modern systems, varying from +/-3" to +/-18". In addition, their applicability to tank monitoring while underway is questionable since many operators find it prudent to lock the floats at the upper ends of their guides to save them from damage due to sloshing of the tank's contents. The system's large number of moving parts in the tank also make it vulnerable to crude oil wash, during which operation it must also be secured.

A previously completed technological assessment of shipboard tank gauging systems for the U.S. Maritime Administration [18] rated float gauges the worst overall of those tested. The systems tested failed to satisfy the accuracy and repeatability requirements of the assessment.

3.6 Ultrasonic

There are three system types which employ ultrasonic wave technology in distinct ways, as described below. At present, these are applied strictly to shore-based tank liquid storage.

3.6.1 Outage measurement The first ultrasonic tank level measuring system to be considered is similar in principle and application to the radar systems. The distance of the liquid surface from the top of the tank is measured by a beam transmitted and its echo received at the electronic unit. The sender/receiver must be positioned so as to negate its "dead zone", which ranges from 4" to 48".

Installation and maintenance of the ultrasonic sender/receiver is conducted without tank entry. There are no moving parts and maintenance is thus minimal. Occasional calibration of the unit is required.

Accuracy of +/- 1% is claimed, which is equal to +/- 228 mm for a 75 foot deep tank. Ultrasonic sensors are vulnerable to alterations of wave speed and direction by conditions in the vapor space, i.e, ambient temperature, vapor composition, and salinity. The speed of the ultrasonic waves changes about 1% for every 10 degrees Fahrenheit (6 degrees Centigrade). Petroleum vapors in particular cause significant changes in wave velocity and can render accurate measurement impossible. Foam on a liquid surface can absorb the beam and prevent reliable detection operation [30].

As is the case for radar systems, stilling wells are a possible requirement for application of ultrasonic level sensing, in order to negate the effects of beam scatter from sloshing liquid. It is also similar to radar in that the signal return deteriorates with significant angles of trim or list (these have not been determined because this system has not been used on tankers).

This type of system must include vapor space temperature sensors in order to compensate for wave velocity changes. The problem of signal degradation due to composition of the outage, however, will be difficult to overcome.

3.6.2 Liquid measurement Another system developed for use primarily in underground gasoline tanks at service stations employs an ultrasonic beam to measure from the bottom of the tank to the surface of the liquid medium. This system has satisfied an EPA protocol for the detection of slow leaks and is claimed to exceed by an order of magnitude the protocol's accuracy and resolution requirements.

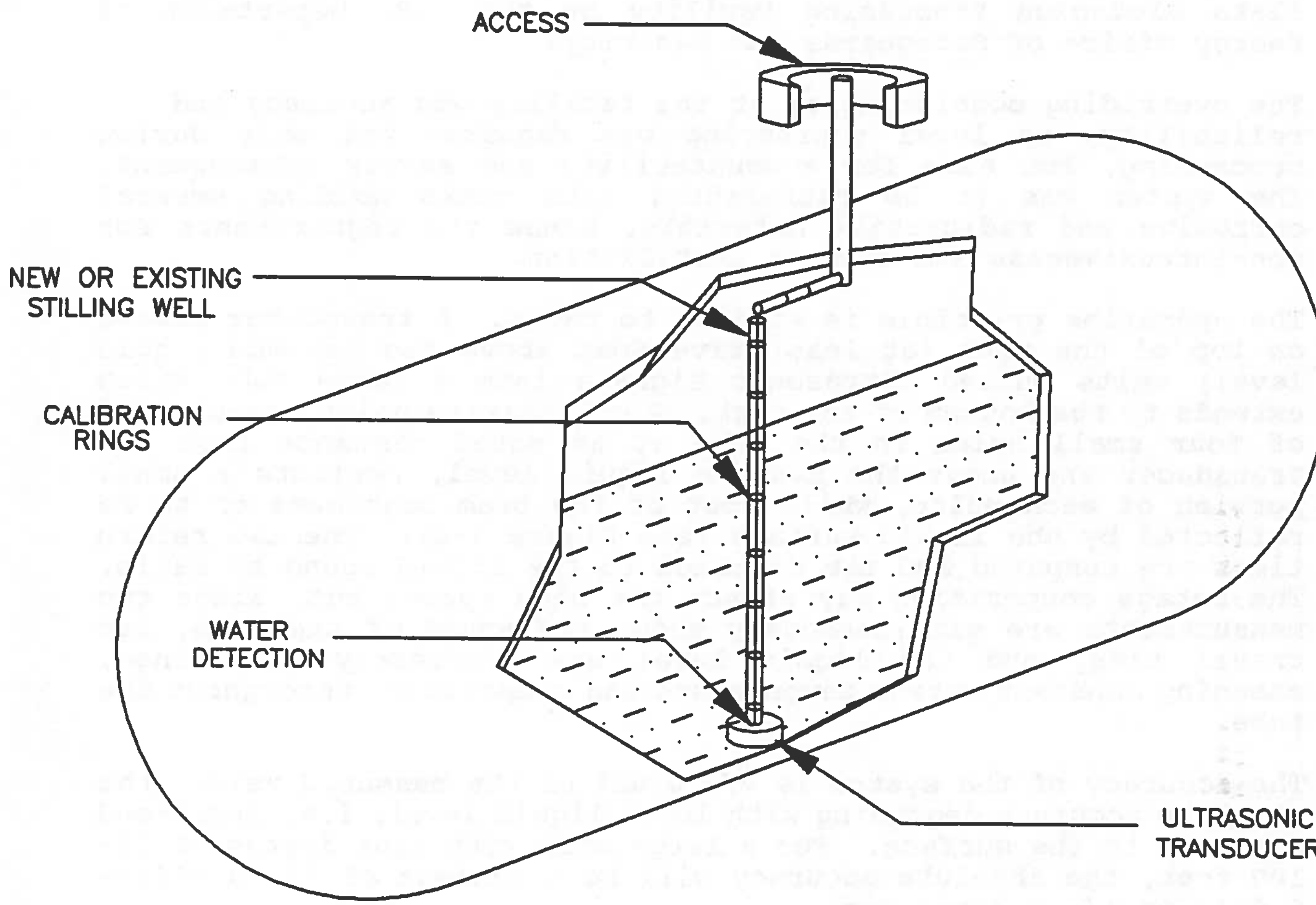
The transmitter/receiver unit is located at the bottom of the underground tank, which is usually configured as a cylinder on its side, with a maximum diameter of 12 feet and a length of up to 40 feet.

The transducer shoots at the liquid surface past a series of ring shaped reference points which are placed at precise intervals in a vertical line from the bottom to the top of the tank (see Figure 3-5). The system monitors density of the liquid by measuring incremental times between each reference point. The close spacing of the points (6") assures that any stratification of the liquid due to temperature or composition will be accounted for. The last measurement is the surface of the liquid. A microprocessor uses a proprietary algorithmic program to process the data, using material data for the liquid in the tank.

The transducer has a short "dead zone" of about 6" due to the height of the mounting hardware and the unit. The unit may thus be slightly less effective than some for dry tank detection during stripping operations. If located adjacent to the aft tank bulkhead, this ultrasonic unit would probably be adequate for dry tank detection.

In a third party EPA standard evaluation, the system was able to resolve a change in level of 0.01 inches and a change in temperature of 1/10,000 degree Centigrade. The system takes readings 4 times a second and achieves detection of a leak of 0.028 gallons/hour (EPA standard is 0.2 gallons/hour) from a 12,000 gallon underground gasoline tank. 99.99999% reliability is claimed by the manufacturer and has been validated by third party tests.

Maintenance requirements are minimal for the system's intended application. All components in the tank are epoxy coated and there are no moving parts. Some modifications in power, arrangement, and preventive maintenance may be needed for application of this technology in a shipboard environment.



<u>Figure 3-5</u>
Ultrasonic Innage Measurement
Underground Gasoline Tank

3.6.3 Pulsed beam system A pulsed sonic liquid level device has been used in nuclear industry applications where the following strict criteria were specified: 1) exceptional accuracy and reliability; 2) non-intrusiveness or non-penetration of the tank; 3) ease of installation; 4) standard interface electronics; and 5) moderate cost [9]. This system was selected for use at the Rocky Flats Plutonium Processing Facility by the U.S. Department of Energy Office of Safeguards and Security.

The overriding consideration at the facility was accuracy and reliability, as level monitoring was required not only during processing, but also for accountability and safety enhancement. The system was to be retrofitted into tanks holding several corrosive and radioactive materials, hence the requirements for non-intrusiveness and ease of installation.

The operating principle is similar to radar. A transducer placed on top of the tank (at least five feet above the maximum liquid level) emits pulsed ultrasonic signals into a range tube which extends to the bottom of the tank. A calibration point, consisting of four small holes in the tube at an equal distance from the transducer and above the maximum liquid level, reflects a small portion of each pulse, while most of the beam continues on to be reflected by the liquid surface (see Figure 3-6). The two return times are compared and the distance to the liquid found by ratio. The outage composition may effect the beam speed; but, since two measurements are simultaneously made, the speed of the beam, its travel time, and the liquid level are accurately determined, assuming constant outage temperature and composition throughout the tube.

The accuracy of the system is +/- 0.01% of the measured value; the absolute accuracy degrading with lower liquid level, i.e, increased distance to the surface. For a large ship with tank depths of 75-100 feet, the absolute accuracy will be a maximum of +/- 0.0075'-0.01', or +/- 2.3mm-3.0mm.

Excellent reliability was found for this system after a recalibration following one year's service. Its maintenance requirements are low as no moving parts exist in the tank. The manufacturer states that there is no drift in the long term accuracy of the sensor.

The interface electronics are standard, widely available equipment. The transducer takes from 5 to 15 readings per second, depending on the distance to the liquid surface. It is possible to modify or upgrade the electronics to perform an averaging function which would account for cargo sloshing.

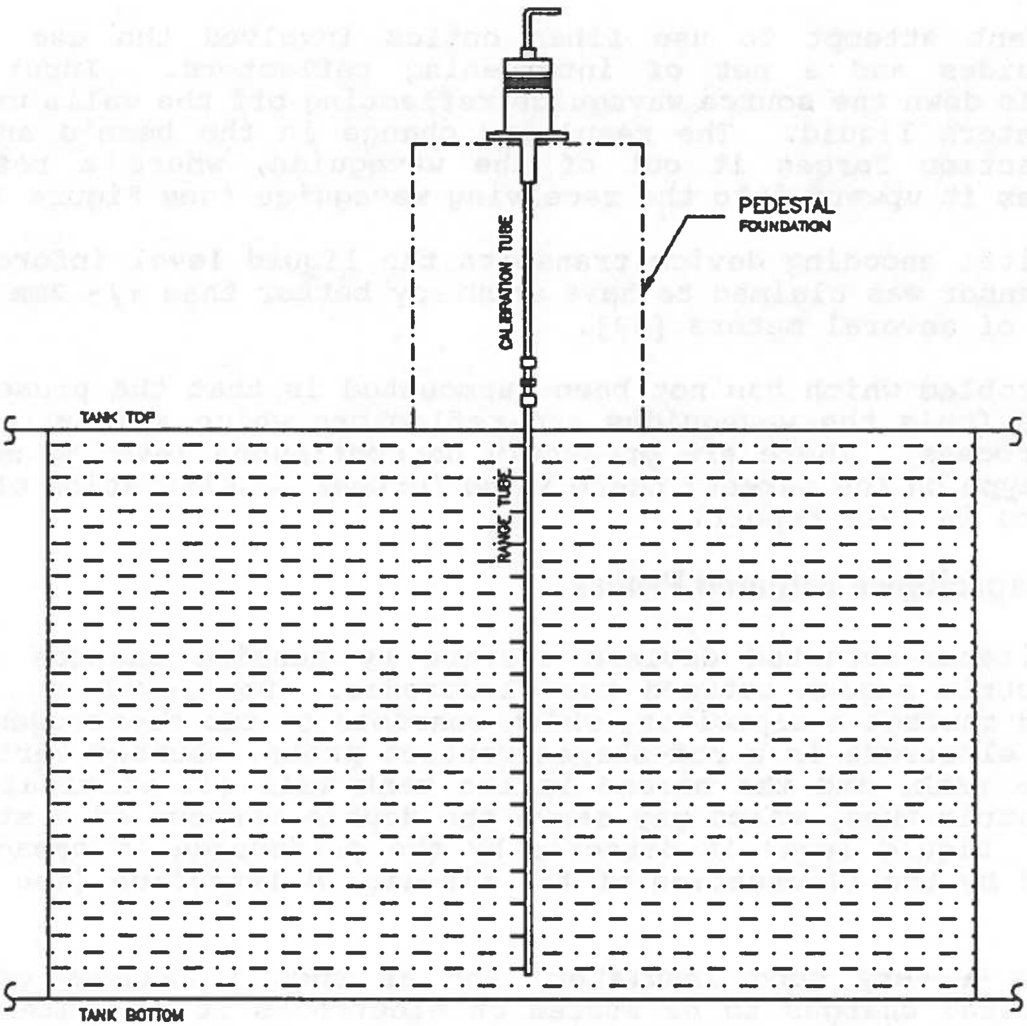


Figure 3-5

Ultrasonic Pulsed Beam

3.7 Fiber Optics

Fiber optics systems are currently in use primarily as level switches. The industry has tried a number of approaches to the use of fiber optics for continuous level sensing, with little success [9, 22, & 39].

A recent attempt to use fiber optics involved the use of two waveguides and a set of intervening reflectors. Input light travels down the source waveguide reflecting off the walls until it encounters liquid. The resulting change in the beam's angle of diffraction forces it out of the waveguide, where a reflector bounces it upward into the receiving waveguide (see Figure 3-7).

A digital encoding device transmits the liquid level information. The sensor was claimed to have accuracy better than +/- 2mm over a range of several meters [22].

The problem which has not been surmounted is that the presence of liquid fouls the waveguides and reflectors which are integral to the process. There are presently no continuous level sensors of this type on the market; there is no further consideration of these sensors in this report.

3.8 Capacitance-actuated Probes

Capacitance-actuated devices operate by sensing changes in the dielectric medium between two electrodes. Low level current is passed through a capacitor, which consists of two electrodes. The first electrode is a rod-shaped contact probe, mounted vertically in the tank, and the second is the tank wall (if vertical) or a concentric tube, which may serve the double purpose of a stilling well. Liquid level is detected by the difference in capacitance caused by the fluctuation of the air-liquid interface (see Figure 3-8).

Air is a very good insulator, and as such it allows opposite electrical charges to be stored on electrodes it separates. The relative ability of a material to allow development of opposite electrical charges on two electrodes (and thereby establish an electric field between them) is the dielectric constant of the material. Water is a good conductor relative to air and has a dielectric constant approximately 80 times greater than that of air. Most oils are in the range of 2 to 3. The capacitance of the instrument changes linearly with the height of the fluid and can be measured by simple circuitry [4].

Proper functioning of this type of probe requires stable values of the liquid's dielectric constant, a known distance between electrodes, for example, from the probe to the tank wall, and a constant ground reference. The dielectric constant can vary with

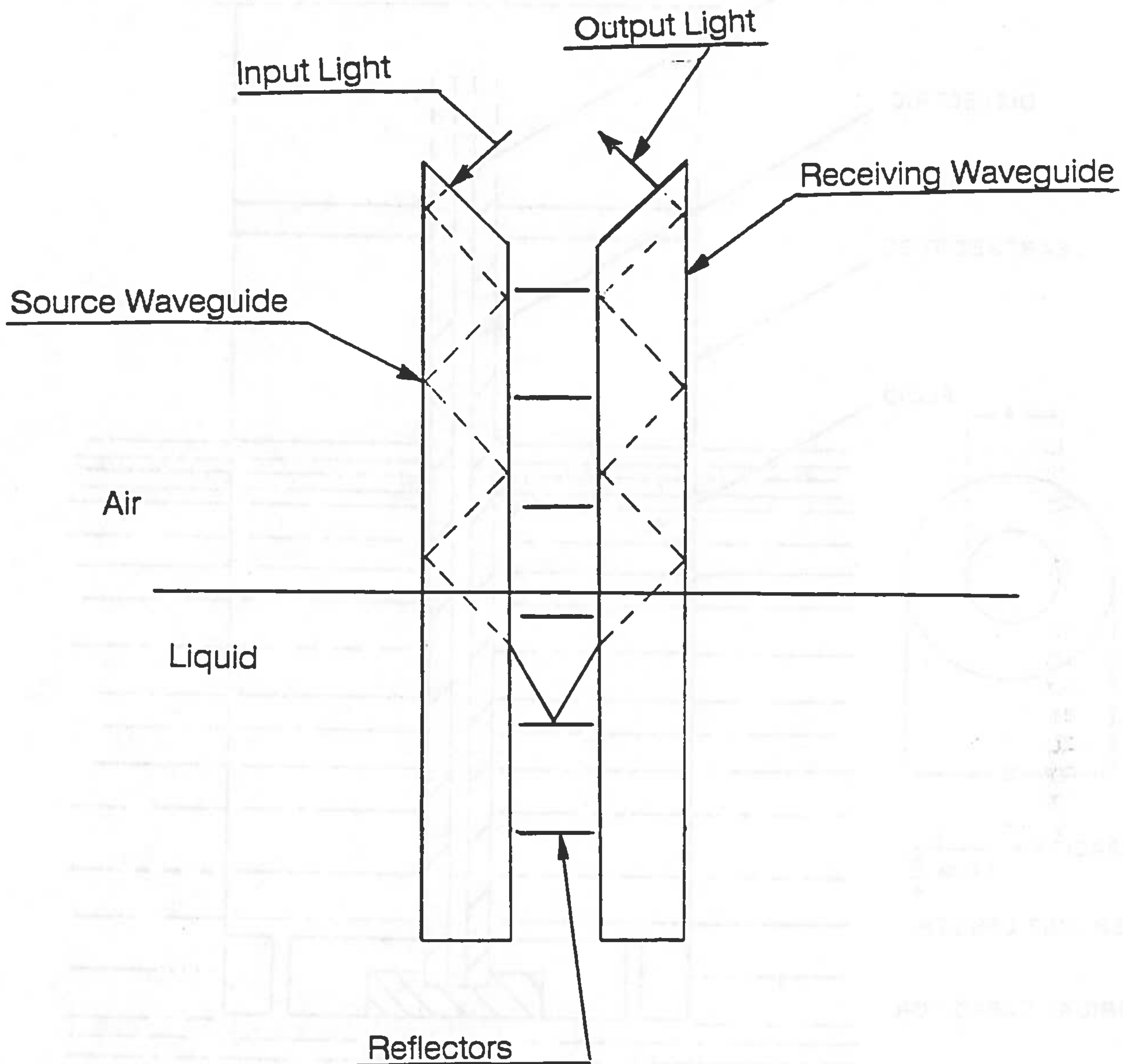


Figure 3-7
Fiber Optics Probe

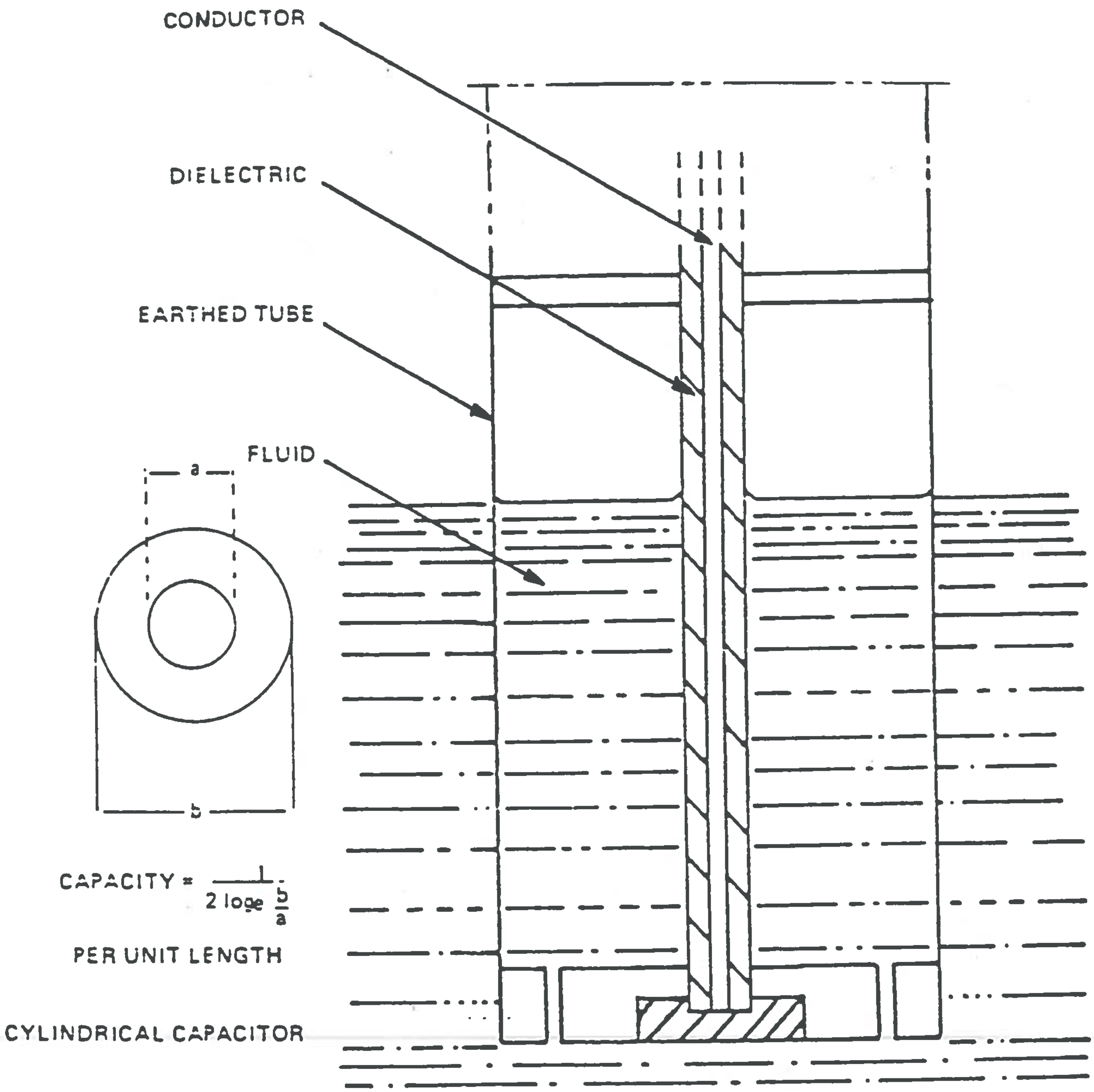


Figure 3-8
Capacitance Probe

temperature and density and composition changes of air or liquid. The material properties may be inconsistent even among different lots of the same grade or type of petroleum product, according to a leading manufacturer of capacitance gauges for airplanes. This problem may be of greater magnitude for crude oil cargoes.

The probe length is established by the installation requirements of the tank. Once these variables have been stabilized, the system functions by monitoring the current flow which varies with the length of the probe covered by the liquid medium. Most current applications of capacitance technology are of much shorter length than those needed for large tankers, but could be adapted for the required depths.

Three types of probes are used: bare probe, insulated probe, and probe with concentric shield. In large tanks, level changes produce relatively less change in the capacitance. The concentric shield increases the sensitivity of the device and is therefore the best in this instance [32]. The shield is also well suited for cargo tanks because it serves as a stilling well and could be constructed to the desired strength to protect the probe from the rigors of the tank environment.

Capacitance probes have no moving parts within the tank. The vertical probe may be constructed of various materials. A rugged system may be specified for tank vessels including a protective stilling well. The well would also provide a smooth, aligned surface to act as part of the capacitor. A sloped tank bulkhead or one with horizontal stiffeners is unsuitable as a capacitor plate.

Claims of accuracy vary from 0.1% to 1-2%, equating to +/- 30-600 mm for a 30 meter deep tank. Maintenance is low, but reliability may be degraded by variation of the values used to calibrate the system. Ship motion and structural deflections can alter the mounting configuration of the probe and, more significantly, the dielectric constant may vary due to composition and temperature changes in both the cargo and the ullage air. Recalibration would be required every time different cargo is loaded, and would even then be effected by value changes during the voyage.

The accuracy of the probe may also worsen due to buildup of fluid above the actual liquid level. The buildup of non-conductive media, including oils, does not cause a signal shift, but sludge and clingage may contain quantities of conductive material which could degrade performance [19]. Cleaning of the probe within a stilling well could be problematic for an operator. Foaming on the surface of the liquid does not affect accuracy.

The performance of this type of system has been excellent in several major industries, but its complexity may render high costs of installation and operation [18].

Maintenance is claimed to be low since there are no moving parts in the tank and, typically, only three connections to make to the transducer. Reliability for a leading aircraft fuel sensor is quoted at 600,000-1,000,000 hours mean time between failures. Such a capability could be specified for tank ships.

3.9 Electromagnetic Level Indication (EMLI)

The U.S. Navy has developed a prototype level sensing system for use in seawater ballasted fuel oil storage tanks. Its operation is similar to that of capacitance level indicators, but it offers the additional capability of detecting the boundary between two different liquids, i.e., oil and water [11, 24].

EMLI uses the pulsing and high frequency sampling techniques of time domain reflectometry (TDR) and measures the heights of air, oil, and water columns in the tank. The TDR unit measures pulse reflections and velocities from the interfaces of the different line dielectrics; this information is converted into heights and locations of each material. This is possible because of the previously discussed wide variance in dielectric constants among oil, air, and water.

The signal processor uses equations relating the length of each medium to waveform voltages and transit times in a manner that eliminates the uncertainty of dielectric variations due to temperature fluctuation and material composition.

The Navy design uses a cable mounted within a 4" diameter half-pipe with constant intervening distance maintained. The large diameter minimizes clingage problems, and the half-pipe is used to avoid the difficult maintenance of a closed pipe.

The results reported from system testing are the following:

- The sensor tolerates coating by highly viscous fluids without loss of accuracy.
- Limited fluid agitation and foaming are handled by signal averaging.
- The system can be used to measure fluid levels in single and multi-fluid tanks.
- The system achieved good linearity (maximum of 0.7 cm).
- System resolution was generally better than 0.5 cm in a 3 meter span.
- Accuracy was 0.1% over a 3 meter span (0.3 cm) in the controlled test environment.
- The system achieved good repeatability, especially with the use of signal averaging.

3.10 Pneumatic Sensors

Pneumatic systems operate by air pressure which is moved through a piping system by the hydraulic forces of the cargo in the tanks. The air, in turn, moves columns of mercury in the control room, which yield tank level readings to the crew. Industry sources indicate that this system is old technology and is no longer specified for any newbuildings. The piping and tubing inside the tanks and out require extensive maintenance and provide poor accuracy relative to other systems now available.

3.11 Nucleonic sensors

This is a non-contact sensor with applications for liquids whose temperatures and pressures preclude the presence of sensors in the tank. Its principle is the detection of radioactive energy, whose levels vary depending on the presence of an energy absorbent medium, i.e., the liquid in the tank. A strip of isotopic material is hung vertically outside the tank and emits low level radiation which is detected by a vertical receptor strip positioned on the opposite side [32].

The development of this technology for marine cargo tanks would have to include much longer strips than those currently being used and other major application modifications, such as oil-tight wells for the radioactive and receptor strips. Such a development would also require the establishment of performance parameters such as accuracy and precision.

This technology has very limited applications while not offering greater accuracy than many other systems. Its obvious drawbacks of safety, special handling requirements for radioactive substances, and negative perception by the crew and the public would most probably preclude its adoption for marine service.

3.12 Stilling Wells

A commonly available method for mitigating the deleterious effects of surface disturbance is a stilling well. Sea level measurement is a closely analogous regimen to cargo tanks since waves are a constant factor. The idea of a stilling well for mitigation of the effects of waves in tidal measurements was first suggested in 1666 by Moray, and was first put into operation in 1831 in England.

The well may be connected to its medium by orifices in its surface or through a pipe at its base. It is reported that the pipe connection gives a linear, and therefore more reliable, response to outside level oscillations. Liquid currents outside the stilling well can distort the pressure and the level within. The single pipe connection to the well would be more vulnerable to such an occurrence. The subsurface movement of the cargo oil is not, however, likely to have an appreciable effect in this regard.

Variations in the density of the liquid medium may lag within the well, particularly in the case of a pipe connection [28].

Fouling of the well may occur due to collection of sludge and may be particularly so in the case of a single pipe medium connection at the bottom of a cargo tank. Sludge and clingage in the stilling well may pose a maintenance problem. As previously mentioned, the U.S. Navy uses an open half-pipe section for its prototype EMLI system to mitigate this problem.

It is concluded that stilling wells of the orifice type would probably improve the quality of the liquid level data, if designed properly for the sensing system to be used, and may prove a critical component of some systems, such as capacitance probes. Their installation and maintenance would increase the expense of the detection system, however.

3.13 Other surveys and test programs

3.13.1 Maritime Administration (MarAd)

The Southwest Research Institute prepared a report for MarAd entitled "An Assessment of Shipboard Tank Level Indicating Systems" in 1981 [18]. The technologies surveyed were closely similar to those now available.

The study used weighted criteria of safety, reliability, performance, and accommodation to rate the equipment, the maximum score being 1000. The scores ranged from a low of 563 points for the "buoyancy-mechanical" system (float gauges) to a high of 684 for the "pressure-electromechanical" system (resistance tape).

The authors concluded that none showed superior performance and that substantial work was required by government and classification societies to remedy the situation. Some classification societies, Bureau Veritas and Det norske Veritas in particular, provide procedures for the certification, or "type-approval", of equipment by manufacturers before shipboard installation. The American Bureau of Shipping has also adopted equipment approval specifications.

Significant findings were:

- All systems tested passed specified safety criteria.
- Reliability scores varied from 63% to 84%. Hydrostatic gauges and resistance tape rated highly, while pneumatic and radar systems rated poorly.
- Performance, a measure mainly of accuracy and repeatability, ranged from a low of 15% for float gauges to 89% for resistance tape. Radar and pneumatic systems also scored well. The required accuracy of +/- 1/2" was derived from

safety considerations of overfill and the need to allow thermal expansion of the cargo.

• Accommodation is a measure of maintenance, service, diagnostics, and display readability. All the systems had mediocre scores in this category.

The results of the MarAd test program and the recommended "type approval" standard for liquid cargo level detection are attached as Appendix A.

3.13.2 Environmental Protection Agency (EPA)

The EPA has conducted an extensive study entitled "Evaluation of Volumetric Leak Detection Methods for Underground Fuel Tanks" [29]. This study preceded the development of the underground tank testing protocol referred to in paragraph 3.6.2. and was a testing program for commercial leak detection systems under very tightly controlled conditions.

The report suggests that the results are now obsolete because manufacturers have responded to suggestions to improve their products. The report concentrates largely on the methods of conducting the tests and may thus be helpful if a "type-approval" regime is to be implemented.

3.13.3 U.S. Geological Survey (USGS)

The USGS regularly conducts testing of commercial liquid level devices for placement on its Qualified Products List (QPL). The QPL is used for the acquisition and installation of level sensors at diverse river, lake, storm-sewer, and observation well sites.

The specification includes 75-day unattended operation, size and weight limitations, operation in full range of weather conditions (temperature of air and water, humidity, barometric pressure), various liquid depth ranges, disturbed, moving, and cluttered water surfaces, biological fouling, and silt and sand deposits. The allowable error range is from +/- 0.005' for depths of 0-10' to +/- 0.100' for depths of up to 200', i.e., full-scale error of 0.5%. Precision is not specified [36].

The results of USGS testing during the period 1985-1989 indicate that attained accuracy is of the same magnitude found for the systems surveyed herein. The USGS specification may be useful also in the implementation of type approval requirements.

3.14 Future developments

Substantial advances in the field of liquid level instrumentation must be anticipated as the need for custody control and environmental accountability grows. The technological limitations reported herein may be eliminated or minimized by technical advances.

Optical sensors are now under investigation by the U.S. Navy, which may soon address application and testing. Fiber optics data transmission can multiplex signals from various sources to the processor, resulting in a weight reduction which is attractive for many applications, especially for airplanes.

Highly sensitive quartz crystal hydrostatic sensors, with fiber optic data transmission are also in development. These may be more effectively used strictly to detect minute changes in liquid level in conjunction with an ordinary system used for custody transfer.

3.15 Conclusions

Different advantages and disadvantages accrue with the use of any of the previously described systems. A matrix comparison is given in Table 3-2. Conclusions based upon the findings of this section are the following:

1. The available level sensing technologies, including the most precise shore-based systems, have limitations which will circumscribe the range of detectable oil outflow incidents, particularly with the additional noise factors to be discussed in Section 4.

2. Technological innovations and new adaptations to marine and shore-based systems will be needed to effectively detect small liquid level changes in a wide range of operating conditions. These advances should include software for signal averaging and information output to the crew, the adaptation of some systems to the greater depths of large cargo tanks, and the "hardening" of sophisticated sensors for the difficult operating environment.

3. A shipboard gauging standard and a test and certification program as suggested by Johnson et al [18] are desirable, and should include specifications for accuracy, repeatability, reliability, drift, proper integration with ship's services, safety, and shipboard ambient conditions. The program should be based upon the equipment approval procedures used by some classification societies, for general principles of sound marine engineering practice, and protocols developed by EPA, USGS, and others, in order to attain the maximum possible base of knowledge. Appendix A contains excerpts from various documents which could be used in the development of the standard.

4. The principles of modern tank gauging equipment will require that the devices receive more sophisticated support.

TYPE	MANUFACTURER MODEL	ADVANTAGES	DISADVANTAGES	MAINTENANCE	TOP-OFF	ACCURACY	COST (total for 15 tank vessel)
Hydrostatic Tank Gauge	Scarpenord	1. No moving parts in tank. 2. Measures from bottom of tank up, avoids errors from surface movement. 3. Measures mass, density, temperature, standard volume, and tank atmosphere pressure. 4. Withstand corrosion and COW. 5. Self-checking reliability. 6. Dry tank detection.	1. Inaccuracies of liquid level data may result from heavy temperature or density stratification. 2. Ship motion cargo acceleration may effect accuracy.	Low. 10 service failures out of >20,000 working sensors.	Yes	+/-(4mm+ H/1000); 34mm for 100' deep tank	$165K Acquisition 40K HiLevel Alarm $140K Installation $345K Total for 80kdwt, 15 tank ship
Radar Gauging	Saab Autronica	1. No moving parts in tank. 2. No effect from composition, temperature of ullage gas, except for very high petroleum vapor concentrations. 3. Intrusion into tanks is minimal, COW does not disturb. 4. Temperature, pressure gauges and self-diagnostic units optional.	1. Loss of accuracy at lower tank levels. 2. Occasional false empty readings for double bottom ships; correctable. 3. Potential beam scatter from sloshing liquid surface. 4. Can be ineffective for dry tank detection.	Low maintenance.	Yes	+/- 5mm+0.05% X ullage, or +/- 5-20mm for 30 meter deep tank.	$190K Acquisition 40K HiLevel Alarm 125K Installation $355K Total for 80kdwt, 15 tank ship
Resistance Tape	Metritape	1. Simple design, no moving parts in tank. 2. Withstand corrosion and COW. 3. May be installed or replaced from the deck. 4. Good dry tank detection. 5. Good reliability, repeatability.	1. Relatively low resolution.	Minimal. Check breather filter yearly. Replace equalizer coil every four years.	Yes	+/-3mm	$110K Acquisition 45K HiLevel Alarm $130K Installation $285K Total for 80kdwt, 15 tank ship
Float	Varec Whessoe GEMS	1. Most commonly used and well-known technology in the industry.	1. Moving parts in the tank. 2. Low accuracy. 3. Low reliability due to corrosion, impact loads, freezing. 4. Must be locked at top of tank during voyages. 5. Needs frequent calibration. 6. Many not adapted for computer interface.	High levels of maintenance reported.	No	+/- 75-450mm	$150K Acquisition 40K HiLevel Alarm 150K Installation $340K Total for 80kdwt, 15 tank ship
Ultrasonic, outage measurement	Delta Controls	1. No moving parts in tank. 2. Intrusion into tanks is minimal.	1. Wave distortion due to temperature, composition variance in outage gas. 2. Potential beam scatter from sloshing liquid surface. 3. Foam on surface absorbs beam. 4. No previous application to marine carriage of liquid cargo.	Low maintenance.	Unknown	+/- 1%, +/- 300 mm for 30 meter deep tank.	$45K Acquisition.
Ultrasonic, innage measurement	Level Tech	1. No moving parts in tank. 2. Excellent accountability for cargo stratification by temperature, density.	1. Many parts in tank, though non-moving. 2. No previous application to marine carriage of liquid cargo.	Low maintenance.	Probably adaptable	+/- 0.007%, +/- 2mm for 30 meter deep tank.	$70K Acquisition HiLevel Alarm and Installation costs unknown
Ultrasonic, pulsed beam	Bartex	1. No moving parts in tank. 2. Intrusion into tanks is minimal. 3. Excellent reliability.	1. No previous application to marine carriage of liquid cargo.	Low maintenance.	Probably adaptable	+/- 0.01%, +/- 3mm for 30 meter deep tank.	$60K Acquisition HiLevel Alarm and Installation costs unknown
Capacitance probe	Simmonds Precision, Magnetrol	1. No moving parts in tank. 2. Intrusion into tanks is minimal. 3. Excellent reliability.	1. Fluctuations of liquid and air dielectric constants degrade accuracy (affected by temperature, composition of media). 2. Residue or clingage on exposed probe may degrade accuracy and precision.	Low maintenance.	Probably adaptable	+/- 0.1%, +/- 30mm for 30 meter deep tank.	$60K Acquisition HiLevel Alarm and Installation costs unknown
EMLI	U.S. Navy prototype	1. No moving parts in tank. 2. Intrusion into tanks is minimal. 3. Ability to find oil and water levels. 4. Good reliability, repeatability.		Low maintenance.	Probably adaptable.		Acquisition and Installation costs unknown

Table 3-2
Tank Level Detection System Comparison

4 Definition of the Operating Environment

4.1 Summary

The tank level detection systems described in Section 3 will be required to operate in cargo tanks which may contain crude oil and petroleum products, a dynamic, corrosive, and volatile environment. The definition of that environment will be considered in two parts: 1) the operating conditions of the vessels in the marine environment; and 2) the ambient conditions within the tank, defined by the characteristics of its contents and its response to the vessel's attitudes and motions. The premise of this definition is that the desired liquid level detection system will be active at all times, in all modes of operation of the vessel.

The effect upon the detection systems described in Section 3 by the external sources of noise identified will be qualitatively and quantitatively assessed. A computation of the systems' accuracy in shipboard conditions is given in Section 5.

It is sufficient to say at this point that a very fine limit of accuracy will provide the maximum leak detection capability for OPA 90. All factors which might increase the error margins identified in Section 3 are therefore considered.

4.2 The Oil Carrying Fleet

Tank vessel traffic around the United States is projected to increase over the foreseeable future, with a 50% rise in imports predicted by the year 2000 [23]. Oil and petroleum products are carried in a wide variety of tankers and tank barges.

OPA 90 section 4110 extends its mandate to both self-propelled tankers and barges. This discussion will first delineate the spectrum of oil carrying vessels, then describe the environmental and operational factors common to them all which will effect precise measurement of tank levels. Characteristics unique to either tankers or tank barges will also be described.

4.2.1 The tanker fleet The tanker fleet is diverse in terms of size, construction, mission, and condition. These ships range in size from small coastal and inland trade vessels of less than 10,000 DWT to ocean-going ultra-large crude carriers (ULCC) of 400,000-500,000 DWT. More than 80% of the tankers which visit U.S. ports are foreign flagged. Construction standards, which are the province of the classification societies, are not consistent and are, at present, the subject of scrutiny by the Coast Guard and the International Maritime Organization (IMO) [17]. Standards of inspection and maintenance by various administrations, as well as the practice of same, widely differ. The Coast Guard does have the authority to inspect these vessels under the practice of "home port control" to ensure compliance with international safety standards [23].

Recent tanker designs have included two significant trends which tend to reduce the ratio of ship lightweight to deadweight, reducing costs of construction and operation. They are the reduction of strength safety margins and the introduction of high strength steels. The structure is more efficient, but has less tolerance for construction errors, corrosion, and operation in unusually severe weather. A number of domestic and international tankers are, however, double hulled. Preliminary data from a Coast Guard study indicate that there are at least 73 double hulled tankers in service and 19 under construction [6].

This study considers the application of leak detection technology to single hulled tank vessels only. Single hulls in excess of 5000 gross tons are to be phased out by OPA 90 by 2009; those less than 5000 gross tons are exempt until 2015. The IMO presently considers mid-deck height, hydrostatically balanced tankers as an equivalent to double hulls [16]. These ships may be single hulled and, if constructed, could require leak detection systems for their lower tanks. Their two-tiered tank arrangement would eliminate many of the systems considered for conventional single hulled tankers, e.g., deck-mounted sensors such as radar.

Most newbuildings and large tankers are fitted with modern liquid level detection systems in the cargo tanks for sealed tank operations. Many smaller operators continue to use hand taping techniques, according to Coast Guard Marine Safety Office inspectors.

4.2.2 The tank barge fleet The barge fleet includes large ocean-going vessels (up to 30,000 DWT) and inland and coastal operators of smaller size. All are U.S. flagged and built and subject to the Coast Guard inspection regimen. Most barges are unmanned, and include towed and pushed barges. Others are manned, among them integrated tug barges. Construction standards have historically been less stringent than for tankers, although the Coast Guard has eliminated many of the differences. A significant minority of tank barges are now double hulled.

The tank barge typically is a simple, high-block coefficient steel vessel for the carriage of oil. Barges are usually either towed or pushed by tugboats. Towed barges follow the tug on a towline up to 2000 feet long, attached at towing fittings in the bow. Pushed barges may be notched in the stern to provide a multi-directional bearing surface for the tug. The operators are, in most cases, all on the tugboat.

The cargo block is capped on the ends by void spaces and collision bulkheads. The tank arrangement is usually defined by one or two longitudinal bulkheads (two or three tanks athwartship) and transverse bulkheads in accordance with subdivision requirements.

The tanks have access via raised manholes with flame screened ventilation holes and flush manholes. Most tank barges have only one piping system with pump(s) for the loading and discharging cargo. Liquid level detection is by hand taping through sounding tubes.

4.3 Regulation of oil carriers

4.3.1 International instruments

All tankers are subject to regulation by instruments of the IMO, subject to ratification by the flag administration. Significant among these is the International Convention for the Prevention of Pollution from Ships (MARPOL) [15], which requires protectively located segregated ballast tanks, tank size limitations, crude oil washing and slop tanks, and the inert gas system, which provides for fire safety by eliminating oxygen from the ullage gases. MARPOL came into force in 1983 and is still in its phase-in period for older tankers.

The International Convention for the Safety of Life at Sea (SOLAS) contains standards for stability and subdivision, machinery, firefighting, navigation, communication, and lifesaving, among others, all of which apply to the world tanker fleet [14].

The International Convention on Load Lines, 1966 (ICLL 66) regulates the loading of tankers and the safety standards for topside structures and fittings relative to protection from boarding seas and provision of reserve buoyancy [13].

4.3.2 Domestic Regulations

Tank vessels are regulated by the Coast Guard through the Code of Federal Regulations (CFR) and standard inspection schedules. The CFR, with some exceptions, follows the requirements of international instruments. These exceptions are not pertinent to this study of oil tankers.

CFR 46, Subpart 32.20-20, requires that tankships have a method of determining the levels of liquid in all cargo tanks without the opening of ullage holes, cargo hatches, or Butterworth plates. Sounding tubes for hand taping are allowed. This regulation does not apply to tank barges.

4.4 Factors affecting liquid level gauging accuracy

4.4.1 Operating conditions

<u>4.4.1.1 Ship motion</u> The most obvious detriment to obtaining clear, accurate level readings is the disturbance of the surface of the cargo by ship, or barge, motion. This will occur in all circumstances from being moored at the pier to running in heavy weather. The parameters of ship motion include translation in three directions-- heave, surge, and sway-- and rotation in three directions- roll, pitch, and yaw.

A vessel working in a seaway may also be subject to slamming, when the bow comes out of the water and reenters with attendant impact loads, and submergence of the deck by waves. The latter phenomenon is a more common occurrence for tankers than other cargo carriers because they are allowed to load more deeply than other cargo carriers by national and international regulations. They are designated "Type A" vessels by the 1966 International Conference on Load Lines because their decks are nearly flush (no hatch covers) and also because they meet more stringent subdivision requirements than dry cargo ships.

Coastal and ocean-going tank barges are also prone to heavy deckwetness in rough weather. An operator of a coastal barge (25,000 barrels, 17.5' draft, 3.25' freeboard) remarked during an interview that the vessel was "like a submarine" in heavy weather.

Significant ship motion in open water is also a factor during ballasting operations of large tankers at offshore unloading facilities [10].

The parameters of such motions are unique to each type of vessel, with additional variables for different loading configurations and weather conditions. Every tank vessel, up to the largest ULCC, is subject to violent accelerations in severe weather and mild accelerations under more benign conditions.

The deleterious effects of ship motion for level detection are several. The most immediate is the sloshing of cargo and the difficulties posed by surface disturbance for accurate gauging. The resulting formation of foam can degrade any type of top down electronic sensing of the surface. Finally, motion of the cargo surface can result in pocketing of air in the tank, and a loss of accuracy in the ullage tables.

Another effect of severe ship motion is the attendant acceleration of the liquid in the cargo tanks. The vertical acceleration of the cargo due to surge, roll, and pitch will vary quite widely, as will the hydrostatic data from a pressure sensor, if used. The U.S. Navy standard, "Ship Motion and Attitude", indicates the extent of these accelerations for "conventional surface ships". Heave acceleration in sea state 4 is in the range of 0.04-0.10 g's, depending on length, and 0.2-0.6 in sea state 8. Surge accelerations are likewise 0.02-0.06 and 0.10-0.35 g's. There are additive second order components due to pitch and roll [37].

While it is unrealistic to expect precise measurement in conditions this severe, it is clear that appreciable accelerations of the cargo will take place at lower sea states and significantly degrade the accuracy of a hydrostatic system. In these conditions, the liquid measurement may degrade up to 10%.

4.4.1.2 Hull Structural Deformation

Another noise contributor is structural deformation due to various stresses to which the hull girder and local structural elements are subjected. Hull stresses are the result of the various load configurations undergone by the ship and are accompanied by strain and deformation of the structure.

The implications for accurate liquid level measurement are twofold. First, subtle changes in the shape and capacity of the tank may result in significant differences in its volume. The second, and more immediate, outcome is that any level detection system keyed to the physical configuration of the tank will be compromised by hull deformations which alter that configuration. Relative movement among system components, tank structure, and the surface of the liquid will contribute to measurement error due to noise.

This is particularly so for those systems which measure from the top down, i.e. radar systems, which are deck mounted. Likewise, any system relying on benchmarks mounted within the tank will be affected by relative translations of the supporting structure. Hydrostatic sensors will be the least affected by structural translations.

A brief consideration of hull deformations follows.

Still water hull bending deflections Longitudinal hull bending deflections occur as a result of the varied loading configurations the ship sees. The terms "hog" and "sag" describe the conditions where, respectively, the ends or middle of the ship deflect downward. The hull deflections are quantified by differences in the vertical distance between the extremes of the keel. A typical 280,000 DWT tanker (1000 feet long) will move from a 1" sag in the ballast condition to a 7" sag in the fully loaded condition, a keel deflection of 6".

The deflection in a single tank (about 150' long by 50' wide) in that case would be 1" and represents approximately 625 ft^3 of added capacity at the bottom of the tank below the plane connecting the lower extremities of the bounding transverse bulkheads. The result would be a drop of about ½" (12 mm) of the surface of the fluid in the tank relative to the tank top.

A significant error factor is thus introduced which would particularly effect the accuracy of sensors whether they measure ullage or innage. The error is dependent on the longitudinal location of the sensor (see Figure 4.1). If the fluid level is assumed to drop one half the distance of the deflection of the segment of the hull along the tank (designated X) and the main deck is assumed to remain parallel to the bottom, the error of ullage measurement would vary from -½X at the center of the tank to +½X at the ends (the innage measurement would vary by +½X and -½X, respectively).

A level sensor installed in its preferred position at the aft end of the tank (e.g., hydrostatic gauge or electrical resistance tape) will be subject to the greatest error, as will any beam unit which is located at the center of the tank.

<u>Dynamic Loading Stresses</u> The critical design criterion of the hull girder of a tanker is its response while operating in a seaway under severe weather conditions. It undergoes bending stresses about all three of its inertial axes due to the influence of the types of motions already described. Longitudinal bending is induced by the passage of waves producing a variety of buoyant conditions which vary hull loading and stresses, also known as "hog" and "sag". Variation of lateral loads causes bending about the minor axis of the hull girder and, finally the hull is subject to torque, or twisting, moments.

Second order effects include the following:

-The shipping of green water on deck will cause deflections, which will degrade the accuracy of any system having components on the deck.

-Ship motions also cause variations of hydrostatic pressure on the hull, resulting in relative shell deflections and changes in tank capacity.

-Different cargo loads will induce different hull loadings and responses.

<u>Tank Deformation during Load/Unload Operations</u> Tank boundary deflections occur in two modes during load and unload operations, when different combinations of tanks are empty and full prior to reaching full load or ballast condition in port. The first is the general deflection of the hull girder already discussed.

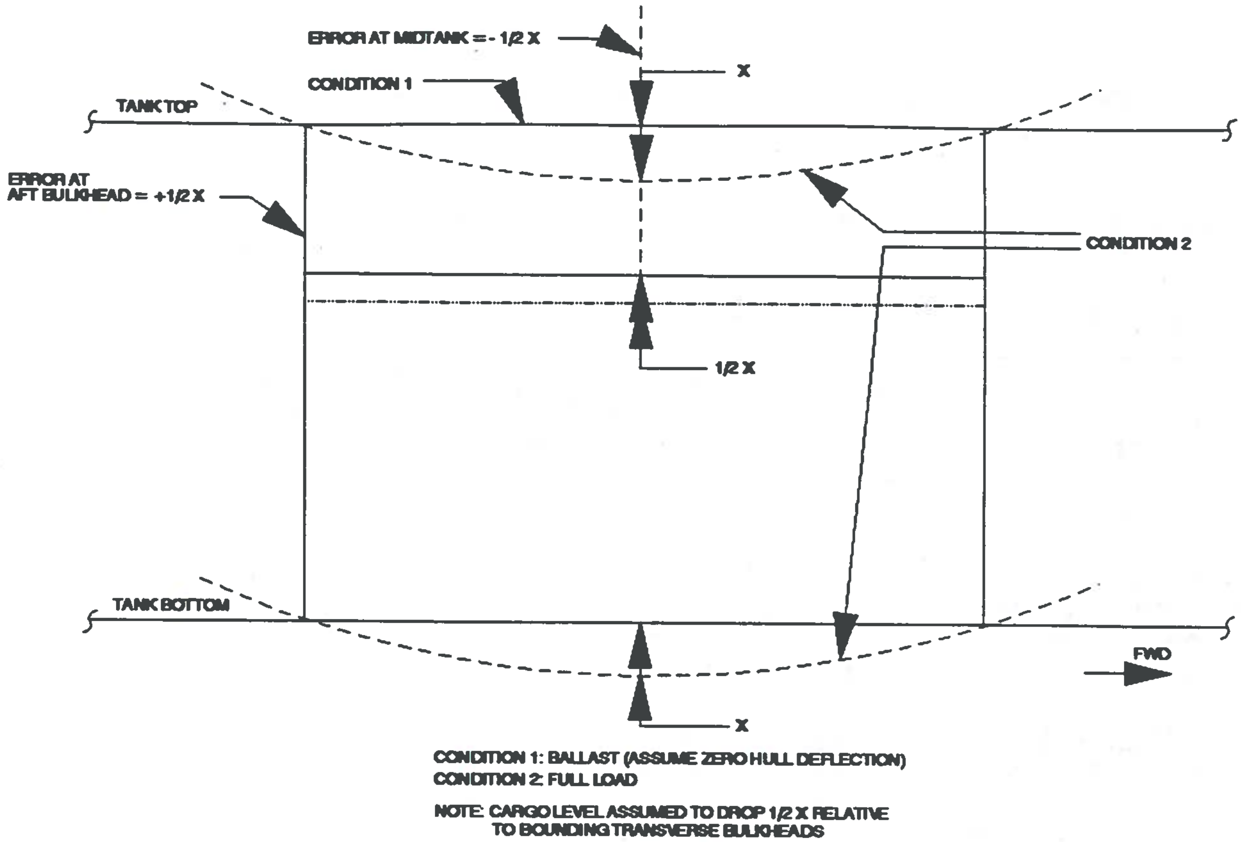


Figure 4-1
Static Hull Bending Deflection

Local bulkhead deflections also occur as cargo tank loading combinations change. For instance, a full tank surrounded by empty tanks will expand relative to its configuration when it is surrounded by full tanks; the bottom will also deflect under the loading of cargo [21].

A similar phenomenon has been noted by the Environmental Protection Agency (EPA) for underground fuel storage tanks [29] and by the bulk liquid storage industry [27]. EPA's testing program for liquid level detection systems addresses subsurface storage tanks at gas stations. These tanks are cylindrical vessels, usually no more than 12 feet in diameter and 40 feet long. They are much smaller than cargo oil tanks found on tankers and tank barges and undergo lower magnitudes of liquid loading.

EPA notes that variable level tests are error-prone because the tank deforms when filled to different heights, and add that the deformation characteristics are not usually known. This conclusion is noteworthy because it indicates that structural tank distortion in a less strenuous environment can significantly degrade the detection of slow leaks.

Analysis of Tank Volume Distortion During Load/Unload Operations

An analysis of bulkhead deflections, resultant volume changes in cargo tanks, and the consequent liquid level changes was carried out for a 77,000 DWT lightering tanker and a 400,000 DWT VLCC. The calculations determined deflections caused by a common situation in tank loading, which is from a net load of zero on the tank bulkheads to one where one side only is fully loaded. The initial condition may be both tanks full or empty. The same problem occurs to a lesser extent in the side tank of a single hulled tanker when changes in draft, list, and trim occur during loading and unloading operations.

Each bulkhead is analyzed by units of stiffened panels which are bounded by vertical and horizontal girders (assumed rigid). Several rows of panels, designated by letters starting with "A" for the bottom row, make up the bulkhead. The average nodal deflection for each row (nodes are in a regular grid) under the local loading is multiplied by the area of the row, yielding a change in tank volume due to deflection of the bulkhead. The two longitudinal bulkheads only were included in the VLCC calculation; likewise only the transverse bulkheads were considered for the lightering tanker.

In the former case, the long aspect of the center tank makes neglecting the transverse bulkheads a slightly conservative step. In the latter case, the lighter's configuration was such that only the transverse bulkheads are affected by this loading scenario. Deflections of the tank bottom are also ignored. A typical graphic output of deflections in a panel appears in Figure 4-2.

The results, summarized in Tables 4-1 and 4-2 indicate that the liquid level can change plus or minus 1.91 millimeters on the lightering tanker (equivalent to 279 gallons) and 6.27 millimeters on the ULCC (equivalent to 1480 gallons), as a result of tank loading sequences. The complete methodology and results are attached as Appendix B.

<u>Thermal Stress</u> The hull is also subject to deformation from thermal stresses, which may occur seasonally, from day to night, and among the thermal influences of cargo, water, and air. The coefficient of thermal expansion is $1.2 \times 10^{-5}/^{\circ}C$ for steel [2]. A change of temperature of 20°C to the above waterline hull (8 meters height, in the example of the 400,000 DWT ULCC) during a 24 hour period would result in a vertical expansion of nearly 2 millimeters. The main deck above a cargo tank of the sample ship (37 meters long by 14 meters wide) will expand longitudinally 9 millimeters and transversely 4 millimeters due to the stipulated temperature changes.

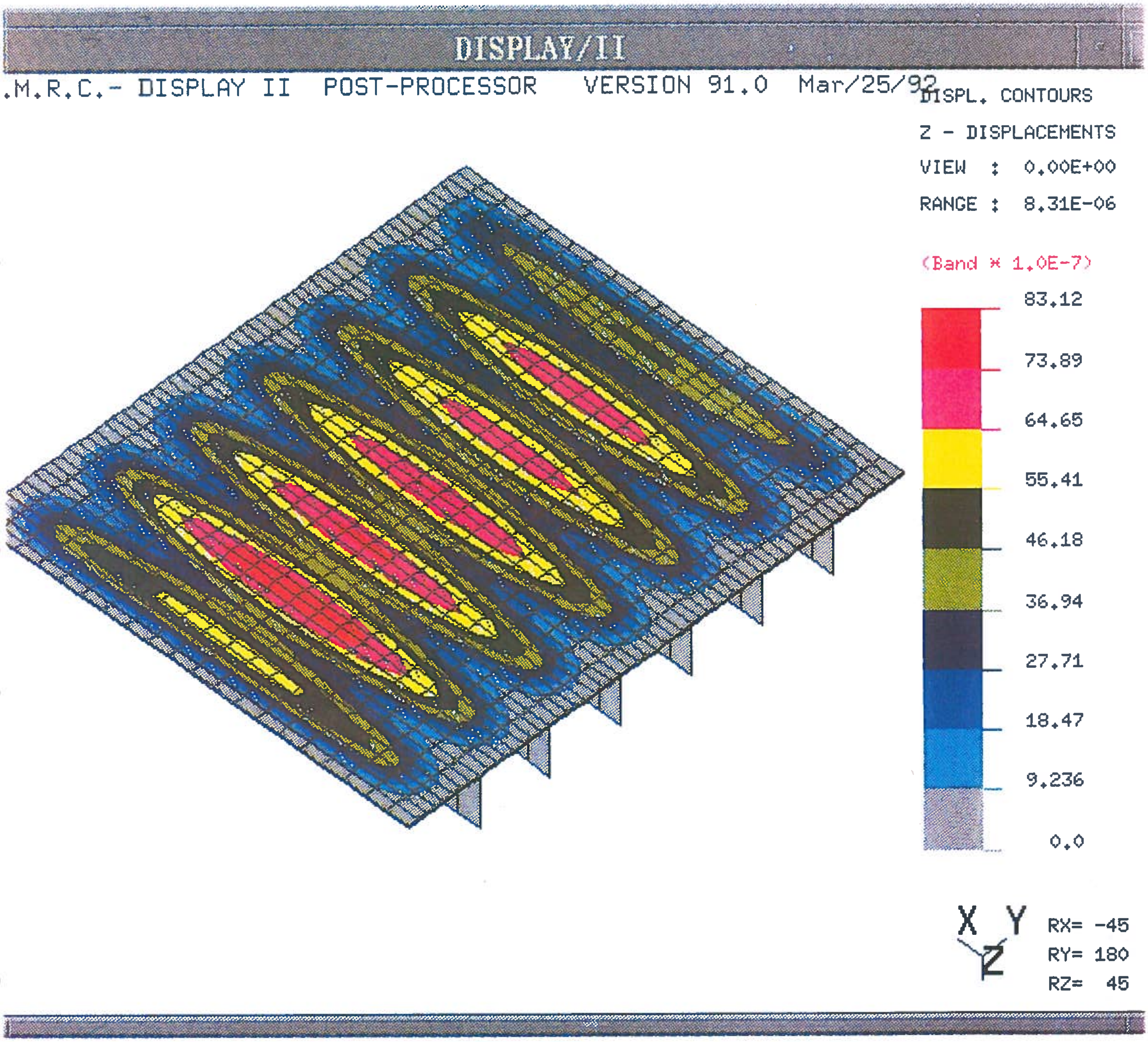


Figure 4-2

Bulkhead deflection graphic

400,000 DWT VLCC center tank, Longitudinal bulkhead
Lowermost panel
Deflections due to full cargo load, near side only

The temperature of the cargo oil may vary greatly in the course of a long voyage. This is so only in particular circumstances, for example a crude carrier bearing oil from the Persian Gulf to the northeastern United States. According to operators, the oil may be loaded at a temperature in excess of 100° F (about 30°C) and cool in the course of the voyage by as much as 50°F (20°C) An internal tank bulkhead of 25 meters height would contract 10 millimeters in that circumstance.

Cargo heating systems are employed on some ships and are used to varying extents in different seasons. Cargo may be heated throughout a winter voyage, or only prior to unloading in more temperate weather, or not at all in the summer. Dramatic cargo and tank structure temperature swings of up to 20°C may occur at the end of a voyage as the heaters are activated for cargo transfer.

A second order effect is the translation of the deck relative to the baseline due to the varying temperature differential between water and air. The seawater temperatures encountered on a long voyage may vary from 5 to 20°C.

Thermal deformations will compromise accuracy of the level measurement system in the same two ways described for dynamic stress and strain, i.e. alteration of tank configuration and capacity, and, directly, by translation of the measuring devices themselves. Total deformations are a function of length and thus thermal stress gains significance as a negative influence proportionally with the size of the vessel. Thermal hull structure expansion may conservatively be stated to cause an uncertainty of +/-1 mm; it can certainly be higher in some circumstances, particularly for "top-down" systems such as radar.

<u>Static Attitude of Vessel</u> Tank level measurements and mass/volume cargo calculations are affected by the static attitude of the ship, that is, its stillwater aspect with regard to list, trim, and draft. These of course change with different loading configurations, but may also be effected en route as consumables are used, or even slightly so as the ship passes through areas of changing salinity or water temperature, or transits shallow water, tending to squat down in the water.

Most modern systems are able to cope with the requirement of cargo measurement with list and trim, within certain limits, usually 4 degrees, sufficient for most circumstances. This is a requirement for loading operations such as topping off, preventing overfill, and dry tank detection, the assurance during unloading that a tank is completely empty. Older technologies, such as float gauges, do not however have this capability.

<u>Vibrations</u> An inescapable part of shipboard environment is vibration. Any system which provides precision measurements must function reliably and for long periods of time

	Max. nodal deflection (ft)	Ave. nodal deflection (ft)	Panel area (ft^2)	Panel volume change (ft^3)
Bottom panel	0.015	0.006	260.1	1.57
Mid panel	0.015	0.006	207.1	1.23
Top panel	0.011	0.003	292.6	0.96
			Total	3.76

*Each column of three panels moving outward adds 3.76 ft^3 to the volume of the tank.

Total added volume= (5 columns) x (2 bulkheads) x 3.76 ft^3 = 37.6 ft^3

(37.6 ft^3)/(6000 ft^2) = liquid level drop of 1.9mm

Bulkhead deflections during load/unload operations cause the volume of a tank to change, and the liquid level within to move. This scenario is that of a full center tank whose longitudinal bulkheads deflect as surrounding tanks are pumped down from full to empty. Deflections of longitudinal bulkheads only are considered. The surface area of the tank is 6000 ft^2.

Table 4-1

Tank volume change due to bulkhead deflection

77,000 DWT Lightering Tanker

	Max. nodal deflection (ft)	Ave. nodal deflection (ft)	Panel area (ft^2)	Panel volume change (ft^3)
Bottom panel (Panel A)	0.011	0.005	350.3	1.73
Panel B	0.012	0.005	252.0	1.30
Panel C	0.011	0.005	303.4	1.50
Panel D	0.011	0.004	345.4	1.48
Top panel (Panel E)	0.014	0.006	377.9	2.29

			Total	8.31

*Each column of five panels moving outward adds 8.31 ft^3 to the volume of the tank.
Total added volume= (12 columns) x (2 bulkheads) x 8.31 ft^3 = 199.51 ft^3

(199.51 ft^3)/(9700 ft^2) = liquid level drop of 6.3mm

Bulkhead deflections during load/unload operations cause the volume of a tank to change, and the liquid level within to move. This scenario is that of a full center tank whose longitudinal bulkheads deflect as surrounding tanks are pumped down from full to empty. Deflections of longitudinal bulkheads only are considered. The surface area of the tank is 9700 ft^2.

Table 4-2

Tank volume change due to bulkhead deflection

400,000 DWT Tanker

under this condition. The main source of vibrations is the propelling machinery, specifically the propeller. It emits a "blade frequency" caused by variations in water resistance as each blade passes through its topmost vertical position in the shadow of its struts or other support structure. The blade frequency is the shaft speed times the number of blades per unit time and varies with the speed of the ship. These vibrations will have their greatest effect on cargo tanks in the after portion of the ship.

The infrequent occurrence of slamming will also cause vibrations, whose main effect will be in the forward cargo tanks. Other vibrations may be caused by auxiliary machinery, anchor handling equipment, etc., but are not likely to be significant.

Shipboard vibrations will not necessarily degrade the accuracy of liquid level measurement but are an adverse condition with which any system must function effectively. The shipboard application of land-based technologies will have to take account of this factor. Tanker vibration data is not readily available.

4.4.2 Tank Conditions

Crude oil and petroleum product tanks present two problems in the specification of level sensing equipment-- severe operating conditions and significant ambient noise factors. Precise data output and slow leak detection thus become more difficult to achieve.

<u>4.4.2.1 Corrosion</u> Petroleum products, especially crude oil, are by their nature corrosive substances. "Sour" crude oils contain sulfur and are the most corrosive of the group. The inevitable presence of water, sometimes seawater, in the tanks is an added detriment. Electrolytic corrosion is a constant threat which shipbuilders and operators counter with strictly specified tank coatings for the protection of structural steel and, in some instances, with cathodic protection systems inside the tanks. Ullage gases can also be very corrosive (see para. 4.4.2.3).

Any liquid level measurement system in the tank is also vulnerable to corrosion. It is therefore desirable that the system have few components and no moving parts in the tank, and that they have good corrosion resistance and are easily maintained. This point is addressed for systems surveyed in Table 3-2, "advantages" and "disadvantages".

<u>4.4.2.2 Cargo Sloshing</u> This problem has already been discussed. The excitation of the liquid free surface due to ship motion renders accurate level sensing very difficult; in some cases, operation of the sensors is not possible. Float gauges, in practice, are locked in the up position for protection from the cargo movement. The constant sloshing is known to cause erosion of scantlings in the tank and poses the same threat to level sensing

components in the tank.

The problem of accurate level detection with a disturbed surface will affect any kind of measurement system; hydrostatic pressure will vary, as well as any gauging of the ullage or the innage. The situation differs between tanker and tank barge. After MARPOL and the requirement for segregated, protectively located ballast tanks, modern tankers have become "cubic-limited"; that is they cannot load to their deepest allowable drafts with cargo only in designated cargo tanks. This, among other reasons, is why tankers load cargo to 98% tank capacity (this is why many tankers employ topping off and overfill prevention devices).

Tank barges, on the other hand, tend to be deadweight limited; that is, their deepest allowable drafts may be reached without completely filling the cargo compartments. They commonly run with the cargo tanks 80-90% full, depending on the cargo being carried.

Much more free surface motion may therefore be expected in barges, while in tankers a very small volume of ullage will change shape as the liquid moves (see Figure 4-3). The magnitudes of cargo motion will tend to be smaller on tankers, but cargo measurement no easier.

<u>4.4.2.3 Ullage Conditions</u> The ullage space is that volume above the surface of the liquid cargo in the tank. It is occupied by a variety of different gases and subject to differing conditions of pressure.

Ullage gases commonly consist of a mixture of atmospheric or inert gas and the vapor which arises from the cargo. Their composition is affected by the composition of the cargo, the ullage temperature, and other factors including operations which introduce other gases into the tank.

Venting of the tank during loading and unloading allows the entrance of atmospheric gas which mixes with the cargo vapor. After closure of the tank, vapor may continue to form, and cause layers of gas stratified by composition and density. The performance of some systems which measure ullage using beam reflection can be adversely affected.

Ullage pressures may fluctuate due to temperature changes in the tank and the formation of new petroleum vapors. Temperature changes not only vary vapor pressures, but cause volumetric expansion and contraction of the liquid cargo, causing the ullage volume to vary as well. Barges and some tankers employ pressure/vacuum valves which relieve excessive pressure in the tank by the release of ullage gas to the atmosphere or allow atmospheric gas into the tank to relieve a vacuum condition. The pressure and composition of ullage gases thus may be variable throughout a voyage.

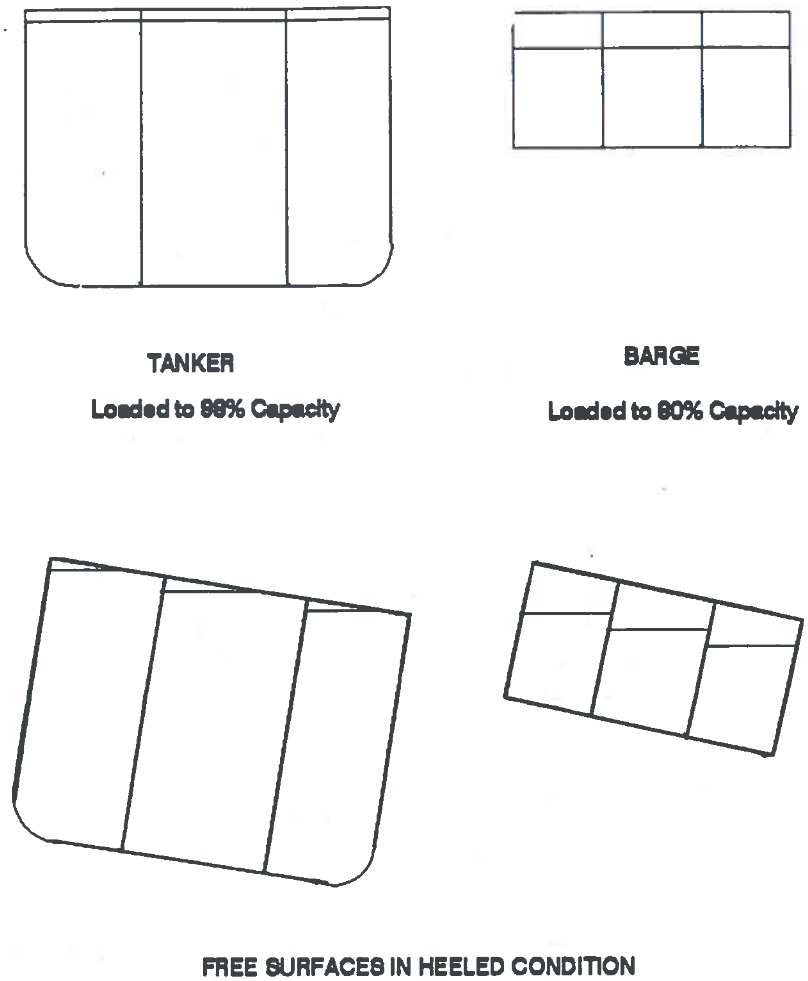


Figure 4-3
Movement of Cargo on Tanker and Barge

It must finally be noted that many tankers are required to have inert gas systems (IGS) installed as a fire protection measure under the requirements of SOLAS 74/78, Chapter II-2. The essentials of IGS are that flue gases from the engine room are purified and pumped into the ullage spaces of the cargo tanks as a means of reducing oxygen content and minimizing the risk of fire and explosion. IGS usually operates with a positive pressure of 1-2 psig and alters the composition of the ullage gas to include nitrogen (77%), carbon dioxide (13%), water vapor (5%), oxygen (3-4%), and traces of other gases (1-2%).

The trace components include sulfur dioxide (SO_2), sulfur trioxide

(SO_3), and salt (NaCl). Heating of the tank causes the synthesis of acidic compounds such as sulfuric acid (H_2SO_4), sulfurous acid (H_2SO_3), sodium sulfate (Na_2SO_4), and hydrochloric acid (HCl). These are very aggressive against steels, including stainless steel [10].

In short, the tank level detection system must operate reliably and without loss of accuracy in, or through, a complex, gaseous medium, whose composition, temperature, and pressure are variable due to several influences. This uncertainty will affect beam-based ullage measurement systems such as ultrasonic, as well as hydrostatic sensors, which require ullage pressure measurement for correct calculation of cargo mass.

This uncertainty will effect some systems which measure ullage by reflected beam, ultrasonic in particular. A noise factor of 0.5% can be expected for these systems.

<u>4.2.2.4 Thermal expansion of cargo</u> Cargo tanks are subject to fairly large swings in temperature in the course of a day. Direct sunlight exaggerates the day/night differential, as well as the high thermal conductivity of the hull steel. The contents of both cargo and slop tanks may be hot following tank cleaning and cool rapidly thereafter.

Thermal expansion and contraction of oil can thus be significant. The coefficient of thermal expansion for oil is $9.55 \times 10^{-4}/°C$ [38]. A twenty degree temperature swing results in a change of volume of 1.91%; ten degrees means a change of 0.96%. Coefficients of thermal expansion for refined products are slightly greater. Previously described conditions related to cargo heating will cause like changes in cargo temperature.

A ten degree temperature differential in a 25 meter deep tank can thus result in a change of liquid level of +/- 0.24 meters, assuming constant temperature throughout the tank. Thermal stratification will most likely occur, causing lesser, but still significant, volumetric expansion or contraction. This problem worsens in absolute terms with increasing tank depths.

Thermal expansion and contraction of the cargo, as well as thermal stratification, must be accounted for by the level detection system. Complete accuracy is not possible without continuous temperature sensing from top to bottom of the tank. All systems surveyed rely on one or two temperature readings for cargo mass calculations, often taken from the bottom half of the tank, where thermal fluctuations are less severe.

This uncertainty affects every cargo measurement system since the height of the liquid surface changes and mass measurements depend upon accurate temperature data. Temperature stratification, both vertical and horizontal, is recognized as a problem in the measurement of aircraft fuel tanks, where quantities are far smaller and mixing action much more thorough, according to a leading manufacturer of aircraft fuel gauges. The collection of temperature data must be significantly improved to address this issue.

This factor of uncertainty can conservatively be called 1.0% for the worst conditions of temperature change, and is likely to be worse for some types of systems. Hydrostatic gauges measure temperature and, most importantly, mass and are thus less likely to yield a gross random error. They are, nonetheless, susceptible to considerable error because of the limited temperature data collection earlier referred to.

4.4.2.5 Cargo variability The accurate measurement of crude oil or product in the cargo tank depends in part on material constants, whether density, coefficient of thermal expansion, dielectric constant, etc. These vary among types and grades of petroleum and its products and also among batches of the same product.

The ballast handling procedure known as "load on top" results in the stratification of the tank according to its contents of oil and water, together called by "dirty ballast" [20]. The monitoring of tanks holding both dirty and clean ballast will of course also be required. The presence of varied substances of varied densities, stratified in the tank, will introduce calibration errors into most systems.

Aircraft fuel gauging employs sensors for measurement of critical material constants, e.g., densitometers for the calculation of fuel mass. Effective cargo measurement within the OPA 90 regime may require additional instrumentation in the tank for the validation of a system's data.

As a conservative estimate, this factor can introduce an uncertainty of 0.2% into the cargo measurement.

4.4.2.6 Tank Washing Oil tankers employ rigorous methods by which to wash tanks between voyages. MARPOL compliant ships with IGS use crude oil wash (COW), in which high speed jets of crude oil are directed over the tank's inner surfaces to remove clingage and sludge. Nozzle pressures of 140 psig are typical.

Other ships still use a high speed water wash. Seawater, varying from injection temperature to 180 degrees Fahrenheit, depending on the cargo carried, is sprayed at nozzle pressures of up to 180 psig [20]. Both methods require that any sensing equipment in the tank be rugged and durable.

4.4.3 Tank calibration

Cargo tanks are calibrated by the shipbuilder at the time of construction for the compilation of the ullage tables. In most instances, the calibration is completed using the ship's drawings. This method is cheaper, and less accurate, than liquid calibration, in which the tank is filled with incremental volumes of water, and calibration by linear measurement.

Two major sources of error inhere in the use of ship's drawings for calibration. The first is that the tank boundaries-- bulkheads, deck, and tank bottom-- may not be exactly where the drawings specify. The second is the deduction for "deadwood", the volume in the tank of structural elements, piping, etc. for which the calibration must be corrected.

The error in the deduction is of varying magnitude. Some shipbuilders merely take an arbitrary percentage of the tank's molded volume, e.g., 0.5% for a center tank and 1.5% for a wing tank, and spread the deduction evenly throughout the tank's depth. They have otherwise calculated the actual deadwood volumes and then used various distribution assumptions with varying degrees of accuracy.

Wedge formulas for determining the volume of cargo near the bottom of the tank nearly always contain errors of geometric omission. Trim and list corrections can be inaccurate as well [21].

Inaccuracies in an ullage table may in a worst condition case may be conservatively given as 0.5%. The worst condition could be one of the two following, or an additive case of the two:

- Longitudinal bulkheads whose location adds or subtracts 2" to a nominal tank width of 50 feet, an error of 0.33%.

- Major longitudinal structure, e.g., a 48" deep X 3/4" web plate with a 12" X 1" flange, on each side of the tank, which is not accounted for by the deadwood allowance used in the calibration. In the same 50 foot wide tank, a 1.3% error will be found in the 12" deep stratum of the tank occupied by the scantling.

The American Petroleum Institute Committee on Static Measurements has made several recommendations for the preparation of new calibration standards which can mitigate this uncertainty factor.

4.5 Other operating requirements

The installation of tank level detection equipment on a tank vessel must in each case take account of the vessel's particular operating mode. Included in this area are whether the vessel operates with sealed tanks, employs high level alarms, overfill prevention, and topping off procedures, carries mixed cargoes, employs crude oil tank washing, or requires particularly accurate data for stripping tanks.

Tank stripping and dry tank detection are a particular concern, especially for closed, sealed tank operation (see Figure 4-4). The selection of a tank level detection system may depend in good part on this requirement. The operator must make other decisions balancing cost, vessel operation, and whether the installation is during a newbuilding or a retrofit.

A test and performance standard, as suggested in Section 3, must allow flexibility to the operators in the selection and installation details of a tank level detection system while ensuring the capability of the system to protect the environment as intended by OPA 90.

4.6 Conclusion

The discussion of the working conditions in which a tank level measurement system must operate has revealed many working requirements, as well as several factors which will introduce uncertainties into the measurement of tank levels (see Table 4-3). Some uncertainties are particular to one or more of the sensor types, while others will effect all systems. In addition, some noise factors are present on all tank vessels and others only on particular types, or in varying degrees of severity on different vessels.

None but one of the noise factors identified can be mitigated by reasonable means, as they are inherent aspects of tank vessel operation. Cargo tank calibration, however, can be improved in accordance with the recommendations of the American Petroleum Institute Committee on Static Measurements [21].

The implications of these potentially degrading influences will be addressed in discussion of various leak scenarios and the possibilities for false positive and false negative spill indications.

SENSOR TYPE	Hydrostatic	Radar	Resistance Tape	Float Gauges	Ultrasonic Ullage	Ultrasonic Innage	Ultrasonic Pulsed Beam	Capacitance
Cargo Sloshing*	5	5	5	5	5	5	5	5
Surface Foam	0	5	0	0	5	0	5	3
Ship Motion Cargo Accel	4	0	0	0	0	0	0	0
Dynamic Hull Deformation*	3	3	3	3	3	3	3	3
Tank Load/Unload Deformation*	3	3	3	3	3	3	3	3
Hull Thermal Stress	1	4	4	2	4	2	4	4
Hull Bending Static*	3	3	3	3	3	3	3	3
Variable Ullage Pressure	3	0	0	0	2	0	1	0
Variable Ullage Temp, Composition	0	2	0	0	5	0	1	4
Cargo Thermal Expansion	3	3	3	3	3	3	3	3
Clingage	0	1	0	0	0	0	0	4
Differing Cargo	1	3	3	3	3	3	3	3
Tank Calibration*	4	4	4	4	4	4	4	4

Code: 0 (No effect) -----> 5 (potentially severe degradation)
*Noise factor is equal for all types of sensors.

Table 4-3
Performance Uncertainty Factors

5 Routine System Performance Evaluation

The performance of the previously described level sensing systems will be evaluated for normal operating conditions (no leakage of cargo), accounting for the various environmental uncertainties identified in Section 4.

Several assumptions will be made for this evaluation:

- Accuracy is the sole attribute of the sensors to be considered. Others such as precision, reliability, and resolution are assumed to be equal and adequate, in part because technology and product development may be expected to solve these problems. Best-condition accuracy of 1-3% is typical of all the sensors in the survey.

- The determination of sensor accuracy will include additive noise factors for several scenarios of operation. The uncertainties determined in Section 4 will be used.

- Cargo sloshing will not be considered among the noise factors. Although it is the single greatest uncertainty, it cannot be positively quantified. System modifications aimed at mitigating its effects will be discussed later.

5.1 Operating system performance

The problem of false indications due to uncertainty of operating conditions is well known. The EPA's volumetric tank testing study concluded that "unless the deformation characteristics of the tank...are known, it is not possible to distinguish between the volume changes due to a leak and those that normally occur in a non-leaking tank." [35]. This conclusion applies to stationary underground gasoline tanks, for which few uncertainties exist relative to tank vessel cargo compartments, and, in a narrow way, to tank vessels.

The EPA's finding may be more expansively stated for tank vessels: unless all measurement uncertainties are specifically trackable by the crew, it will not be possible to distinguish between liquid level changes due to a leak and those that normally occur in a non-leaking tank; nor will it be possible to know whether constant level indication can occur when the tank is leaking.

It is clear from the discussion of operating environment in Section 4 that most uncertainties will not be trackable by any available or technologically foreseeable equipment. It is therefore necessary to define the limits of modern instrumentation for this application; the approach will be to suggest a number of operating conditions and determine the true "attainable accuracy".

5.1.1 Operating scenarios Several operating scenarios will be considered in which numerous uncertainties have an additive effect, leading variously to false positive leak and false negative leak indications, defined as follows:

- **False positive**-- a situation in which one or several uncertainties causes an apparent drop in the cargo level indication when the tank's tightness has not been impaired and no leak has occurred.
- **False negative**-- a situation in which one or several uncertainties causes the cargo level indication to remain apparently constant, when cargo is, in fact, leaking from the tank.

The following situations are a sampling of realistic scenarios and are by no means representative of all possibilities. Each scenario represents the additive effect of two or more factors of uncertainty.

Scenario 1: A tanker loaded with crude oil from the Persian Gulf is in the North Atlantic two days out of a northeast port during January. A cold night has given way to a sunny, warm day, and the ship has moderate motions due to a following sea. The cargo has cooled 20°C since loading, is stratified in the tank by temperature, and is being warmed in the upper 20% of the tank by the hull, which is 15°C warmer than it was early in the morning.

An uncertainty of about +/- 1.0% will result due to cargo temperature, depending on where the single cargo thermometer is located. In addition, the hull thermal expansion will translate any top-down system measuring ullage as much as 2 millimeters. The ship motion will cause foaming of the liquid's surface, with resultant signal scatter for any reflected beam sensor and motion-induced accelerations of the cargo causing uncertainty for a hydrostatic sensor, if used.

Altogether, an apparent drop in the liquid level of up to 1.5% is possible; and a false positive leak reading may be registered on the watch.

Scenario 2: The amidships center tank is the first to be loaded. As the ship goes from ballast condition to fully loaded, the liquid level in the tank falls 8 mm due to hull sagging. The liquid level drops an additional 2 mm because piping and structure in the top of the tank was not accounted for in the calibration of the ullage tables. The drop is somewhat limited because cargo oil filling the surrounding tanks causes the bulkheads to deflect back inward, causing the liquid level in turn to rise about three mm.

In the control room, the liquid level in the tank is observed to drop about 7 mm. No sheen is observed on the water, but a strong current creates doubt as to whether one would be seen. Loading operations are stopped so that the crew may observe whether or not the level in the tank stabilizes.

Scenario 3: A small hull crack in the bottom of a tank has developed as the tanker approaches port. Oil leaks slowly, but is not detected because the cargo heaters have been activated and the oil is expanding, causing the liquid level to rise faster than the leak lowers it. The crack lengthens as the ship works through an offshore wind, but ullage conditions give rise to additional noise in the instrumentation. The gas composition and pressure varies, causing the faster return of a beam signal, indicating less ullage. If a hydrostatic sensor is being used, a malfunction in the ullage pressure sensor could mask a temporary rise in the pressure output of the IGS, while the hydrostatic sensor would indicate an apparent high liquid level.

An uncertainty of about 1.5% might arise in this case, and the leak go undetected by the crew for double that amount until the indicated liquid level actually drops. This is a case of false negative leak indication.

5.1.2 Attainable accuracy Attainable accuracy is defined as the limit of cargo level change which causes the crew to confidently register the existence of a cargo tank leak. In its determination are included the best operating capabilities of modern level indicating systems, the various uncertainties described, and the human interaction with the system.

The level indicating systems investigated are accurate, under ideal operating conditions, to +/- 3mm to 5mm. These numbers increase for some systems with measured distance. The resolution (ability to discern a change in the measured quantity) is in some cases less than 3mm and could in other cases probably be improved if needed.

Any system in a cargo tank will be subject to considerable noise, all sources of which have been described individually and in combination in a limited number of scenarios. It is clear that those scenarios give rise to false positive leak indications which will certainly affect the human/system interaction.

More simply stated, the crew can learn how much of an indicated level change reflects the expected amount of noise and how much means that a leak has definitely occurred. As shown, the uncertainties can add up to a considerable amount, an amount which equals or exceeds the claimed accuracy of a modern system. The aggregate uncertainty well exceeds the fine resolution offered by some systems, particularly those designed for shoreside applications with tightly controlled environments.

The total uncertainty may be put at 1.5-2.0%, based upon the limited sampling of additive noise scenarios given. The attainable accuracy is therefore that which exceeds this amount. A minimum of 1.5% will be used for present purposes, assuming that, if the crew sees the liquid level in a tank falling beyond that amount, they will take proper responsive actions.

5.2 Prospective system modifications

OPA 90, Section 4110 implies a new application for cargo tank level indicating systems beyond gauging for load/unload operations. This could mean constant real time surveillance of shipped cargo oil and some improvements to help mitigate the identified noise factors.

5.2.1 Continuous real time cargo monitoring Both the physical system arrangement and crew watchstanding responsibilities may require modification to satisfy leak detection requirements.

Tanker operators will have to decide between manning the cargo control room full time or adding extra data repeaters and alarms on the bridge so that the watchstander can monitor the cargo tanks. The latter option probably makes more economic sense since an extra crewman might be required for the first.

The remote location of the tugboat crew from a barge will have to be accounted for in the selection of an active, real time detection system which will operate during voyages. Transmission of tank level data from the barge(s) to the tugboat, is a requirement attended by some complications. Hard-wired connections are already in use on some integrated and articulated tug-barge units, but a radio link is the most likely option for towed barges.

The barge would require a signal processor for data from its cargo tanks, a data transmitter (radio or otherwise), and a power source if not already on board. The tugboat would require a radio receiver (towed barge only), a data processor, and a data readout, perhaps a video monitor.

Issues that must be resolved include the following:

- Can the tugboat crew, which includes one tankerman, handle the extra duty of cargo monitoring without extra manpower?
- Which radio frequencies are available for such data transmission, and most effective?
- Different barges will each have unique tank calibration data which will require entry into the data processor. Where inland barges are rafted together, a single towboat may have

to handle tank level data from multiple dissimilar tank barges.

- Loaded barges may be moored for considerable periods of time. How will the level detection systems operate and notify operators of leaks at such times?

- Space limitations on board a tugboat must be considered, particularly if tank monitoring equipment is to be located in the pilot house.

- Standardization of equipment may be required since tugboats may work with many different barges from different companies.

5.2.2 Other system enhancements Enhancements to existing marine and shoreside level sensing systems could improve their performance relative to the many uncertainties in a cargo tank.

<u>5.2.2.1 Signal averaging</u> The uncertainty caused by cargo sloshing can be mitigated by the use of signal averaging, which is now commonly applied in many instances. Up to 15 readings per second were reported for existing systems. Signal averaging could be achieved by computerized enhancement.

<u>5.2.2.2 Stilling wells</u> As previously discussed, stilling wells can damp out the effects of sloshing and could be advantageous, particularly in conjunction with signal averaging capability. Maintenance and clingage problems must be addressed when considering them.

<u>5.2.2.3 Temperature data collection</u> The uncertainty due to thermal expansion and stratification can be lessened by the collection of more cargo temperature data from precisely located positions in the tank. In the case of hydrostatic sensors, extra pressure gauges at different heights will serve the same purpose and also mitigate the problem caused by slightly differing lots of cargo.

<u>5.2.2.4 Beam system calibration</u> Ullage composition can effect the performance of radar and other reflected beam systems. A calibration point, similar to that employed by the pulsed beam system, can be used measure beam velocities and correct for changing gas composition. This might require higher foundations on deck for the transponders.

<u>5.2.2.5 Hull stress monitoring</u> The effects of hull static bending could be accounted for by an active data base which records liquid level fluctuations in each tank as a function of different loading configurations. This would complement the experience of the crew gained from observation of the readings and could be integrated into a leak alarm program.

A limited number of strain gauges located on tank bulkheads could also track local deflections; their data could then be tracked against liquid level changes and the information stored for reference by an alarm program.

5.2.2.6 Leak alarm system Effective cargo monitoring will require a leak alarm system. It must be calibrated so as to avoid repetitive false alarms; an "attainable accuracy" will need to be established on an individual basis so that endemic uncertainties do not activate the alarm. Other suggested system enhancements could be integrated with the alarm program to effectively account for the worst uncertainties.

5.3 Conclusions

There are presently a number of liquid level detection systems in use for cargo oil on tank vessels which are considered adequate by the industry for purposes of custody transfer, topping off, dry tank detection, etc. The definition of routine performance is changed by Section 4110 to include full time cargo monitoring. In this light, the following conclusions are given:

- With exceptions, modern tank level detection devices can be modified for full time operation. Several possibilities exist for refining leak detection and alarming.

- The many uncertainty factors in cargo tanks mean that false leak indications, both positive and negative, are possible. An "attainable accuracy" is defined, as the range within which detected cargo level fluctuations may have causes other than leaks. This, in practice, will be the confidence limit of the crew.

- The attainable accuracy is found to be 1.5% in a variety of additive uncertainty scenarios.

6 Slow Leak Outflow Scenarios

The performance assessment of available liquid level sensing technologies for leak detection must be related to realistic occurrences of leakage and outflow. This section will examine some of the available casualty data and construct a group of hypothetical leakage incidents for selected tanker and tank barge hulls. These incidents will be used in Section 7 to assess the leak detection capabilities of the sensors identified in Section 3.

6.1 Development of leak scenarios

The breach of a tank vessel hull may result in oil leaking out or water leaking in. The direction of flow depends on the depth of the breach's location below the waterline and the height of oil in the tank.

This study has noted that the detection of a rise of fluid in a tank due to water inflow is also a way of detecting hull failure. A leak detection alarm system could include notification of the crew in this case. This analysis will examine outflow and inflow scenarios in a variety of tank loading and draft conditions.

6.1.1 Vessel particulars Four vessels are used for the analysis, two tankers and two barges. Their specifics follow in Table 6-1.

Vessel	Length overall	Depth	Draft at assigned load line
	(all dims. feet)		
400,000 DWT VLCC	1200	95	74
77,000 DWT lightering tanker	785	58	40
25,000 bbl tank-barge	240	17	14
"450 Series" barge 130,000 bbl	512	25	20

Table 6-1

Vessels for outflow study

The barges are both single skin construction and are both unmanned. The VLCC is a single hull ship and the lightering tanker is assumed to be so for the purposes of the analysis.

6.1.2 Historical casualty data Limited information on casualties consisting of small cracks and holes is available. Leak and outflow scenarios are developed from the following sources of information.

6.1.2.1 Coast Guard tank barge damage study This report [33] analyzed 1289 incidents of tank barge damage and found the following:

- o 50% of reported cracks were less than 1 foot in length.
- o 40% of holes were smaller than one square foot.
- o There were 246 cases, 19% of the total, of bottom damage.
- o Damage to other tank boundaries (i.e., not the deck or the ends of the barge) comprised 647 cases, 50% of the total.
- o Approximately 30% of all damage cases were at the ends of the barges.
- o Damage above the waterline was distributed heavily towards bow and stern. Bottom damage was evenly distributed over length and was attributed to the causes of corrosion and erosion.

6.1.2.2 TAPS tanker cracks The fleet of oil tankers in the Trans-Alaska Pipeline Service (TAPS) has recently come under scrutiny because of hull cracking problems [34]. The causes of the cracking have been determined to be poor structural detailing, workmanship, and quality control, use of high tensile steel resulting in smaller wastage margins, and low cycle fatigue due to the harsh operating conditions in the Gulf of Alaska.

Cracks were reported in a variety of sizes, up to 20 feet long. The most common occurrences in the sideshell and bottom plating were small cracks, from 3" to one foot long. The widths are not reported, but were of the "hairline" variety according to Coast Guard inspection staff at Headquarters, G-MVI.

6.1.3 Tank leak scenarios Using historical data as a guide, hypothetical cracks and holes are placed at various locations on the stipulated hulls.

Outflow locations are considered at the waterline and at half the full draft in the side plating, and in the bottom plating at full draft. Tanks are assumed to be at amidships, and the vessels loaded to their summer freeboards. The tanks are first considered 98% full on the tankers and 90% full on the barges, then 50% full on all the vessels. No ship motion or cargo sloshing is assumed.

6.2 Outflow Calculation

Application of Bernoulli's equation is employed. Free communication of the tank to the sea is assumed. Its general form is:

$$(P_2 - P_1)/\underline{d} + (V_2^2 - V_1^2)/2G_c + g(Z_2 - Z_1)/G_c = 0 \text{ where}$$

V_2 = outflow velocity
V_1 = velocity at surface of cargo oil (taken as zero)
P_2 = external pressure at point of outflow
P_1 = external pressure at surface (taken as zero)
$\underline{d}$ = force density of oil (taken as 57 lb/ft^3 for crude oil)
Z_1, Z_2 = heights of surface and outflow points, respectively
$Z_2 - Z_1 = h$
g = acceleration of gravity
G_c = 32.2 $lbm\text{-}ft/lbf\text{-}sec^2$

Hull holed at waterline

In this case, the equation reduces to a conversion of potential energy to kinetic energy. It is: $V = (2gh)^{0.5}$, where V is the outflow velocity, g is the acceleration of gravity, and h is the head from the surface of the cargo oil to the hole. Outflow volume, Q, is V x A, where A is the area of the opening in the hull. Friction losses in this and other cases considered are negligible.

Hull holed below waterline

Two cases are considered: breach of hull on the bottom and halfway from the waterline to the bottom. The counteracting hydrostatic heads are thus T and 0.5T, respectively, where T is the full load draft of the vessel. The general form of the equation reduces to:

$$V_2^2 = ((P_1 - P_2)/\underline{d}_{oil} + gH_o/G_c) \times 2G_c; \quad P_1 - P_2 = -H_w(\underline{d}_{H2O})$$

$$V_2^2 = 2[(-H_w G_c(\underline{d}_{H2O})/\underline{d}_{oil}) + gH_o]$$

Finally,

$$V_2 = (2(32.2H_{oil} - 36.15H_{H2o}))^{0.5}$$

where
$\underline{d}_{H2O}$ = density of immersion water
$\underline{d}_{oil}$ = density of cargo oil
H_{H2O} = external head of water
H_{oil} = internal head of cargo oil

All calculations assume a situation of free communication, that is, flow unrestricted by tank closure or ambient tank pressure. Flow rates are found for the <u>initial</u> conditions of intact draft and specified tank loadings.

6.3 Hull breach selection

A variety of small holes and cracks are chosen for the analysis since the purpose of the study is to detect slow leaks. They are holes of 6", 3", and 1" diameter and cracks from 3" to 12" long of various widths.

6.4 Results The calculations were initially carried out for two loading conditions for each vessel for the variety of holes and cracks indicated in para. 6.3. The tankers were loaded to 98% capacity, per common practice, and to 50%. The barges were loaded to 90% capacity, per common practice, and 50%.

A sample set of results, for breaches in the bottom, is presented in Table 6-2. Tables C-1 and C-2 in Appendix C give the results for breaches at the waterline and at half the draft. Negative flows are indicated in those cases where the location of the breach and the tank loading will result in inflow of water vice outflow of oil. This situation can occur when tanks are not fully loaded.

6.4.1 Outflow/inflow conditions A simple relationship determines whether the hull breach results in inflow or outflow. Internal and external pressure heads at the point of the hull breach expressed as fluid heights and densities will determine the direction of flow. Generally, V_2, the outflow velocity, will be positive when the internal head times the cargo density exceeds the external head times the density of the water:

$$H_o(\underline{d}_{oil}) > H_w(\underline{d}_{H2O}) \;\text{---->}\; H_o > H_w(\underline{d}_{H2O}/\underline{d}_{oil})$$

For a ship carrying crude oil in salt water, outflow occurs when:

$$H_o > H_w((64.0 lb/ft^3)/(57.0 lb/ft^3)) \;\text{--->}\; H_o > 1.12 H_w$$

Refined products are lighter; greater internal heads are therefore required to result in cargo outflow. When operating in fresh water, slightly less internal head relative to salt water will cause outflow. Table 6-3 gives the density ratios for a variety of oil products in salt and fresh water (SW and FW). These ratios may be substituted in the equation above for the determination of the direction of outflow.

VESSEL	DEPTH (ft)	DRAFT (ft)	ULLAGE (ft)	BREACH DESCRPT'N	HOLE AREA (ft^2)	OUTFLOW VELOCITY (ft/s)	OUTFLOW Q * (gal/min)	TANK SURFACE AREA (m^2)	TRANSLATION OF CARGO SURFACE * (mm/min)
400,000 dwt VLCC	95.15	74.15	1.90	6" diameter	0.200	25.4	2305.7	470.4	18.55
(tank at 98% cap.)	95.15	74.15	1.90	3" diameter	0.050	25.4	576.4	470.4	4.64
	95.15	74.15	1.90	1" diameter	0.006	25.4	64.6	470.4	0.52
Tank dimensions=	95.15	74.15	1.90	12" long X1/2"	0.042	25.4	484.2	470.4	3.90
110.2'L x 45.9'W	95.15	74.15	1.90	6" long X 1/2"	0.020	25.4	230.6	470.4	1.86
	95.15	74.15	1.90	12" long X1/8"	0.010	25.4	119.9	470.4	0.96
	95.15	74.15	1.90	6" long X1/16"	0.003	25.4	30.0	470.4	0.24
	95.15	74.15	1.90	3" long X1/16"	0.001	25.4	15.0	470.4	0.12
77,000 dwt lighter-	58.36	40.04	1.17	6" diameter	0.200	28.1	2550.2	630.7	15.30
ing tanker	58.36	40.04	1.17	3" diameter	0.050	28.1	637.6	630.7	3.83
(tank at 98% cap.)	58.36	40.04	1.17	1" diameter	0.006	28.1	71.4	630.7	0.43
	58.36	40.04	1.17	12" long X1/2"	0.042	28.1	535.5	630.7	3.21
Tank dimensions=	58.36	40.04	1.17	6" long X 1/2"	0.020	28.1	255.0	630.7	1.53
75.0'L x 90.4'W	58.36	40.04	1.17	12" long X1/8"	0.010	28.1	132.6	630.7	0.80
	58.36	40.04	1.17	6" long X1/16"	0.003	28.1	33.2	630.7	0.20
	58.36	40.04	1.17	3" long X1/16"	0.001	28.1	16.6	630.7	0.10
25,000 bbl tank-	17.25	13.75	1.73	6" diameter	0.200	2.3	210.4	89.2	8.93
barge	17.25	13.75	1.73	3" diameter	0.050	2.3	52.6	89.2	2.23
(tank at 90% cap.)	17.25	13.75	1.73	1" diameter	0.006	2.3	5.9	89.2	0.25
	17.25	13.75	1.73	12" long X1/2"	0.042	2.3	44.2	89.2	1.87
Tank dimensions=	17.25	13.75	1.73	6" long X 1/2"	0.020	2.3	21.0	89.2	0.89
47.9'L x 20.0'W	17.25	13.75	1.73	12" long X1/8"	0.010	2.3	10.9	89.2	0.46
	17.25	13.75	1.73	6" long X1/16"	0.003	2.3	2.7	89.2	0.12
	17.25	13.75	1.73	3" long X1/16"	0.001	2.3	1.4	89.2	0.06
"450 Series" barge	29.31	20.00	2.50	6" diameter	0.200	16.8	1521.6	192.2	29.96
130,000 bbl	29.31	20.00	2.50	3" diameter	0.050	16.8	380.4	192.2	7.49
(tank at 90% cap.)	29.31	20.00	2.50	1" diameter	0.006	16.8	42.6	192.2	0.84
	29.31	20.00	2.50	12" long X1/2"	0.042	16.8	319.5	192.2	6.29
Tank dimensions=	29.31	20.00	2.50	6" long X 1/2"	0.020	16.8	152.2	192.2	3.00
60.0'L x 34.4'W	29.31	20.00	2.50	12" long X1/8"	0.010	16.8	79.1	192.2	1.56
	29.31	20.00	2.50	6" long X1/16"	0.003	16.8	19.8	192.2	0.39
	29.31	20.00	2.50	3" long X1/16"	0.001	16.8	9.9	192.2	0.19

*Positive value indicates oil outflow;
negative value indicates water inflow

Table 6-2
Outflows, hull holed at bottom

Table 6-2 continued next page

VESSEL	DEPTH (ft)	DRAFT (ft)	ULLAGE (ft)	BREACH DESCRPT'N	HOLE AREA (ft^2)	OUTFLOW VELOCITY (ft/s)	OUTFLOW Q * (gal/min)	TANK SURFACE AREA (m^2)	TRANSLATION OF CARGO SURFACE * (mm/min)
400,000 dwt VLCC	95.15	74.15	47.58	6" diameter	0.200	-47.9	-4353.9	470.4	-35.03
(tank at 50% cap.)	95.15	74.15	47.58	3" diameter	0.050	-47.9	-1088.5	470.4	-8.76
	95.15	74.15	47.58	1" diameter	0.006	-47.9	-121.9	470.4	-0.98
Tank dimensions=	95.15	74.15	47.58	12" long X1/2"	0.042	-47.9	-914.3	470.4	-7.36
110.2'L x 45.9'W	95.15	74.15	47.58	6" long X 1/2"	0.020	-47.9	-435.4	470.4	-3.50
	95.15	74.15	47.58	12" long X1/8"	0.010	-47.9	-226.4	470.4	-1.82
	95.15	74.15	47.58	6" long X1/16"	0.003	-47.9	-56.6	470.4	-0.46
	95.15	74.15	47.58	3" long X1/16"	0.001	-47.9	-28.3	470.4	-0.23
77,000 dwt lighter-ing tanker	58.36	40.04	29.18	6" diameter	0.200	-31.9	-2895.1	630.7	-17.37
	58.36	40.04	29.18	3" diameter	0.050	-31.9	-723.8	630.7	-4.34
(tank at 50% cap.)	58.36	40.04	29.18	1" diameter	0.006	-31.9	-81.1	630.7	-0.49
	58.36	40.04	29.18	12" long X1/2"	0.042	-31.9	-608.0	630.7	-3.65
Tank dimensions=	58.36	40.04	29.18	6" long X 1/2"	0.020	-31.9	-289.5	630.7	-1.74
75.0'L x 90.4'W	58.36	40.04	29.18	12" long X1/8"	0.010	-31.9	-150.5	630.7	-0.90
	58.36	40.04	29.18	6" long X1/16"	0.003	-31.9	-37.6	630.7	-0.23
	58.36	40.04	29.18	3" long X1/16"	0.001	-31.9	-18.8	630.7	-0.11
25,000 bbl tank-barge	17.25	8.25	8.63	6" diameter	0.200	-6.4	-581.8	89.2	-24.69
	17.25	8.25	8.63	3" diameter	0.050	-6.4	-145.5	89.2	-6.17
(tank at 50% cap.)	17.25	8.25	8.63	1" diameter	0.006	-6.4	-16.3	89.2	-0.69
	17.25	8.25	8.63	12" long X1/2"	0.042	-6.4	-122.2	89.2	-5.18
Tank dimensions=	17.25	8.25	8.63	6" long X 1/2"	0.020	-6.4	-58.2	89.2	-2.47
47.9'L x 20.0'W	17.25	8.25	8.63	12" long X1/8"	0.010	-6.4	-30.3	89.2	-1.28
	17.25	8.25	8.63	6" long X1/16"	0.003	-6.4	-7.6	89.2	-0.32
	17.25	8.25	8.63	3" long X1/16"	0.001	-6.4	-3.8	89.2	-0.16
"450 Series" barge	29.31	12.00	14.66	6" diameter	0.200	8.7	792.9	192.2	15.61
130,000 bbl	29.31	12.00	14.66	3" diameter	0.050	8.7	198.2	192.2	3.90
(tank at 50% cap.)	29.31	12.00	14.66	1" diameter	0.006	8.7	22.2	192.2	0.44
	29.31	12.00	14.66	12" long X1/2"	0.042	8.7	166.5	192.2	3.28
Tank dimensions=	29.31	12.00	14.66	6" long X 1/2"	0.020	8.7	79.3	192.2	1.56
60.0'L x 34.4'W	29.31	12.00	14.66	12" long X1/8"	0.010	8.7	41.2	192.2	0.81
	29.31	12.00	14.66	6" long X1/16"	0.003	8.7	10.3	192.2	0.20
	29.31	12.00	14.66	3" long X1/16"	0.001	8.7	5.2	192.2	0.10

*Positive value indicates oil outflow
negative value indicates water inflow

Table 6-2 (cont'd.)

Outflows, hull holed at bottom

Cargo	Density (lb/ft^3)	d_{SW}/d_{cargo}	d_{FW}/d_{cargo}
Crude	57.0	1.12	1.09
Diesel	54.0	1.19	1.16
Lube Oil	52.1	1.23	1.20
Gasoline	44.8	1.43	1.39

Table 6-3
Water/Cargo Density Ratios

6.4.2 Outflow curves Calculations for flow through a particular crack at a particular location are given for each hull investigated for a variety of drafts and tank loading levels. A 3" x 1/16" crack on the bottom is chosen since it is a very small breach and occurs in a likely location of a fatigue failure. Table 6-4 is a sample calculation, for the 400,000 DWT VLCC. Tables C-3, C-4, and C-5 in Appendix C are calculations for the other vessels. The results are graphed in Figures 6-1, 6-2, 6-3, and 6-4. All cases are for a vessel carrying crude oil and operating in saltwater. Again, negative values indicate inflow of seawater vice outflow of oil.

The graphs show a wide variety of flow rates into and out of a tank depending on draft and tank loading, including many instances of zero or negligible flow.

6.5 Conclusions

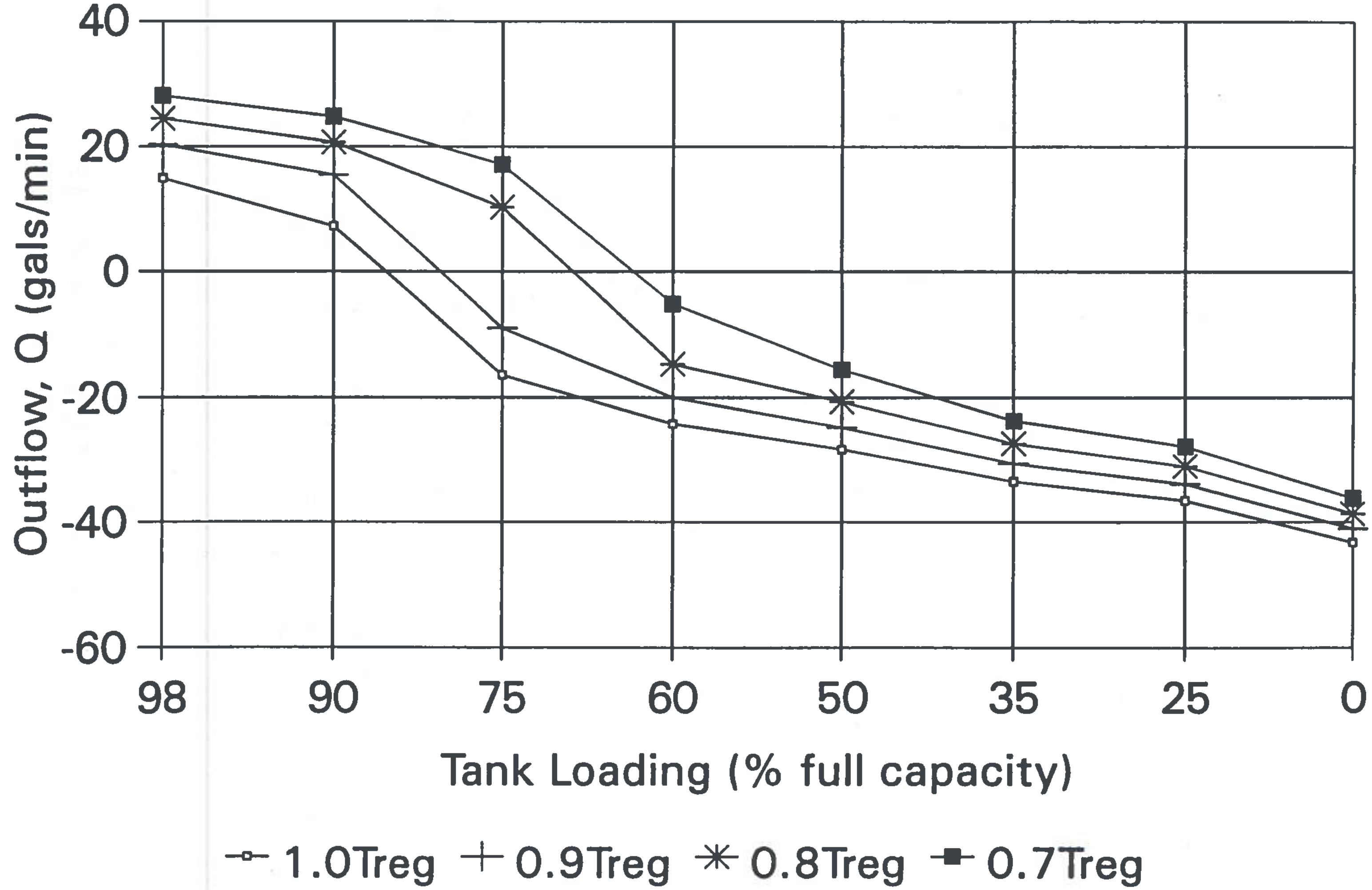
The leakage scenarios identified and quantified in Section 6 show a wide range of outcomes from a selection of very small hull breaches. It is seen that small holes can result in high flow rates, as do the larger hull cracks. Small cracks of the sort likely to propagate in the bottom of a hull result in very slow outflows and, under many circumstances of draft and loading, result virtual zero outflows, according to hydrostatic calculations. Ship motion and flow of water beneath the hull would in such a case cause some outflow to occur.

Section 7 will address the ability of a level sensor to detect the types of outflows described, concentrating on small breaches below the waterline. Side breaches of the sort likely to occur as a result of minor collisions with tugboats, piers, etc. would merit the immediate attention of the crew in any case, particularly when the resulting outflows are quite large. A crack is more likely to develop on the bottom, undetected by the crew. Detection of leaks through bottom cracks would be the primary advantage of an automated level sensing and alarm system.

VESSEL	TANK LOAD (% CAP.)	DEPTH (ft)	DRAFT (ft)	ULLAGE (ft)	BREACH	HOLE AREA (ft^2)	OUTFLOW VELOCITY (ft/s)	OUTFLOW Q (gal/min)	TANK SURFACE AREA (m^2)	TRANSLATION OF CARGO SURFACE (mm/min)
400,000 dwt VLCC	98	95.15	74.15	1.90	3" long X1/16"	0.001	25.4	15.0	470.4	0.12
	90	95.15	74.15	9.51	3" long X1/16"	0.001	12.4	7.3	470.4	0.06
T = 1.0Treg	75	95.15	74.15	23.79	3" long X1/16"	0.001	-27.7	-16.3	470.4	-0.13
	60	95.15	74.15	38.06	3" long X1/16"	0.001	-41.0	-24.2	470.4	-0.19
	50	95.15	74.15	47.58	3" long X1/16"	0.001	-47.9	-28.3	470.4	-0.23
	35	95.15	74.15	61.85	3" long X1/16"	0.001	-56.7	-33.5	470.4	-0.27
	25	95.15	74.15	71.36	3" long X1/16"	0.001	-61.9	-36.5	470.4	-0.29
	0	95.15	74.15	95.15	3" long X1/16"	0.001	-73.2	-43.2	470.4	-0.35
400,000 dwt VLCC	98	95.15	66.74	1.90	3" long X1/16"	0.001	34.4	20.3	470.4	0.16
	90	95.15	66.74	9.51	3" long X1/16"	0.001	26.3	15.5	470.4	0.12
T = 0.9Treg	75	95.15	66.74	23.79	3" long X1/16"	0.001	-15.1	-8.9	470.4	-0.07
	60	95.15	66.74	38.06	3" long X1/16"	0.001	-33.9	-20.0	470.4	-0.16
	50	95.15	66.74	47.58	3" long X1/16"	0.001	-42.0	-24.8	470.4	-0.20
	35	95.15	66.74	61.85	3" long X1/16"	0.001	-51.8	-30.6	470.4	-0.25
	25	95.15	66.74	71.36	3" long X1/16"	0.001	-57.4	-33.9	470.4	-0.27
	0	95.15	66.74	95.15	3" long X1/16"	0.001	-69.5	-41.0	470.4	-0.33
400,000 dwt VLCC	98	95.15	59.32	1.90	3" long X1/16"	0.001	41.4	24.5	470.4	0.20
	90	95.15	59.32	9.51	3" long X1/16"	0.001	35.0	20.7	470.4	0.17
T = 0.8Treg	75	95.15	59.32	23.79	3" long X1/16"	0.001	17.5	10.3	470.4	0.08
	60	95.15	59.32	38.06	3" long X1/16"	0.001	-24.7	-14.6	470.4	-0.12
	50	95.15	59.32	47.58	3" long X1/16"	0.001	-35.0	-20.7	470.4	-0.17
	35	95.15	59.32	61.85	3" long X1/16"	0.001	-46.3	-27.3	470.4	-0.22
	25	95.15	59.32	71.36	3" long X1/16"	0.001	-52.5	-31.0	470.4	-0.25
	0	95.15	59.32	95.15	3" long X1/16"	0.001	-65.5	-38.7	470.4	-0.31
400,000 dwt VLCC	98	95.15	51.91	1.90	3" long X1/16"	0.001	47.5	28.0	470.4	0.23
	90	95.15	51.91	9.52	3" long X1/16"	0.001	42.0	24.8	470.4	0.20
T = 0.7Treg	75	95.15	51.91	23.79	3" long X1/16"	0.001	29.0	17.1	470.4	0.14
	60	95.15	51.91	38.06	3" long X1/16"	0.001	-8.7	-5.2	470.4	-0.04
	50	95.15	51.91	47.58	3" long X1/16"	0.001	-26.3	-15.5	470.4	-0.12
	35	95.15	51.91	61.85	3" long X1/16"	0.001	-40.1	-23.7	470.4	-0.19
	25	95.15	51.91	71.36	3" long X1/16"	0.001	-47.1	-27.8	470.4	-0.22
	0	95.15	51.91	95.15	3" long X1/16"	0.001	-61.3	-36.2	470.4	-0.29

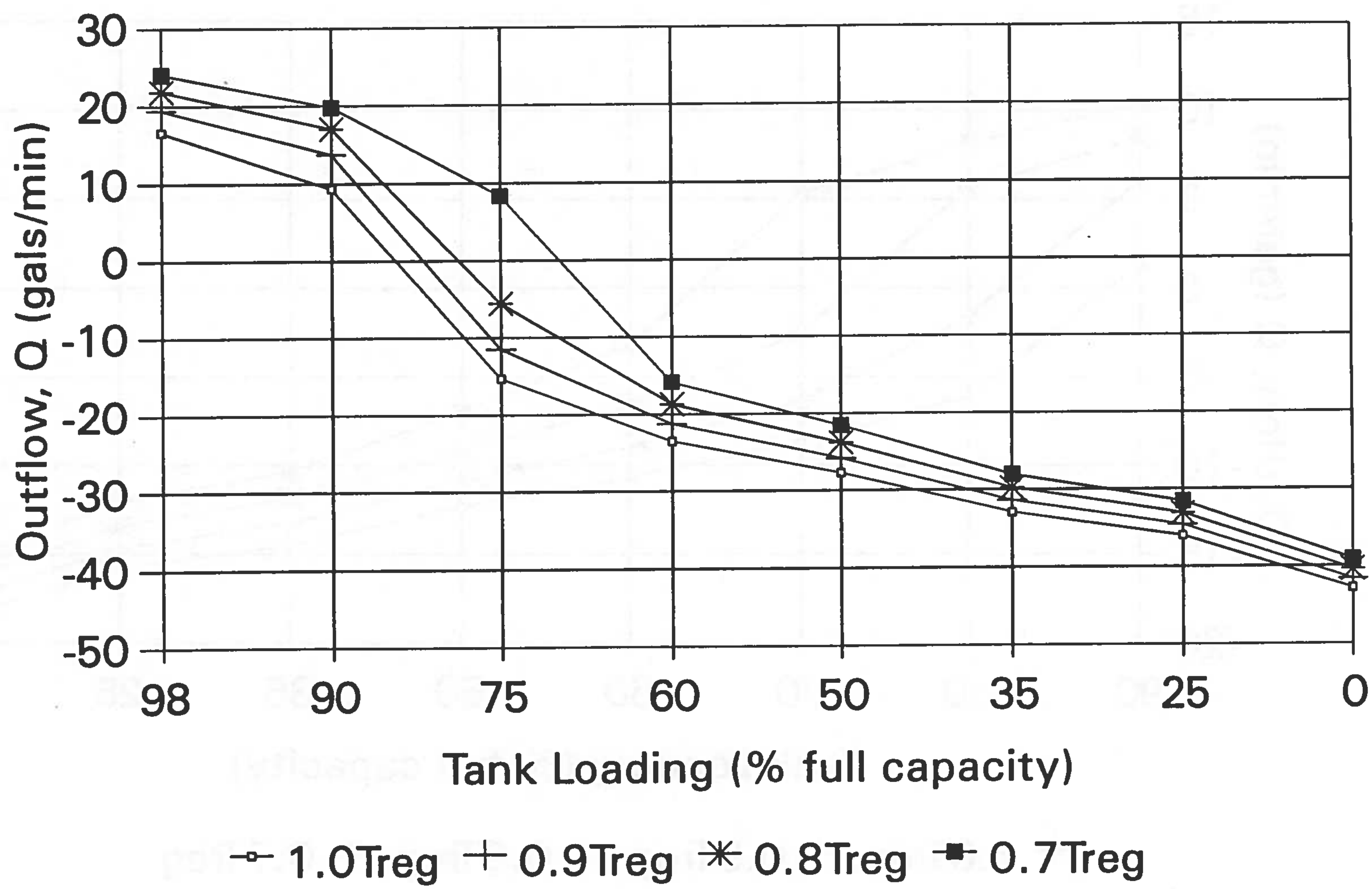
Table 6-4
400,000 DWT VLCC, crack on bottom
Various drafts and loadings

FIGURE 6-1
400,000 dwt VLCC, 3″x1/16″ crack at bottom



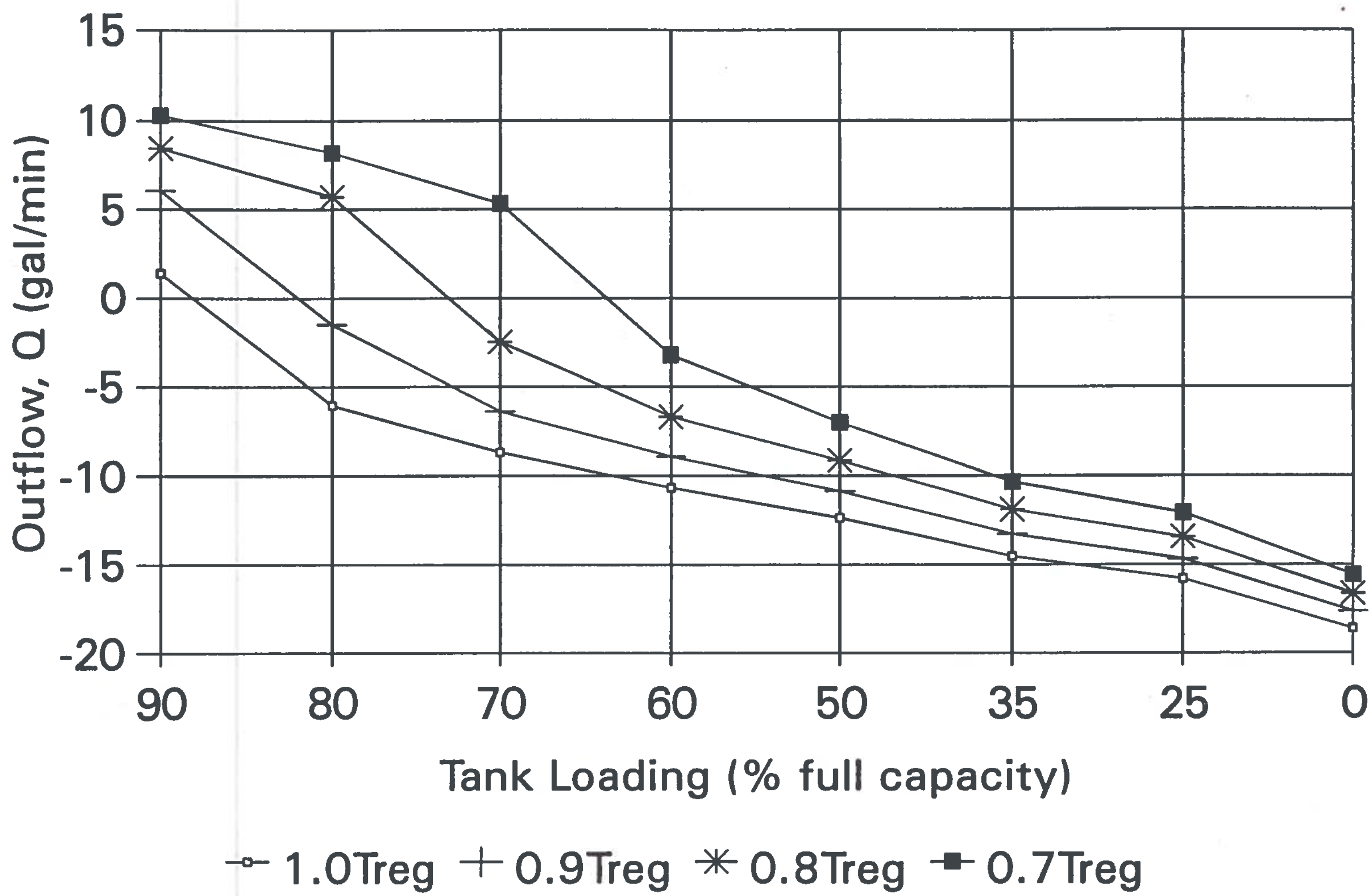
Saltwater immersion, crude oil cargo
Treg = draft at assigned load line

FIGURE 6-2
77,000 dwt tanker, 3″x1/16″ crack at bottom



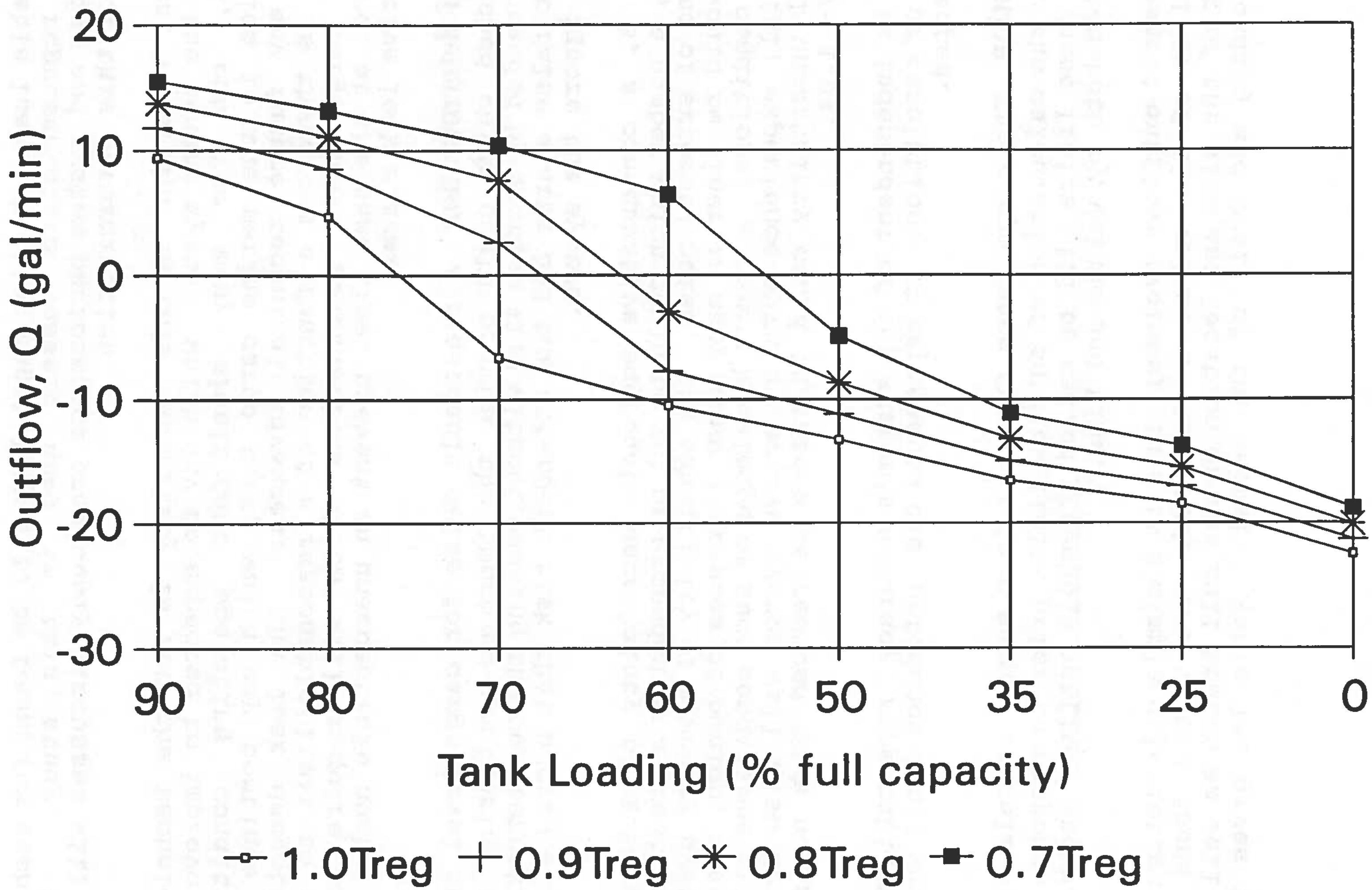
Saltwater immersion, crude oil cargo
Treg = draft at assigned load line

FIGURE 6-3
25,000 bbl barge, 3″x1/16″ crack at bottom



Saltwater immersion, crude oil cargo
Treg = draft at assigned load line

FIGURE 6-4
130,000 bbl barge, 3″x1/16″ crack at bottom



Saltwater immersion, crude oil cargo
Treg = draft at assigned load line

7 System Leak Detection Performance

The attainable leak detection capability will be found for each of the four representative vessels used in this study. The uncertainties and system performance previously discussed will be the basis of this determination.

The critical restraint on this capability is not the technical ability of the sensor system, which may be expected to improve in any event, but the many significant operating condition uncertainties in the marine cargo tank, which may continue to challenge any future technical advances. The leak detection capability is therefore a function of a reasonable limit to the detectable cargo level fluctuations which will require crew response and, at the same time, prevent an unacceptable number of false positive leak alarms.

7.1 Basis of determination

A reasonable *delta* for cargo level must be established which could provide the improved monitoring and response intended by Section 4110 without causing the consternation of frequent false alarms and the attendant risk that a crew will, at length, ignore the system.

In Section 5, a conservative aggregate uncertainty of 1.5% was determined, a number which could be met or exceeded by a great many combinations of external noise. The sensitivity of a modern system to a leak would be finer in many other instances of benign, steady cargo tank conditions. A crew's knowledge of such conditions might be beneficial; experience with an active system will also help. The overall uncertainty could therefore be reduced to a nominal value of +/- 1.0%.

This value is independent of any system's accuracy, repeatability, precision, or resolution. It represents the confidence limit which may be expected.

7.2 Application

The cargo tanks from the four sample vessels will be used for the calculation of outflow limits prior to response by the crew. These limits will be called threshold outflows and will be delineated both by volume and time.

7.2.1 Threshold outflows (volume) This is a simple calculation to determine 1.0% of the volume of the tank. The volume found is independent of the size and location of the hull breach as well as the tank loading and draft of the vessel. Table 7-1 gives the results.

Vessel	**Tank capacity (meter^2)**	**1.0% outflow (gallons)**
400,000 DWT VLCC	13,655	36,075
77,000 DWT lightering tanker	11,226	29,660
25,000 bbl tank-barge	469	1,239
"450 Series" barge 130,000 bbl	1,716	4,535

Table 7-1

Threshold outflows (volume) for sample vessels

7.2.2 Threshold outflows (time) The time from which the breach occurs to when the crew is cognizant of the leak will vary with the size and location of the breach, as well as the tank loading and vessel draft (as detailed in Section 4). Other circumstances may intervene, e.g., a sheen on the water during terminal operations could be noticed by the crew or shoreside personnel before the tank level system gives an alarm.

Small hull breaches (3" x 1/16" and 12" x 1/8" cracks) in the bottom at full load and draft will be used as examples in this calculation. Conditions are assumed such that only the level detection system can notify the crew. Table 7-2 gives the threshold times.

Vessel	**Hull breach**	**1.0% threshold time (minutes)**
400,000 DWT VLCC	3" x 1/16"	40.3 hours
	12" x 1/8"	5.0 hours
77,000 DWT lightering tanker	3" x 1/16"	29.7 hours
	12" x 1/8"	3.7 hours
25,000 bbl tank-barge	3" x 1/16"	14.6 hours
	12" x 1/8"	1.8 hours
"450 Series" barge 130,000 bbl	3" x 1/16"	47 minutes
	12" x 1/8"	6 minutes

Table 7-2

Threshold outflows (time) for sample vessels

These times would be much reduced for larger cracks or holes, cases where the crew might otherwise have good reason to suspect hull damage.

7.3 Anticipated benefits The following are the positive changes that could result in tank vessel operations from implementation of Section 4110. They are qualitative rather than quantitative in nature and are based on the assumption that modern, reliable, and continuously operated and monitored systems are used:

- Crew notification and response to small leaks could be vastly improved, despite the limitations of available systems. In particular, continuous, real time monitoring of cargo tanks while under way will be routine for all tank vessels. If a slow leak is detected, the master can undertake corrective response, which may include pumping oil from a breached tank or tanks and/or a change of itinerary to get repairs or to avoid sensitive coastal areas and fisheries. This is also true for larger hull breaches, such as that which occurred with the Chesapeake barge.

- In the case of a serious grounding casualty, the extent of damage will be quickly ascertained, including tanks with large and small breaches. This information can be used for response both by crew and by shore personnel.

- The detection of inflow as well as outflow situations will enable the operator to be cognizant of a small hull breach whenever it occurs. If, for example, a crack develops when the vessel is in ballasted condition, its detection will lead to corrective action which will be preventative rather than remedial. Pollution by oil may thus be prevented altogether by an effective tank level indicating system.

7.4 Need for type approval and a test program

An effective approach to addressing the need for tank level detection systems with expanded capabilities may be with an upgraded type approval regime which would include a controlled test program similar to that run by EPA for underground gasoline tank sensors.

The type approval would build upon those standards presently used by classification societies, measurement standards organizations, and government agencies such as EPA and the Geological Survey. Such a requirement was suggested by Johnson et al in 1981 in their tank level detection study for MARAD.

The standard could include performance specifications for normal operations, leak detection threshholds, and a range of sea conditions under which effective operation is required. The following could, in addition, be addressed:

•Measurement: the system would be required to meet standards of accuracy, hysteresis, linearity, precision, and resolution.

•Reliability and maintainability: the system would be required to match or exceed good reliability specifications for tank level detection systems. Minimal maintenance would also be desirable from the points of view of the regulator and the operator.

•Shipboard environment: the system must be robust against all adverse elements of marine service including corrosion, vibrations, wind and ice loading, temperature variations, and accelerations due to ship motion. Any components in the tank must resist its hazards, which include corrosion by oil and ullage gases, cargo sloshing, variations of pressure, and tank cleaning forces.

•Other: classification society building rules should be further consulted for such requirements as provision of ship's power and other services, dissimilar metals, welding techniques, fasteners, human factors, and other aspects of good shipbuilding practice.

Appendix A includes potential type approval reference documentation as well as excerpts from the EPA test program report.

Alternatively, a performance standard based upon low threshold outflows could be applied to other leak detection systems. One major oil shipping company is studying the use of a towed buoy which marks oil in the water with a phosphorescent substance. This and other technologies may necessitate a different certification regime.

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APPENDIX A

Type Approval and Testing Reference Documentation

1. Excerpts from "An Assessment of Shipboard Tank Level Indicating Systems", by Johnson et al, April 1981.

2. Excerpts from ""Evaluation of Volumetric Leak Detection Methods for Underground Fuel Storage Tanks", Volume 1, prepared for U.S. Environmental Protection Agency, Roach et al, November 1988.

3. "Specification for Procurement of Water-level Sensing Instrumentation, Specification number HIF-I-1", Open-File Report 82-89, United States Geological Survey Hydrologic Instrumentation Facility, Jan 82.

4. Excerpts from Det norske Veritas, "Rules for Classification of Steel Ships; Machinery and Systems, Main Class", Part 4, Chapter 5, "Instrumentation and Automation", January 1985.

PB81-221160

An Assessment of Shipboard Tank Level Indicating Systems

Southwest Research Inst.
San Antonio, TX

Prepared for

Maritime Administration
Washington, DC

Apr 81

U.S. Department of Commerce
National Technical Information Service
NTIS

III. SELECTION CRITERIA AND CPERATIONAL GUIDELINES

Level indicating systems typically receive approximately one-half page of highly generalized specifications in a ship purchase order. Yet, the intent of the specification is to prescribe a level gauge that can be safely operated, easily maintained, and it must provide sufficient accuracy to insure the avoidance of spills and reliance for custody transfer operations. Through numerous interviews and surveys, one concludes that the procedures used for gauge selection varies considerably from organization to organization and the selection process relies heavily upon crew acceptance and knowledge, company past experience, and a negotiating triad composed of the shipbuilder, owner/operator, and the gauge supplier. In summary, no strong baseline selection methodology exists, but there is a consensus among suppliers and purchasers that selection criteria set forth in a marine standard would be useful if made flexible to variations of the industry's needs and if all important gauging aspects are completely and clearly defined. Throughout the remainder of this section, a national standard is developed and justification is given for each component of the standard.

III.1 General

The purpose for organizing and publishing selection criteria for shipboard tank level indicating systems is to provide a complete and unified set of baseline considerations from which marine organizations may adopt in total or in part. The criteria described herein has been integrated into a marine standard which provides considerable detail regarding expected performance, shipboard environments, and qualification requirements. Application of the proposed standard is appropriate for non-cryogenic marine liquid bulk carrier liquid level gauging systems and many of the specifications will also apply to liquid bulk level metering equipment. The intent of the selection criteria is to insure that applicable safety standards and practices are incorporated into the gauge design, ascertain product hidden faults or weaknesses, and verify the gauge operation through a type-approval procedure. The proposed standard which is a technically rationalized composite of prevailing selection criteria, is given in Subsection III.3.

Four major attributes addressed in the selection criteria for gauging are safety, reliability, performance, and accommodation. Safety applies to intrinsic safety, electrostatic hazards, personnel safety, and alarms and redundancy. Reliability is the attribute that expresses the ability of the instrument to perform as it is expected or required, and the selection criteria provides a check list of a reliability assessment. Performance is assessed in terms of the manufacturer's claims; however, certain minimum but vital performance standards are identified in the criteria. Accommodation involves in-service calibration, diagnostic aids, logistics, and auxiliary equipment needed for maintenance or repair.

In practice, market demand for liquid-level gauging systems designed and constructed for the marine industry is relatively small. Owners/operators and shipbuilders generally set forth loose specifications in order not to eliminate multiple bidders and many times their selection is based upon availability as much as cost. However, it is recommended that an industrial standard which is specifically dedicated to marine liquid cargo gauging systems be developed and utilized for the proper evaluation of the system design, construction, installation, and operation. Therefore, much of the evaluation for design would occur during the bid approval process and thus the bid award would be based not only on low cost but strongly upon a technical review for safety, reliability, performance, and accommodation.

III.2 Requirements

Specific requirements for marine liquid cargo level gauging systems regarding safety, reliability, performance, and accommodation are identified and discussed below. In general, the gauging system must not cause personnel injury or ship damage, i.e., it must be a sufficiently reliable and accurate indicator of liquid level to ensure safety and not be cause for cargo spills and hull overstress. For custody transfer operations, owners/operators may emphasize higher accuracy requirements than would be expected or needed for safety reasons.

III.2.1 Safety Requirements

(a) Electrical

With the proliferation of electronic instruments for transmitting electrical energy into cargo regions or other regions of the ship, one must address the potential for explosion. Two methods of explosion prevention in hazardous atmospheres are currently in use. The first method is to convey electrical cables in rigid conduit and explosion-proof housings or purged enclosures. Besides being expensive, difficult to install and to maintain, the explosion-proof system is susceptible to human error which could render it useless as a protective system. Common errors include not tightly replacing covers, failing to shut power off before entry into an electrical box, or damaging machined surfaces. A second method for transferring energy into or through an explosive environment is to make the energy transfer system intrinsically safe by designing the system such that it is incapable of releasing sufficient electrical or thermal energy to cause ignition of hazardous atmospheres. Numerous sources are available in the literature which fully describe intrinsically safe systems, and therefore, the specific details will not be discussed here.

(b) Electrostatic

Several sources of electrostatic production are always present to some degree aboard a liquid bulk carrier. Petroleum, in particular, is subject to the "electric double layer" condition which is a phenomenon where two layers of oppositely charged particles are formed at the interface of the petroleum and other materials. Another source is found in turbulent flow through pipes conveying petroleum where the inner layer of charged molecules is scooped up and hence the emerging discharge flow is electrostatically charged. A more detailed description of possible charging mechanisms is found in the *Tanker Safety Guide*, published by the International Chamber of Shipping.

As a consequence of the electrostatic environment, gauging systems must be assessed for conditions favorable to the generation of a spark. No earthed conducting probe capable of concentrating electrical stress, and no unearthed conductor capable of gathering charge from the liquid should be allowed inside a tank during loading operations.

(c) Alarms/Redundant Systems

While the primary emphasis of this study is directed toward the gauging unit, the study intimately interacts with level alarms. Level limit switches and alarms will not be discussed; however, the interfacing and use of alarms as they apply to gauging equipment is discussed below.

Detailed onboard observations by SwRI personnel have shown that a large number of remote readouts located in cargo control rooms display results contrary to the local readout and/or hand ullage results. As a consequence, the confidence exhibited by the crew on many ships towards the remote readout is rather low. There are recorded instances where the reliance on remote level readings has led to cargo spills. Hence, several owners/operators have installed separate topping sensors to serve as an independent check on the full depth sensor. Other owners/operators have developed detailed loading procedures where deck personnel continuously report via radio the hand ullage or local readings obtained from a gauging unit. Obviously, closed loading procedures may be violated in the case of hand ullaging.

Thus, if a remote readout station is designated, it is recommended that a separate and independent topping sensor with a topping remote readout be provided for each tank. The topping sensor may contain the high-high and high level alarm if the electronic circuits are isolated from any other ship function.

Audible cues for high-high and high level alarms must be incorporated into cargo loading systems. These alarms, if activated, must be acknowledged by crew action and the alarm status should be visibly displayed until the out-of-limit condition is corrected.

III.2.2 Reliability Assessment

Reliability or the expectation that a gauging system will perform as designed, ranks second only to safety. Unfortunately, the ultimate proof of a system's reliability is determined at the owner's risk after many months of operation aboard ship. Realizing the need to ascertain the system's reliability, the owner often times selects a limited number of gauging systems for evaluation aboard ship.

Evaluation processes are more formal in the European countries where type-approval procedures are considerably more defined than in the U.S., and much of the burden of proof for systems' reliability remains the responsibility of the manufacturere. Also, in several cases, a full certificate is not issued to a gauging manufacturer until the system is proven reliable for a period of approximately two years in a shipboard environment.

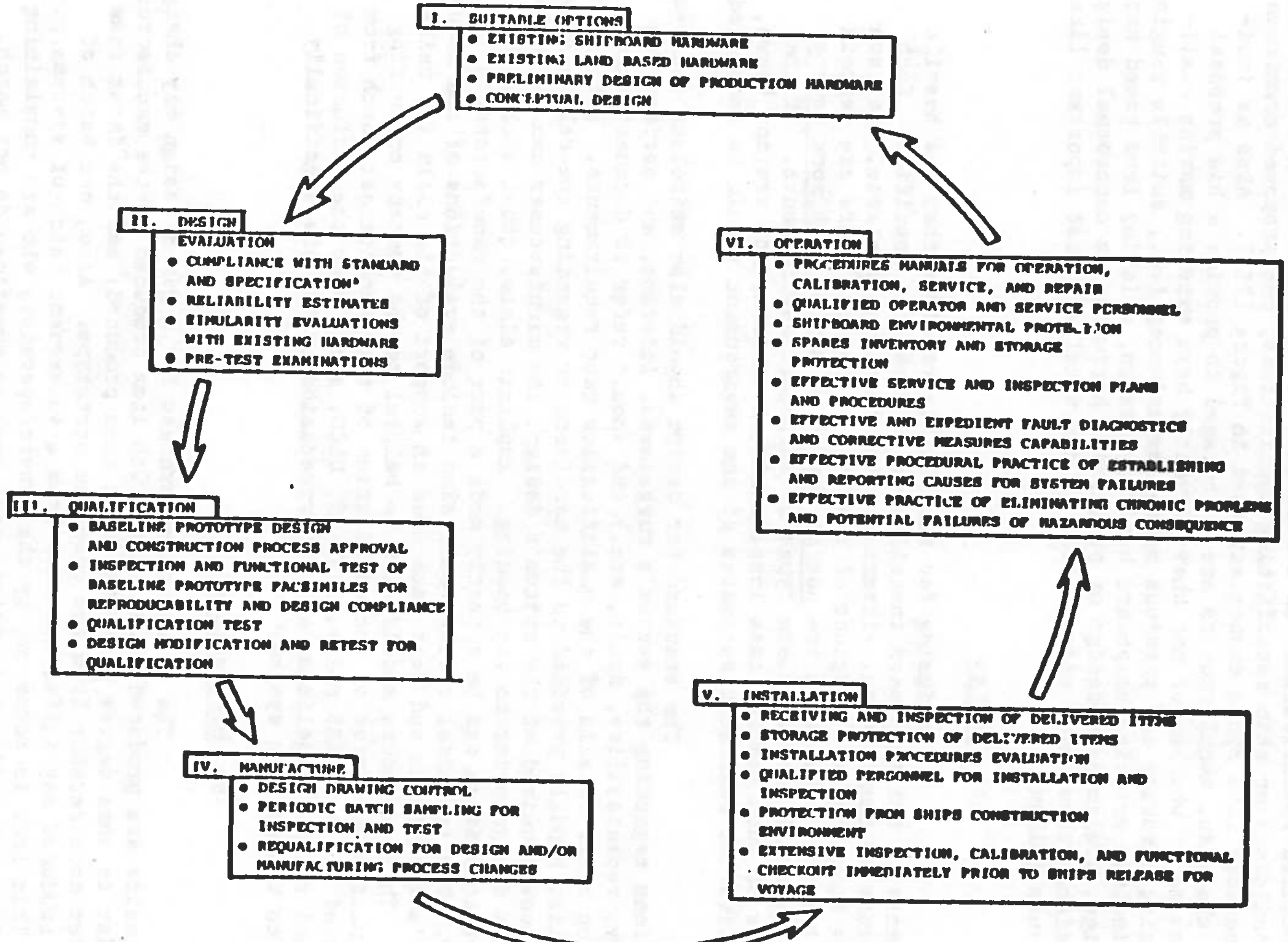
Type approval as identified by the ABS may be issued for control consoles or sections of component assemblies of such consoles provided the tests specified in subparagraph 41.39.3 of the ABS rules have been satisfactorily approved by the attending surveyor and provided the manufacturer makes application for the certificate of type approval. Other than for the ABS provision for type approvals for control consoles, the ABS does not certify liquid cargo gauging systems or individual components of these systems for type approval.

With respect to equipment used on all ships existing as of November 18, 1952 and those contracted on or after November 19, 1952, the U.S. Coast Guard accepts the rules of the ABS for certification. According to the ABS rules, manufacturers are to certify that their components have been satisfactorily tested for the following conditions:

- Shipboard atmospheres
- Ship motion and vibration
- Temperature range
- Voltage and frequency tolerances.

As indicated in Subsection II.3 of this report, the manufacturer has the responsibility for the proper interpretation of the U.S. Coast Guard, ABS, and IEEE 45-1977 rules and standards. Also, the manufacturer is usually required to develop the system's specification. The primary difference between this procedure and those generally followed by foreign organizations is that the foreign or domestic manufacturer supplying systems for foreign flagships is provided a consolidated and complete standard that he must meet. The standard includes considerable detail as to how systems are to be designed and tested. For example, the manner in which vibration tests are to be conducted are clearly defined by foreign classification agencies, but only generally defined by the ABS. Another example is that for comprehensive functional units such as remote control systems, computers, or similar electrical/electronic equipment, the manufacturer may be required to conduct a failure mode and effects analysis prior to testing, i.e., rules for conducting such an analysis are explicitly delineated by Det norske Veritas. In this way the U.S. or foreign manufacturer of systems utilized on foreign flagships has little doubt as to what the requirements are for qualifying equipment, in contrast to the very generally stated and incomplete set of rules and standards currently employed in the United States for liquid cargo gauging systems.

Our research has shown that reliability must be a strong consideration throughout the gauging system's life cycle events of construction, shipboard installation, and operation, and a description of the interdependence of each of the major life cycle events is portrayed in Figure III.1. Usually, conflict occurs when the gauge reliability is judged upon an assumed expectation. Hence, a formalized and universally recognized reliability evaluation criteria must be instituted. Obviously, the evaluation process must be conducted by technically qualified personnel who represent the interest of the shipbuilders, owners/operators, and manufacturers.



*AVAILABILITY OF A GOOD QUALITY AND COMPLETE MARINE STANDARD AND ASSOCIATED SPECIFICATION IS REQUIRED

FIGURE III.1 INGREDIENTS AND PROCESS FOR THE ACQUISITION AND PRESERVATION OF SYSTEMS RELIABILITY*

The plan provided in Figure III.1 for attaining good reliability first requires that a good quality and complete marine standard (and associated specification) is available. At the time manufacturers bid for new buildings or ship retrofitting applications, the proposed commitment should consider life cycle events stressed in Figure III.1. Also as indicated in the plan, manufacturers are encouraged to provide a bid proposal regardless as to whether or not they currently have existing marine qualified gauging hardware and previous marine experience; i.e., suitable gauging options include existing shipboard hardware design, existing land based hardware design, preliminary design of production hardware, or conceptual design. Further discussions which address four of the vital and most important life cycle events follow.

(a) Design

Designing for reliability requires that the hostile environments of the shipboard installation be known and specified. Such environments as temperature, vibration, electrical interference, etc. are generally known for most regions of the ship. However, there are certain special installations which are not as severe or may be much more severe than the generally stated basic types of shipboard environments. If the magnitudes of such special case installational environments are not known, conservative but realistic estimates of the environment should be generated.

The standard for design should also stipulate the user's expectations regarding the system's ruggedness, lifetime, and performance (accuracy, repeatability, drift, etc.) and should refer to documentation containing clear details of the qualification test requirements. With such a check list handily provided to the manufacturer regarding the reliability expectations required of the system's design, the manufacturer can directly assess his design prior to the bidding. Explicit claims about each major topic for compliance can be directly made a part of the manufacturer's warranty. The technical review would also include evaluations of the manufacturer's experience and test data used in support of his claim for reliability. This procedure should also be helpful to the company conducting the evaluation by virtue of the compilation of requirements set forth from a number of sources (ABS rules, IEEE 45, USCG, etc.) plus the inclusion of additional rules, guidelines, and interpretations which are specifically germane to the gauging system.

(b) Manufacture

The construction process for a given design may change as more units are produced, i.e., the 100th item produced by the manufacturer may differ to some degree from the first item produced, and the first item may differ considerably from the baseline prototype. Also, one batch of systems produced may differ somewhat from a subsequent batch of systems produced. This fact is borne out by the owners/operators who are complaining that replacement parts of identical part numbers sometimes do not match, and as a matter of fact, cannot be used.

The manufactured system being supplied must therefore be checked on a periodic basis to verify that it is suitably identical to the qualified design. The standard must outline a realistic/practical set of rules inclusive of inspection procedures to ensure product quality is not degraded.

The bidder's proposal and the final contractual agreements must incorporate this type of quality control detail and specifications for periodic verification of the manufacturing process. These stringent requirements must be mandatory for equipment that is considered vital to the ship's safety. Also, a high degree of reliability may be desired for systems that are non-vital for ship's safety but are desired for operational economy.

(c) <u>Installation</u>

Comments from several of the owners/operators indicate that a liquid cargo gauging system is subject to a very harsh environment during ship construction. Construction personnel do not necessarily avoid the gauging systems during the course of their main duties, thus damage from inadvertent mistreatment occurs such as exposure to weld splatter, paint spray and grit from grinding operations. Owners/operators have stated that they feel their systems may have been more reliable had they been sufficiently protected during the ship's construction. Therefore, as indicated in Figure III.1, it is recommended that the following considerations be emphasized during the installation phase:

- o Receiving and inspection of delivered items
- o Storage protection of delivered items
- o Installation procedures evaluation for completeness and clarity
- o Qualified personnel for installation inspection
- o Protection from ship's construction environment
- o Extensive inspection, calibration, and functional checkout immediately prior to ship's release for voyage.

(d) <u>Operation</u>

The expected operational lifetime of gauging equipment ranges from ten to twenty years. Therefore, if this long period of operation has been properly considered and accounted for during the initial design of the equipment and the proper qualification testing procedures have been identified and satisfied, it is left to the owner/operator to understand and implement a consistent practice for maintaining the system's reliability. Hence, the following considerations should be emphasized during the shipboard operational phase:

(1) Procedure manuals for the operation, calibration service, and repair should be complete, easily understood, and well arranged.

(2) Personnel should be especially qualified and trained to operate and service the equipment.

(3) Shipboard environmental protective provisions should be stressed and implemented.

(4) Spares inventory is necessary for attaining increased reliability; thus, provisions for proper protective storage must be arranged.

(5) Effective service and inspection plans and procedures should be stressed and implemented as a firm company policy.

(6) The system should incorporate an effective and expedient means for fault diagnostics and corrective measures.

(7) An effective procedural practice of establishing and adequately reporting causes for system failures should be established and implemented as a firm company policy.

(8) An effective practice of eliminating chronic problems and potential failures, especially those of a hazardous consequence, should be established and implemented as a well understood company policy.

III.2.3 Performance

Rules of the ABS and regulations of the USCG do not specify performance requirements for marine liquid cargo gauging systems, i.e., requirements for response time, repeatability, accuracy, stability, drift, etc. are not specified and are not specifically relegated as the manufacturer's responsibility. Although the foreign classification agencies also do not specify system performance in specific terms, they do cite the manufacturer with this responsibility and in one case (Lloyds Register of Shipping) it is stated that the assessment of performance parameters such as accuracy, repeatability, etc. are to be in accordance with an acceptable national or international standard. One such standard referenced in this regard is Publication No. 51 of the International Electrotechnical Commission entitled *"Recommendations for Indicating Electrical Measuring Instruments and Their Accessories."* In summary, a U.S. commercial standard which specifies the performance requirements for domestic marine liquid cargo gauging systems does not exist.

A number of military standards and specifications exist which provide very detailed performance requirements for liquid level gauging systems. One such military specification utilized by the United States Navy (MIL-L-23886A(SHIPS)) entitled *"Military Specification, Liquid Level Indicating Equipment"* includes the following requirements:

(a) Accuracy - The indicators shall indicate to within ±3% of full scale of the actual liquid level in the tank.

(b) Repeatability - The repeatability of electrical output shall be within $\pm 1\%$ of full scale at any one point on the scale.

(c) Hysteresis - Electrical output hysteresis shall not exceed 2% of full scale at any point on the scale.

(d) Response Time - The system shall have a time constant not exceeding 0.5 seconds for an input step change. Time constant of electrical indicator need not be considered.

It should be noted, however, that gauging performance requirements for the U.S. Navy apply primarily to relatively small tanks of diesel fuel oil, lubricating oil, waste oil, refrigerants, and JP-fuel, whereby the gauging systems of primary concern in this report applies to large tanks and to any and all types of liquid being transported as a ship's primary cargo. Therefore, it is through the information such as illustrated in Table II.7 that a set of specific performance requirements are now made available in Subsection III.3.

III.2.4 Accommodation

A large ship that is operated and maintained by 10 to 30 personnel leaves little time for crewmen to specialize on given types of systems except those that are vital to the ship's operation and those that require the immediate need for service and repair. This problem is especially compounded by normal rotation of crew personnel. It has become apparent from numerous observations of cargo loadings (see Table II.1) that liquid cargo gauging systems should be improved to better accommodate the capability of personnel operating and servicing the equipment. It is with this problem in mind that considerable emphasis should be placed on the development of selection criteria regarding the following accommodation features for crew personnel who are relatively untrained and who require close supervision:

- o Accessibility
- o Maintenance, repair, and replacement
- o Interchangeability
- o Functional testing
- o Fault diagnosis
- o Calibrations
- o Marking
- o Spare parts
- o Display

The U.S. Coast Guard regulations (IEE 45-1977) and the ABS rules are stated in general terms with respect to accommodation features. Table III.1 provides these rules to illustrate this point. In contrast, the accommodation features specified by foreign classification agencies, as summarized in Table III.2, are more specific. This summary does not include all these agencies' requirements, but those which may be regarded in addition to those included in Table III.1.

In consideration of rules of the various foreign and domestic classification agencies and the number of specific recommendations cited by the owners/operators in Subsection II.5 of this report, a set of criteria regarding accommodation features were formulated and are included in the next subsection.

III.3 Acceptance Criteria and Qualification

A document is presented herein under Table III.3 which has been built upon all preceding discussion. This document may be used as a guide for originating purchase specifications and as a means to implement a mutual understanding between the owners/operators, shipbuilders, and gauging manufacturers.

Owners/operators, shipbuilders, and manufacturers have requirements that are specific to their operation and company policy, and each vintage or type of ship falls under unique regulatory requirements in force at the time of construction. Therefore, it is recommended that the qualification acceptance criteria document provided in Table III.3 be utilized as the basic document from which the user modifies, as necessary, to fit the prevailing needs. The qualification tests should be considered as minimum requirements for gauging systems. An example of one such type gauging system that would have requirements that are additional to those specified in Table III.3 are those utilized on cryogenic tankers (LNG and LPG cargo ships). It should be noted that the purchase specifications or owners/operators of LNG or LPG tankers are considerably more extensive and contain much more technical detail for liquid level gauging systems than utilized by owners/operators of non-cryogenic cargo tankers.

Foreign classification agencies provide procedures by which manufacturers may certify their equipment for shipboard use and these agencies provide publications of such qualified equipment, citing the extent to which they have met their qualifications. Foreign agencies who maintain type approval lists include:

- Lloyds Register of Shipping
- Det norske Veritas
- Bureau Veritas
- Germanifscher Lloyd
- Nippon Kaiji Kyokai.

All such equipment that has been certified by these foreign classification agencies is then categorized as type-approved.

Type-approval as identified by the ABS may be issued for control consoles or sections or component assemblies of such consoles providing certain tests specified in the ABS rules have been satisfactorily completed.

Other than for control consoles, type-approvals are not issued by the ABS for individual components. The only classification agency which mandates that equipment must be certified as type-approved before such equipment is allowed onboard ship is the Bureau Veritas. Otherwise, type-approvals from one or more of the above listed classification agencies are customarily obtained and preferred by governments of Europe.

Det norske Veritas recently expressed considerable concern about the operations of some classification societies which set their minimum requirements at too low a level. Thus, DnV can no longer accept the attitudes of some classification societies regarding minimum requirements. It has been pointed out that an upper trend in accident levels has occurred in recent years and that the classifying society should take more of a leading role in safety activities. This apparent problem was discussed in the December 1980 issue of the publication *"The Motor Ship"* (Volume 61, No. 25, p. 9).

The concerns of Det norske Veritas exemplify that a steadfast goal of implementing a type-approval certification procedure for liquid cargo gauging systems in the United States should be based upon technical requirements that are meaningful and well suited to the actual needs of the industry. Minimum qualification acceptance criteria should have a justifiable base and be continually reviewed and updated to the latest regulatory rules of national and international law (USCG, IMCO, etc.). The minimum requirements set forth in this subsection (Table III.3) should be considered as a base from which actual specifications and qualification acceptance criteria should be formulated. In other words, acceptance criteria set forth by owners/operators, shipbuilders, and gauging manufacturers should always include additional requirements to the baseline plan (Table III.3) that are germane to their specific requirement. In this context, minimum baseline requirements as defined herein will require evaluation by the owners/operators, shipbuilders, and gauge manufacturers, and where justified, such requirements are to be revised and adapted to the needs of the application. In practically all applications, additional requirements to those specified in this subsection will be required and can be accordingly incorporated into the baseline set of acceptance criteria provided herein. Further discussions pertaining to additional requirements that may be considered are covered in the next subsection (III.4) entitled "Additional Options to Qualification Acceptance Criteria."

III.4 Additional Options to Qualification Acceptance Criteria

The following additional tests may be required depending upon the installation:

- o Low temperature test
- o Extended dry heat test
- o Salt mist test
- o Test for water-tight equipment
- o Endurance test
- o Further tests.

A listing of the many types of qualification tests employed by foreign and domestic classification agencies and the U.S. Coast Guard is shown in Table III.4. This table identifies the types of tests specified, but does not indicate the severity of one agency's requirements for a given test in comparison to the same type of test employed by the other agencies. The intention of the Table III.4 matrix is to illustrate the variety and number of qualification tests currently employed. Symbol A in the chart designates minimum requirements and symbol B designates additional requirements that may be specified because of the specific nature of the installation. Section VI of the chart entitled "Further Tests" indicates that although certain agencies list additional tests (symbol B) there may be additional categories of tests not presently identified that could be identified later and required. Note that the proposed standard recommends this practice.

Table III.5 provides a reference list of documents published by foreign and domestic classification agencies and the U.S. Coast Guard which describes the qualification tests shown in Table III.4. A review of such documents will reveal a certain degree of commonality in specific requirements as well as a considerable degree of difference. For example, certain of the test plans for vibration are very brief and incomplete, and other plans are very complete with a considerable degree of selectivity, depending upon the specific case in point. A summary of the vibration requirements required by these various agencies is provided in Table III.6. Note that some agencies require endurance vibration testing whereby other agencies do not require endurance testing. The proposed standard does require endurance vibration testing as a mandatory requirement. This example of the variations in severity of test requirements is typical of many of the variations to be found for most all of the qualification tests listed in Table III.4.

The owner/operator may elect to and insist on the conduct of additional types of qualification tests emphasizing reliability and long term endurance. For such special cases, qualification tests for mechanical endurance, extended dry heat, storage life, thermal aging, and special tests to develop mean time between failure (MTBF) data should be considered. Certain of these types of tests are described in the references provided in Table III.5.

Methods and procedures for conducting reliability analyses are available and references to such information is provided in Table III.7. The MIL-HDBK-217C handbook provides reliability, stress, and failure rate data for electronic equipment which could be used for the MTBF evaluations of special equipment considered by the owner/operator to be vital to the shipboard operation and economy. The MIL-STD-781C standard is a good reference for the conduct of reliability, design, qualification, and product acceptance tests. This standard also provides plans and practical guidelines for combining tests such as vibration and dry heat.

The thermal life of components can be ascertained by means of accelerated aging tests. The IEEE Standard 101-1972 document provides a guide for the statistical analyses of thermal life test data. This document describes the Arrhenius equation which sets forth the temperature dependence of aging processes for nonmetallic materials. For complex conditions where a number of nonmetallic materials are used within the same component and subjected to different temperature environments within the part, the approach for evaluating such a part is to determine which material is controlling in the aging process and to apply the analysis to the controlling material.

The Arrhenius equation for the chemical reaction rate is given by

$$L = Ae^{\left[\frac{\phi}{k}\left(\frac{1}{T}\right)\right]}$$

where:

- L = desired qualified life, hours
- A = constant for each nonmetallic material
- e = base of natural logarithms
- T = normal service temperature, °K
- ϕ = material activation energy of the reaction (may be assumed constant for the temperature range considered), electron volts
- k = Boltzmann constant, 0.8617×10^{-4} eV/°K

By identifying subscript 1 as the case for real life time aging and subscript 2 as the accelerated time for lifetime aging, the following equation establishes test times and test temperatures for accelerated aging tests.

$$L_2 = L_1 e^{\left[\frac{\phi}{k}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right]}$$

where:

- L_1 = desired qualified life time
- L_2 = accelerated aging test time
- T_1 = desired qualified operating temperature
- T_2 = accelerated thermal aging test temperature
- ϕ = 0.8 eV, conservative estimate for nonmetallic seal materials.

An example of times and temperatures for acceleration aging tests is provided in Figure III.2. This example assumes that the component must have a lifetime of 25 years and survive through these years at an operating temperature of 25°C. This approach for conducting accelerated thermal aging tests is utilized in other industries (aerospace, nuclear power, etc.). The major considerations when employing this approach is to establish which material or materials of the component experience the highest aging reaction rates, and to establish the activation energy (ϕ) for such material.

TABLE III.1. USCG AND ABS RULES AND REGULATIONS FOR ACCOMMODATION FEATURES

PARAMETER	USCG	ABS *
ACCESSIBILITY	CG-259,111.05-15(C) The design and arrangement of electrical apparatus should provide accessibility to parts requiring inspection. IEEE 45-1977, 201 Maintenance of components and subsystems should be conducted without removal of or interference with other components and subsystems.	41.29.4 The design and arrangement of all devices is to provide ready accessibility to parts requiring inspection, adjustment, or periodic replacement.
MAINTENANCE, REPAIR, AND REPLACEMENT	IEEE 45-1977, 201 Circuits should be easy to adjust and maintain and should be designed for maintenance by replacement.	41.29.4 Where devices are parts of subcircuits assembled in physically identical modular units for easy mounting or removal from the console, suitable arrangements such as matched plug-in modules with coated plugs are to be provided to facilitate direct replacement of modules in the console.
INTERCHANGEABILITY	IEEE 45-1977, 201 Special attention should be given to the types of components used. Readily available items should be used wherever possible.	
FUNCTIONAL TESTING	IEEE 45-1977, 201 Systems with remote reading instruments should have provisions for the installation of direct reading instruments at the equipment.	41.29.5 Built-in circuitry is to be provided for use in adjusting of module functions.
FAULT DIAGNOSIS	IEEE 45-1977, 201 Isolation of faults should be readily accomplished. Means for testing faulty complex circuits and check points for calibration purposes should be provided.	

*Paragraphs denoted apply to corresponding paragraphs in the ABS Rules for Building and Classing Steel Vessels, 1980.

TABLE III.1. USCC AND ABS RULES AND REGULATIONS FOR ACCOMMODATION FEATURES (Cont'd.)

PARAMETER	USCG	ABS*
FAULT DIAGNOSIS (Cont'd.)	IEEE 45-1977, 201 (Cont'd.) Alarms should be of the self-monitoring type, that is, an open circuit will cause an alarm condition.	
MARKING	IEEE 45-1977, 201 Components and circuits should be clearly identified and labeled. Circuit diagrams, in block form, should be prominently displayed in or near the associated cubicle. All electrical/electronic components should have suitable markings indicating the electrical characteristics of the equipment. Such markings may be by reference to drawings and parts lists.	
SPARE PARTS	IEEE 45-1977, 23.14 Spare parts for electrical distribution equipment and their attendent parts (fuses, plugs, receptacles, etc) should be provided as required by the application societies.	Appendix E Because of the varied nature in the need for spare parts, a general list of spare parts may not be suitable in all cases. Therefore, the spare parts furnished to each vessel are to be determined by the owner. The maintenance of spare parts aboard the vessel is the responsibility of the owner.

*Paragraphs denoted apply to corresponding paragraphs in the ABS Rules for Building and Classing Steel Vessels, 1980.

TABLE III.2 ACCOMMODATION FEATURES SPECIFIED BY FOREIGN CLASSIFICATION AGENCIES

<u>International Electrotechnical Commission</u>

"Control equipment should be constructed to permit easy access to the interior parts, and those requiring maintenance should, as far practicable, be clear of high voltage, high temperature, or other unsafe working conditions."

"Terminal boards on control equipment, including transducers, should be so constructed so sufficient space is available to enable cables to be satisfactorily connected, preferably each conductor on its own terminal."

"Circuits should preferably be suitable by unit or card replacement."

"Each replaceable assembly should be simple to replace and should be constructed for easy and safe handling."

"All replaceable parts should preferably be so arranged that it will not be possible to connect them incorrectly or to use incorrect replacements. Where this is not practicable, the replaceable parts as well as the appertaining plug are similar should be clearly identified."

"In some cases, it may be desirable to provide simulation circuits or similar means to check correct operation of the equipment."

"The sit points should be retained during vibration by suitable means and should be protected against accidental changing."

<u>Det norske Veritas</u>

"The component design and installation is to be such that operation, adjustment, repair, and replacement are facilitated. As far as practicable, screw connections are to be secured."

"The installation should, as far as possible, be built up from easily replaceable units and designed for easy troubleshooting, checking and maintenance. When a spare unit is mounted, only minor adjustments/calibrations of the unit should be necessary. Faulty replacements should not be possible."

"Systems, components, and signals should be standardized as far as practicable. When replacing parts, units, etc., it must <u>not</u> be possible to connect them incorrectly or to use incorrect replacements. Where this is not practicable, the replaceable parts are to be clearly marked to insure correct connection."

TABLE III.2 ACCOMMODATION FEATURES SPECIFIED BY FOREIGN CLASSIFICATION AGENCIES (Cont'd)

"Analog temperature measuring circuits are to be provided with means for condensating changes in fire resistance."

"Maintenance, repair, and performance tests of systems and components are as far as practicable to be possible without affecting the operation of other systems and components."

"Test equipment is to be kept onboard. The equipment is to be sufficient for all tests specified in the instructions for planned, systematic maintenance and function testing onboard."

"Monitoring of circuit faults outside card-mounted components will normaly be accepted. Short circuit and line interruptions are to be covered by the "self-checking" system. Means for self-checking such as triplication of components, signal range monitoring, dummy bit circulation, watchdog, etc. are accepted if appropriate."

"Set point adjustment devices are to be secured to prevent accidental change of set point."

"When a spare unit is mounted, only minor adjustment-calibrations of the unit should be necessary."

"All units, terminal strips, cable ends, and test points are to be clearly and permanently marked. Transducers, controllers and actuators are to be marked with their system function so they can be identified easily and without ambiguity on plans and in instrument lists."

"Ends of internal wiring for instrument and control circuits are to be marked, preferably according to designations used on wiring diagrams."

"Where maintenance work requires disconnection of cables, proper wiring diagrams should be provided, preferably attached to the inside removable covers, doors, etc."

"Where it is practicable tc not connect replacement parts incorrectly, the replaceable parts are to be clearly marked to insure correct connection."

"It is advised to keep onboard spare parts for important replaceable parts/units of the system."

"The quantity of spare parts should preferably be as recommended by the manufacturers, and sufficient to cover the replacements necessary for at least one year's service. Spare parts should amount to 10% minimum, one of each of such components as:

TABLE III.2 ACCOMMODATION FEATURES SPECIFIED BY FOREIGN CLASSIFICATION AGENCIES (Cont'd)

Transducers
Controllers
Indicating instruments
Printed circuit boards
Actuators
Relays, fuses, lamps, etc.

Spare parts should preferably consist of complete units; however, solenoids, springs, gaskets, and similar parts will be useful as substitutes for complete units, if replacement of defective parts within the unit is easily made by the engine staff."

Bureau Veritas

"Pneumatic and hydraulic piping and monitoring for control circuits are to be easily accessible on their length and their arrangement near apparatus is to give facilities for dismantling and reassembling."

"Automated installations should be as simple as possible, easy to operate, easy to maintain, and easy to repair after a failure."

"Spare parts are to be listed in a document submitted to the head office for approval (head office at Bureau Veritas)."

"Electronic devices are to be built in the form of plug-in elements with as little diversity as possible. These elements are to be fitted with unmistakable devices rendering impossible to put an element of one type in the place of another type."

"Replacement of a subunit of an element, by another subunit or element satisfying the same specifications should not require adjustments other than those which are normally at the disposal of the ship's personnel."

"The automated circuits and equipments are to be such that their failure is immediately known and easily identified. These conditions can involve, in particular, the use of self-monitoring to eliminate any risk of passive failure. If such conditions cannot be fulfilled, the necessary justifications are to be given to the head office (Bureau Veritas)."

"Pneumatic and hydraulic piping for monitoring of control circuits is to be suitably marked."

"Cables are to be so arranged and terminal boxes so designed and marked as to facilitate fault finding and to enable the necessary repairs to be made with the minimum possible disturbance to other circuits."

TABLE III.2 ACCOMMODATION FEATURES SPECIFIED BY FOREIGN CLASSIFICATION AGENCIES (Cont'd)

"Unless otherwise specified, the number of sub-units or spare units which are to be found onboard should amount to 5% with a minimum of 1."

"All spare electrical parts should be suitably packed to resist deterioration and should be stored in dry places. They are to be, where necessary, replaced or repaired at the first opportunity of application from the owner."

Germanischer Lloyd

"The appliances should be simply and conspicuously arranged. Good accessibility in repair work is to be insured."

"The instructions should be composed of easily replaceable units, preferably by using the modular construction or a similar system."

"The number of different types of modules is to be limited because of the necessity for carrying spare parts for each type."

"Printed circuit boards are to be provided with protection against unintentional exchange or there must be no possibility for damage by inserting in a wrong position."

"Means for carrying out performance tests and for localizing faults are to be provided which enable a system to be scanned or scrutinized for proper functioning."

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEMS

1.0 Purpose

To provide detailed qualification acceptance criteria for the application and selection of shipboard tank level indicating systems as applied to marine liquid bulk carriers transporting non-cryogenic cargos.

2.0 Intent

To insure that applicable safety standards and practices are incorporated into the design of liquid level gauging equipment.

To ascertain that no "hidden" faults or weaknesses will appear when the product is operating in environments normally expected onboard ships.

To verify the operational parameters stated by the manufacturer.

3.0 General Information

Unless otherwise specified in this document, the American Bureau of Shipping Rules for Building and Classing Steel Vessels and the U. S. Coast Guard Regulations are applicable for instrumentation designated as tank gauging systems.

The scope of the four major sections of the acceptance criteria is as follows:

3.1 Safety - The gauging system shall be evaluated with regard to (a) intrinsic safety, (b) electrostatic hazards, (c) mechanical and personnel safety, and (d) alarms and redundancy.

3.2 Reliability - The gauging system shall be assessed for reliability expectations during detailed design reviews and through laboratory qualification testing.

3.3 Performance - The gauging system shall be evaluated in terms of manufacturer's claims and in terms of minimum acceptable performance specifications as given in this document.

3.4 Accommodation - The gauging system shall be evaluated with regard to (a) in-service calibration, (b) available diagnostic aids, (c) logistics, (d) endurance, and (e) auxiliary equipment.

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

4.0 Safety Assessment

4.1 Intrinsic Safety

Liquid cargo gauging equipment must be certified by a competent independent testing laboratory to be intrinsically safe if such equipment is to be located in cargo tanks or in enclosed or semi-enclosed spaces (1) immediately adjacent to cargo tanks, (2) containing cargo tanks, or (3) having a direct opening into any gas dangerous space or zone. Intrinsic safety must apply for equipment use in Class I, Division 1 requirements set forth by the USCG (CG-259). Unless otherwise approved by the Coast Guard, the gauging equipment shall carry ratings for chemical groups A, B, C, and D as specified by the National Electrical Code (Article 510) or CFR, Title 46, Subchapter 111.8. The USCG and the ABS must acknowledge and approve such certification before it is an authenticated certification.

4.2 Explosion Proof

It is preferred that all liquid cargo gauging systems be completely intrinsically safe. However, for equipment located on open decks, such equipment which is not intrinsically safe is permitted providing it is certified as explosion proof by a competent independent testing laboratory. The USCG and ABS must acknowledge and approve such certification before it is an authenticated certification.

4.3 Electrostatic Safety

As a minimum, each sensor system shall be analyzed for charge collection potential and spark generation potential. No potential shall exist which can cause ignition of the cargo vapors.

4.4 Mechanical and Personnel Safety

Deck-mounted instruments must exhibit the structural integrity necessary for accommodating closed loading operations and inerting, if applicable. Toxic or explosive vapors shall not be emitted from the instrument during service and repair operations.

4.5 Alarms/Redundant Systems

Minimum requirements for alarms and redundant systems shall include the following:

4.5.1 Independent Alarms

If a remote readout station is designated, a separate and independent topping sensor and remote readout shall be provided to reach cargo tank. High-high and high level alarms may originate from this sensor system; however, the electronic circuits must be isolated from any other ship function or instrumentation. All cargo and slop tanks require full depth gauging systems with local readout.

4.5.2 Optical and Acoustic Cues

Each local readout shall be designed with an optical cue that indicates a designated topping condition. Remote readouts must incorporate audible cues for high-high and high level alarm conditions and each cue must be acknowledged by crew action. Acknowledged alarms must indicate their alarm condition by optical means. A display lamp shall remain on when the high alarm activates and the display lamp shall continuously blink when the high-high alarm activates. Alarm systems shall be designed to be tamper proof and they shall not be disabled by normal crew operating procedures. A means for checking burned out indicator lamps and alarm function shall be accomplished by depressing an appropriate switch.

5.0 Reliability Assessment

5.1 Design Review

Each tank gauging system shall be reviewed for its reliability expectations. The following items shall be assessed.

5.1.1 Mechanical

Each gauging system design must show (a) materials compatibility, (b) structural integrity, and (c) mechanical integrity in accordance with USCG regulations (CG-259), IEEE 45-1977, and the ABS rules. Additionally, the following requirements must be satisfied.

5.1.1.1 Materials Compatibility

(a) Electric cables for damp or wet locations shall have an outer covering of lead and armor, moisture resistant jacket, and armor or mineral insulated-metal sheathed.

(b) Contacts have either to be of inoxidable material or the design must provide for a non-oxidizing atmosphere.

(c) Wiring connections are to be made so as to ensure satisfactory performance of the contacts, taking into account vibrations and risks of corrosion.

(d) Electronic information systems are to be galvanically separated from the common electrical system.

(e) Parts which would be damaged or rendered ineffective by corrosion are to be corrosion-resistant.

(f) Encased components should be selected so as to be compatible with atmospheres and impurities from leakage through the closure housing, or casing.

5.1.1.2 Structural Integrity

(a) Desk mounted units inclusive of their mounting structure and internal parts must be structurally capable of withstanding

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

	mechanical shock loads from ocean wave impacts; the ships' structural vibration and acceleration forces; and crew personnel.
(b)	All electrical parts weighing more than 10 grams should <u>not</u> be supported only by their electrical connecting joints.
(c)	Components of the system located internal of the cargo tanks must be capable of withstanding washing jets and cargo slosh loads and/or shall be amenable to use of protective enclosures such as still wells.
(d)	Plug and sealant connections should not carry any mechanical load other than is necessary for ensuring satisfactory contact pressure.
(e)	Instrument housings shall be impact and spark resistant.
5.1.1.3	<u>Mechanical Integrity</u>
(a)	Plug in connections such as plug-in trays and printed circuit boards should incorporate a retainer to prevent unintended disconnections as could occur by human error or due to shock or vibration.
(b)	All nut and bolt connections on cabinets should be locked.
(c)	Cabinets should be vermin and rat proof and openings may require wire mesh with maximum squares of 6 mm (0.25 inch).
(d)	Pneumatic components requiring extremely clean air are not to be used and extremely small openings in air passages are to be avoided.
(e)	Relays are to be provided with dust-proof enclosures; hermetically enclosed relays are recommended.
(f)	If anti-shock or anti-vibration mounts are used, adequate clearance should be provided to allow freedom of travel without contact with adjacent components of the cabinet.
(g)	All instrument appendages shall be either recessed or guarded.
(h)	Glass or plastic view parts for readout shall be shatter and scratch proof.
5.1.2	<u>Electronics and Electrical</u>
	Electronic systems (local and remote) shall be in conformance with the USCG regulations (CG-259), IEEE 45-1977, and the ABS rules. Circuit boards shall conform to EIA standards or equivalent. Additionally, the following requirements must be satisfied:

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

(a) Printed circuits should be sufficiently coated to prevent tracking between conductors due to humidity, fatty deposits, dust, etc.

(b) Direct connections to the printed circuits are to be avoided.

(c) Circuits should be designed to prevent damage of the unit or adjacent elements by internal or external failures. Such failure should lead to a comparatively safe condition.

(d) Circuits should be such that there is no direct connection to any point of the ships main power supply system, e.g., isolating transformers should be used for power supplies.

(e) Silicon and selenium semiconductor devices are to be used in preference to germanium.

(f) Cables for circuits susceptible to interference should be shielded or isolated to minimize spurious signaling from outside sources.

(g) Ground connections should be of the low inpedance type.

(h) Systems which depend on high-insulation resistance for accurate functioning should be avoided where practicable. However, if such systems are necessary special precautions should be taken to maintain high-insulation resistance and special circuits should be provided with ready means for checking insulation resistance.

(i) Chasses may not form part of any circuit.

(j) Connections, wires, and cables which are liable to influence one another or those co cerning the redundant circuits, are to be physically separated as far as possible.

(k) Potting compounds are permissible if compatible with Class I, Division 1 environments specified in the USCG CG-259 regulatory document.

5.1.3 System Function and Guarantees

The liquid cargo gauging system must be designed such that all its interfacing and interconnecting part are functionally and physically compatible and must be of good quality in design and workmanship. The system must be

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

of the type specified by IMCO (Resolutions A.212 (VII) and A.328 (IX)) and must be in accordance with USCG regulations (CG-259 and CG-115) and the ABS rules. Additionally, the following requirements must be satisfied:

5.1.3.1 Warranty and Traceability

As a minimum the gauging system shall carry a warranty for workmanship and materials to ensure the instrument is manufactured as qualified under this document. Traceability of each instrument shall be designated by appropriate means.

5.1.3.2 Shipboard Shelf Life

Electronic assemblies shall have a minimum shelf life of five years.

5.1.3.3 Failure Mode and Effect

The following guidelines for design should be met:

(a) A failure of any tank gauging unit shall not affect the operations of the remaining gauging systems.

(b) For purposes of redundancy, each cargo tank liquid level gauging system with remote monitoring indicators must also be provisioned with a local readout.

(c) The probability that failure in components causes damage to other components is to be acceptably low. Such probability must be specifically identified and numerically ascertained. Depending on the severity of such consequence, all data used in the evaluation must be justified as statistically correct. Otherwise, an easy and readily implemented remedy for such consequence should be offered and approved acceptable.

(d) Where the failure of a single component and/or subsystem (power supply, multiplexer, computer, etc.) affects more than one tank gauging system, such shared components and/or subsystems must be verified via extensive testing and evaluations to have a reliability factor predetermined by owner/operator for a specified operational lifetime.

(e) Electronic systems (local and remote) shall not require forced air cooling.

(f) Where remote monitoring indicators are provided, failure of any subpart of the system necessary for remote monitoring (signal and power transmission lines, power supply, signal conditioners, computer, etc.) shall have no effect on the required on-deck local readout.

5.2 Qualification Testing

As a minimum, a gauging system will be type approved if it successfully completes the tests listed below. Tests may be conducted by an independent testing organization or at the manufacturer's facility. Witness of the test by a surveyor is at the discretion of the surveyor. Data substantiating compliance to said testing shall be processed for convenient assessment by the

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

reviewing agency and shall be well documented and submitted to the regulating agency for review and approval.

5.2.1 Performance Test

Performance tests of the equipment are to be carried out to ensure that the manufacturer's specified limits for accuracy, repeatability and rangeability, and for static and dynamic characteristics, are fulfilled. Where National or IEC standards are applicable the equipment shall comply with such requirements.

5.2.2 Pressure Test

Deck-mounted instruments are to be subjected to pressure tests at 1.5 times the cargo relief valve setting using dry air or inert gas as the testing media. A gas temperature of 23°C±5°C shall prevail. The instrument shall maintain pressure for one hour during which time the mechanical components shall be activated. The instrument will be considered acceptable if the pressure does not decrease by 1% during the test.

5.2.3 Power Supply Test

ELECTRIC: Satisfactory operation is to be demonstrated for:

(a) Mains Supply

(i) With voltage variation of ±10 per cent together with simultaneous frequency variation of ±5 per cent.

(ii) With transient voltage of ±20 per cent together with simultaneous frequency transient of ±10 per cent. Transient recovery time 3 seconds.

(b) Battery Supply

With voltage variation from +30 per cent to -25 per cent.

HYDRAULIC: Satisfactory operation is to be demonstrated with supply reduction of 20 per cent.

PNEUMATIC: Satisfactory operation is to be demonstrated with supply pressure reduction of 20 per cent.

5.2.4 Vibration Test

The equipment is to be mounted on the vibration table through its normal points of attachment, and in its normal orientation with respect to the vertical. Vibration forces shall be applied in three mutually perpendicular directions, one of which shall be vertical.

The frequencies and amplitudes shall be varied in accordance with Table 1 at a rate sufficiently low to permit the detection of resonance.

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

An endurance test shall then be carried out for not less than 2 hours at each major resonant frequency. Resonance is said to occur if the amplification factor of any component greater than 1.3.

If no major resonance occurs, the equipment is to be tested at 30 Hz acceleration, amplitude ±0.7 g for not less than 2 hours in each direction.

If the equipment is normally fitted with anti-vibration mountings, these are not to be removed during the test.

Satisfactory operation during tests shall be demonstrated, and there is to be no visible damage or loss of accuracy.

TABLE 1

FREQUENCY RANGE Hz	AMPLITUDE	
	Displacement	Acceleration
1 - 13.2	±1.0 mm	
13.2 - 80		±0.7 g

5.2.5 Humidity Test

(a) The test chamber temperature is to be raised from the initial ambient temperature to 55°C±2°C, with a relative humidity of 90 to 100 per cent. The equipment is to be kept in those conditions for a period of not less than 12 hours.

(b) The chamber temperature is then to be reduced to 20°C±5°C in a time between 1 and 3 hours with the equipment enclosed in the chamber. Saturation of the chamber atmosphere with water vapour should occur during the cooling period. The equipment is to remain at this temperature for not less than 6 hours.

At least two temperature cycles are to be carried out, as shown in Fig. 1. Satisfactory operation of the equipment is to be demonstrated during the test periods shown. There must be no visible deterioration, and accuracy shall be within specified limits.

On completion of the cyclic test, the equipment is to be examined and then subjected to a full performance test in test area conditions not less than 1 hour nor more than 2 hours after removal from the test chamber.

Surface moisture may be removed by hand prior to the examination.

NOTE. If heaters or other devices are usually fitted to prevent condensation, they may be used during the test.

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

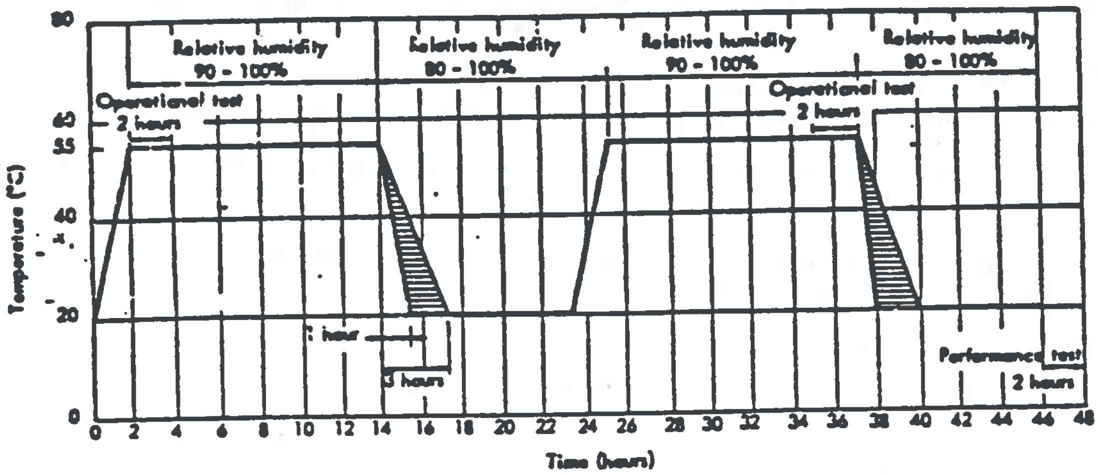


FIGURE 1. HUMIDITY TEST (2 CYCLES)

5.2.6 Dry Heat Test

The equipment is to be placed in a test chamber, the conditions in which are to be adjusted either to 60°C±2°C, or to the specified temperature. Test temperatures higher than 60°C will be indicated on the certificate. The relative humidity is to be verified during the heating of the chamber, and should not exceed 50 per cent at 35°C.

These conditions are to be maintained for a minimum period of 16 hours.

Satisfactory operation of the equipment is to be demonstrated during the last hour of the test. There must be no visible deterioration. Accuracy shall be within specified limits. Specified temperature for this test shall be 60°C or greater.

5.2.7 Inclination Test

The equipment is to be:

(a) inclined to the vertical at an angle of at least 11°,

(b) inclined to at least 11° on the other side of the vertical and in the same plane as in (a),

(c) inclined to the vertical at an angle of at least 11° in a plane at right angles to that used in (a), and

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

(d) inclined to at least 11 on the other side of the vertical and in the same plane as in (c).

Satisfactory operation is to be demonstrated at each angle given in (a), (b), (c) and (d).

5.2.8 Insulation Resistance Test

An insulation resistance test is to be carried out on electrical equipment at the conclusion of the vibration and humidity test.

The minimum insulation resistance values shown in Table 2.2 should be obtained between supply terminals and earth.

TABLE 2

RATED SUPPLY VOLTAGE	TEST VOLTAGE d.c.	INSULATION RESISTANCE	
		Test No. 5.2.1	Test No. 5.2.5
Up to 65 V	2 x supply voltage, minimum 24 V	10 Mohm	1 Mohm
Over 65 V	500 V	100 Mohm	10 Mohm

5.2.9 High Voltage Test

Electrical equipment shall be subjected to a dielectric test where appropriate. The equipment under test shall be capable of withstanding a high ac voltage for 1 minute, between live parts and earth, the test voltage being selected from Table 2.3.

TABLE 3

RATED INSULATION Voltage a.c. or d.c.	TEST VOLTAGE a.c.
Up to 60	1000
60 - 300	2000
300 - 660	2500
660 - 800	3000
800 - 1000	3500

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

Where very low voltage equipment is to be tested, the test voltage may be reduced to 500 V ac The test voltage frequency shall be between 45 Hz and 62 Hz.

5.2.10 Additional Tests

The following additional tests may be required depending upon the intended use of the tank gauging instrumentation.

(a) Low Temperature Test - The equipment is to be placed in a climatic chamber, while the equipment and the chamber are at ambient temperature.

The temperature of the chamber shall then be adjusted to the specified temperature, within a tolerance of ±2°C which is to be maintained for at least 16 hours. Satisfactory operation is to be demonstrated during the test. At the completion of the test period, the equipment is to be allowed to regain temperature by raising the chamber temperature gradually to test area conditions in not less than 1 hour nor more 4 hours. On completion of the test, the equipment is to be examined for damage and tested to confirm that accuracy is within specified limits.

(b) Extended Dry Heat Test - For equipment designed to be incorporated in cabinets, consoles, etc., where heat may be independently generated by other equipment, a 2-hour test at 70°C is required.

This test may be included in the Dry Heat Test, the temperature being raised from the test temperature at a rate not exceeding 1°C per minute to 70°C±2°C and held at that temperature for 2 hours. Following this the temperature shall be reduced at the same rate to the original Dry Heat Test temperature. Satisfactory operation is to be demonstrated during the last 30 minutes at 70°C.

The excursion to 70°C during the Dry Heat Test may be commenced at any time after 5 hours from the time of starting the test and must be completed before the final 2 hours of the test.

(c) Salt Mist Test - The equipment is to be placed in a climatic chamber and allowed to attain test area temperature. Salt solution, at the same temperature, is then to be sprayed in the form of a fine mist into the atmosphere surrounding the equipment The volume of salt solution so sprayed in each hour should be approximately 1 per cent of the volume of the chamber.

It is essential that there be no contamination of the salt solution being sprayed. Salt solution dripping from the walls and ceilings of the chamber, and from the equipment, must not be resprayed.

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

The spraying is to continue for 2 hours, after which the equipment is to be maintained at a temperature of 35°C±2°C, with a relative humidity of between 90 and 95 per cent for a period of 7 days. The process of exposing the equipment to salt spray laden atmosphere for 2 hours and of storage for 7 days at 35°C±2°C and 90 to 95 per cent relative humidity is to be carried out four times.

At the end of the 28 days treatment, the equipment is to be examined for corrosion and deterioration of metal parts, finishes, materials and components, and it is to be given a full performance test.

The salt solution is to be prepared by dissolving the substances listed below in distilled water and making up the volume of the solution to 1 litre. The proportions of the ingredients in the solution are to be within 10 per cent of those shown:

Sodium Chloride	$NaCl$	26.5 grams
Magnesium Chloride	$MgCl_2$	2.4 grams
Magnesium Sulphate	$MgSO_4$	3.3 grams
Calcium Chloride	$CaCl_2$	1.1 grams
Potassium Chloride	KCl	0.73 grams
Sodium Bicarbonate	$NaHCO_3$	0.20 grams
Sodium Bromide	$NaBr$	0.28 grams

(d) Test for Watertight Equipment - The equipment is to be able to withstand (without penetration of water) the application of a stream of water from a nozzle of 12.5 mm inside diameter on the equipment in all directions, at a pressure corresponding to a head of about 10 m of water. The nozzle should be held at a distance of 1.5 m from the equipment under test.

The duration of the test is to be 15 minutes.

Satisfactory operation is to be demonstrated without delay at the conclusion of the test.

(e) Endurance Test - A test program shall be designed and implemented. All test details will be agreed with the manufacturer.

(f) Further Tests - Further tests may be required for specific equipment, and will be agreed between the manufacturer and the Society. Such tests will preferably be based on National or International specifications.

6.0 Performance

The systems performance should prove to be in accordance with the manufacturer's specification which may or may not be as stringent as stipulated by this standard. The minimum performance standards for liquid level tank gauging instrumentation is specified below:

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

6.1 Installed Level Accuracy

The accuracy specified below applies to the actual distances measured between the instrument horizontal reference plane and the liquid surface taken along a vertical line originating from the instrument's normal vertical reference. The specification is valid for conditions of zero degrees roll and zero degrees pitch.

High level .... ±12.5 mm over top 2 m of tank
Low level .... ±38.1 mm over 2 m range above tank bottom
Mid level .... ±76.2 mm

The specified accuracy shall be maintained for the following conditions:

Temperature Range - 35°C to 60°C
Vibration - per Para. 5.2.4
Energy Source Variation - per Para. 5.2.3
Humidity - per Para. 5.2.5
Pressure - per Para. 5.2.2

Cargo bulk property variation - the sensitivity of the sensor to cargo property changes shall be compensated or essentially eliminated. As a minimum the following properties shall be accounted where applicable.

(a) Specific gravity
(b) Electrical properties (dielectric constant, conductivity, etc.)
(c) Contamination
(d) Composition
(e) Viscosity
(f) Surface tension
(g) Acoustic wave speed
(h) Phase (vapor, foam, solids, slug)
(i) Thermal properties
(j) Gradients

Response - must accurately follow level changes of 15 cm/minute.

Electrical interference - electrical noise caused by ship's equipment shall not affect gauge performance.

6.2 Combined Repeatability, Drift, and Hysteresis

The inaccuracy allowed for combined repeatability, drift, and hysteresis is as follows:

High level .... ±6 mm
Low level .... ±19 mm
Mid level .... ±38 mm

6.3 Remote Displays

If remote displays are used, they shall conform to the same accuracy specifications as stated above. Remote displays must undergo qualification

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

testing as specified in Section 5.2. If the remote display is placed in a control room, it must conform to the appropriate ABS rules.

7.0 Accommodation

The gauging manufacturer must provide the following accommodation features:

7.1 Inservice Diagnostics, Calibration and Performance Testing

Provisions for conducting diagnostics, calibrations, and performance testing may be accomplished by separate and independent means or by shared circuity and devices. Following are minimum requirements set forth for each of the three functional operations:

7.1.1 Diagnostics

(a) Means for localizing faults are to be provided which enable a system to be scrutinized for proper functioning (e.g., simulation circuits, test sockets, or lamps). Built-in circuitry is to be provided for use in the testing of module functions.

(b) Insofar as practicable, the gauging system is to incorporate self monitoring provisions to indicate the occasion and type of passive failure.

(c) The manual fault diagnostic and self monitoring alarm network should be capable of being tested during normal operation of the gauging system.

(d) Diagnostic operations are as far as practicable to be possible without affecting the operation of other systems.

(e) Gauging systems with remote readout instruments should have provisions for the installations of direct reading fault diagnostic type instruments at the sensor head.

7.1.2 Calibration and Performance Testing

(a) Inservice Calibrations, as far as practicable, are to be accomplished without affecting the operation and calibration of other systems.

(b) It is preferred that replacement units be pre-calibrated. However, minor adjustments are acceptable.

(c) The gauging system shall be suitably protected from change of calibration set points by human error, accident, or by vibration.

(d) Inservice calibration must be accomplished without entering or opening the tank.

(e) The calibration must be complete in all respects and the method must be accomplished by a ship's crewman without the aid of sophisticated instruments.

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

(f) The normal procedure for inservice calibration checkout and adjustment must include the total integrated function of all the gauging system components. The normal procedure must entail sensing predetermined reference levels of liquid cargo and/or true facsimile representations of the reference liquid cargo levels. Calibration check points shall include the entire liquid level range with specific requirements for refinement calibrations (high, low, and/or mid range) to be as specified in the buyer's specification.

(g) Gauging systems with remote reading instruments shall be provisioned at the sensing element with test receptacles for direct readings from the same transmission type and source as for the remote reading. These provisions are additional to the local readout gauge. Calibration procedures for remote readout systems should include the checkout and adjustment for consistent and accurate readings between the three sources of readout (remote readout, normal local readout, and checkout instrumentation for remote readout at local readout position).

7.2 Inservice Maintenance, Repair, and Replacement

(a) Inservice maintenance, repair, and replacement activities, as far as practicable, are to be possible without affecting the operation of the other systems or components.

(b) Inservice maintenance, repair, and replacement should be accomplished without entering the tank.

(c) The gauging system should be easy to adjust and maintain and should be designed for maintenance by easy and simple replacement.

(d) Ready accessibility to test points and to parts requiring inspection, adjustment, or periodic replacement is to be provided.

(e) Pneumatic and hydraulic piping for the gauging systems transmission and control functions shall be easily accessible throughout their length and the design shall provide facilities for easy dismantling and reassembly.

(f) All replaceable parts should be so arranged that it will not be possible to connect them incorrectly or to use incorrect replacements. Where this is not practicable, the replaceable parts should be clearly marked to ensure correct connection. There must be no possibility for damage or personnel danger by inserting the part in the wrong position. All interchangeable components that are handled by the crew must be keyed and closed.

(g) The system design should emphasize standardized modules and the number of different types of modules should be minimized to facilitate spare parts requirements.

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

(h) Electrical terminals should have protective covers to prevent inadvertent contacts by personnel and ground shorts during inservice maintenance, repair, and replacement operations.

(i) Tools and installation equipment shall be as simple as practicable and shall be sufficient to all required operations for inservice maintenance, repair, and replacement. The need for special tools should be avoided where possible.

(j) All cover plates and removable fixtures must contain retainable fasteners.

7.3 Spare Parts

The type and quantity of spare parts and their protective storage for each vessel is the responsibility of the owner. However, the manufacturer is required to make recommendations as to the type and quantity of spare parts needed for a one-year's service.

Spare parts should preferably consist of complete units; however, components of such units can be considered as a substitute for complete units if their replacement within the unit is simple and can be readily accomplished inservice by ships' crewmen.

All spare parts are to be suitably packed to resist deterioration during shipboard storage. A five-year shelf life capability should be provided for storage environments to be defined by the owner. Deviations to the owner defined storage life environments may be acceptable pending agreement by the owner and providing such deviation is shown to be realistic and justified.

7.4 Automatic Compensations and Corrections

Automatic compensations and/or corrections for the following conditions affecting gauging accuracy are preferred providing such provisions do not in themselves create system failures and unreliable operations:

(a) Ship trim angle (pitch and roll)
(b) Liquid cargo property variations
(c) Environmental temperature variations
(d) Environmental pressure variations
(e) Liquid cargo type
(f) Non-uniformity of liquid cargo temperature and/or concentrations
(g) Tank bottom impurities (water, sludge, etc.)
(h) Liquid cargo level motions due to ship's pitch and roll movements.

7.5 Marking

The following requirements should be satisfied to accommodate crew personnel conducting inservice maintenance and repair operations:

(a) Units, terminal strips, cable ends, and test points to be clearly and permanently marked.

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

(b) Transducers, controllers, and actuators should be marked with system function for ready identification on plans and in parts lists.

(c) Ends of internal wiring to be marked according to wiring diagram designations.

(d) Wiring diagrams for cables to be conveniently located inside removable covers, doors, etc.

(e) Where not practicable to physically prevent improper replacement of parts, parts are to be clearly marked to insure correct connection.

7.6 Display

The units and fractions of a unit used for display of liquid level shall be the same units used for the ship's trim correction tables. The display shall be marked "ullage" and/or "innage" as applicable.

For central monitoring stations consisting of many remote liquid cargo gauges, the following optional provisions are preferred as a useful feature for cargo topping operations:

(a) Each tank level indicator should be provisioned with a manual pointer (or indicator) for reference to the last reading of interest. A departure of the gauge reading from the prealigned manual pointer indicates a change of cargo from the last reading of interest. Consequence of such a level variation could be a malfunctioned control valve.

(b) Each tank level indicator should be provisioned with an indicator to denote the status of cargo topping. "Rapid fill operation complete" and "topping complete" are two important conditions to be indicated. The status indicator should be pronounced and readily obvious to the operator. The provision need not necessarily be a written sign. The partial and complete blanking of the indicator face may be acceptable visual aids for topping status depending on the type indicator and the owner's preference.

7.7 Manuals

A manual for the operation and service of the liquid cargo gauging system is to be provided by the manufacturer. The manual is to be written for two levels of service personnel - trained specialists and crewmen with limited training. Each part of the manual shall be appropriately designated and may be separate volumes. The quality and texture of the manual shall be compatible with shipboard environments and should facilitate exposure to limited amounts of water, oil, grease, and solvents.

TABLE III.3. QUALIFICATION ACCEPTANCE CRITERIA FOR SHIPBOARD LIQUID CARGO GAUGING SYSTEM (cont'd)

The manual shall provide instructions for system operation and for maintenance, trouble shooting, repair, and parts replacements. Readily discernible terminology shall be used and symbols shall be well coordinated throughout the manual, the ships' systems drawings, and the markings provided on the equipment proper.

The section or volume for the trained specialist shall be complete, accurate, and readily discernible for troubleshooting, repairing, replacing, and overhauling operations with the ship inservice. Special equipment for such operations is to be identified and all precautions and special instructions are to be included.

The section or volume for crewmen with no formal training (electronics, mechanics, etc.) shall consist of a relatively complete but simplified procedure for inservice trouble shooting, functional testing, parts replacement, and calibration of the entire gauging system. Pictorial aids, non-technical wording, and simplified sentence structure shall be used for easy understanding of content. Verbal and visual aids as may be provided on cassette tapes, sound or audio-visual tapes, movie film, sound slides, etc. may be substituted for manual text providing proper reference to such aids is provided by the manual and provided that replacements for such aids are readily available for order.

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EVALUATION OF VOLUMETRIC LEAK DETECTION METHODS FOR UNDERGROUND FUEL STORAGE TANKS

Volume I

by

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1 Introduction

This report summarizes the results of the United States Environmental Protection Agency (EPA) research program to evaluate the current performance of commercially available volumetric test methods that attempt to detect small leaks in underground gasoline storage tanks (UST).

1.1 Objectives

The specific objectives of the program were to produce the technical data necessary to support the development of release detection regulations; to define the current practice of commercially available systems; to make specific recommendations to improve the current practice; and to provide technical information that will help users select suitable methods for testing the integrity of underground storage tanks.

1.2 Regulatory Needs

Leaking underground storage tank systems represent a serious environmental threat. Estimates of the fraction of UST systems that are leaking range from 10 to 25% [1, 2]. Records from past release incidents indicate that, without the use of release detection, a release can become substantial before it is detected [3]. The 1984 Hazardous and Solid Waste Amendments to the Resource Conservation and Recovery Act of 1976 have charged the EPA with developing regulations for the detection of releases from UST. The final version of the technical regulation was published in the Federal Register on 23 September 1988 [4]. The performance standard for volumetric testing requires that a method must be capable of detecting a leak rate of 0.38 L/h (0.10 gal/h) with a probability of detection of 0.95 and a probability of false alarm of 0.05.

Development of technically sound and defensible regulations requires that both the threat to the environment and the technological limits of release detection be known. The threat to the environment is extremely difficult to define because the transport, fate, and amount of petroleum that is hazardous to the environment are site-specific.

A performance standard that is based on the current technology will minimize the uncontrolled release of petroleum product. Unfortunately, the data required to formulate a realistic regulatory policy were incomplete or nonexistent before this study was undertaken. While many leak detection methods are available and can be used to detect small releases, the performance of these methods was unknown. Almost all of the volumetric test methods claim to meet the 190-ml/h (0.05-gal/h) practice recommended in the National Fire Protection Agency Pamphlet NFPA 329 [5], but very little evidence, theoretical or experimental, had been provided by the manufacturers to support these claims. The limited evidence available prior to the Edison evaluations [2, 6-8] suggested that the methods are not reliably meeting these claims, a fact that has been confirmed by this study. However, the study has also shown that, with relatively minor changes, many leak detection methods can meet the new regulatory requirements.

1.3 Volumetric Test Methods

Many types of commercial systems are available to detect leaks in underground storage tanks. In 1986, the EPA published a survey of available methods [1], grouping them into four categories: volumetric, nonvolumetric, inventory control, and leak-effects monitoring. For all the methods in the first three categories, tests are conducted inside the tank, while leak-effects monitoring is performed outside the tank.

Volumetric test methods were the first to be selected for evaluation because (1) these methods have the potential for detecting small leaks, (2) the measured quantity can be directly related to leak rate, (3) the main sources of testing errors were believed to be well known, even though the empirical data necessary to quantify and correct many of these errors did not exist, and (4) the technology was commercially available and widely accepted in industry. Volumetric methods that claim to meet the NFPA practice of 0.19 L/h (0.05 gal/h) are commonly known as "precision tests," "tank tightness tests," or "tank integrity tests." Some methods test in a partially filled tank, and others test in a tank overfilled into the fill tube or an above-grade standpipe.

A volumetric method measures the change in product volume that results from a leak in the tank; a leak can represent either the release of product from the tank or an inflow of groundwater into the tank. Most methods measure product level and product temperature. The product-level data are converted to product volumes, which are then temperature-compensated. Next, flow rate is calculated using one or more different analysis schemes. The flow rate is then compared to a threshold flow rate to determine whether the tank is leaking. If the flow rate exceeds the threshold, the tank is declared leaking. If not, the tank is declared tight. While the details of the actual instrumentation, measurement protocols, data reduction and analysis algorithms, and detection criteria differ from method to method, the testing approach is essentially the same for all methods.

1.4 Definition of Test Method Performance

The confident detection of very small releases represents a considerable technical challenge. Release detection is, by its nature, a statistical process. The uncertainty in release detection is a consequence of environmental factors, operational practice, and instrumentation precision and accuracy. Testing errors are manifested in one of two ways:

missed detections (leaking tanks declared to be tight) that result in the undiscovered release of product into the ground, or false alarms (tight tanks declared to be leaking) that lead to additional testing and may result in the needless and considerable expense of tank repair investigations and/or replacement.

A complete specification of system performance requires a description of the probability of detection (P_D) and probability of false alarm (P_{FA}) at a defined leak rate and also requires an estimate of the uncertainty of the P_D and P_{FA}. If, in addition, a frequency of testing is specified, then the limits of the threat to the environment, the confidence with which these limits can be met, and the costs associated with mistakes in testing can be defined.

The performance of each method evaluated is expressed as a leak rate at the product level at which the test was conducted. Some consideration was given to normalizing all results to the same hydrostatic head relative to a leak; this is impractical, because the hydrostatic pressure depends on the level of the product in the tank, the level of the groundwater outside the tank, and the unknown location(s) of the leak(s) in the tank. There is a set of conditions for each test method in which the hydrostatic pressure produced by the product in the tank and the groundwater outside the tank will prevent flow into or out of a tank, even if a hole is present. Proper interpretation of the test result is the responsibility of the test operator.

1.5 Evaluation Approach

The approach was designed to satisfy all four of the objectives listed above (Section 1.1).

1.5.1 Data Quality Objectives

To address the program objectives, a set of data quality objectives was established at the beginning of the program and was adhered to throughout the data collection. The data quality objectives were developed to evaluate the methods claiming to meet the 0.19-L/h (0.05-gal/h) practice recommended by the NFPA. The precision and accuracy of the product-level, product-temperature, and leak rate data collected at the UST Test Apparatus were sufficient to evaluate the performance of each test method at a leak rate of 0.19 L/h with the probability of detection of 0.99 and the probability of false alarm of 0.01 called for in the proposed UST regulations [3]. This level of performance requires that the one-standard-deviation uncertainty in the histogram of the volume rate results compiled from many tests of one or more nonleaking tanks be 0.04 L/h (0.01 gal/h) or less. The UST Test Apparatus instrumentation, the calibration procedures, and the data quality analyses after each test were designed to verify that the data were meeting these objectives (see Section 7).

1.5.2 Evaluation vs. Validation

An important distinction is made between evaluation and validation. The EPA evaluation program was not meant to validate the performance of a test method. Rather, it was intended to estimate the performance of a given system under the tank conditions selected for the evaluation. Ideally, the performance of each method submitted for evaluation has been validated by the manufacturer over the range of testing conditions for the method. Because the EPA recognized that most manufacturers participating in the program had not systematically evaluated or validated their methods, the test conditions selected for the evaluation were fairly comprehensive. The evaluation reported here was designed to verify the manufacturer's performance claim over a limited set of test conditions. A thorough discussion of the test conditions is presented in this report in order to help the reader interpret the applicability of the results.

1.5.3 Approach

The performance of a leak detection system was determined from the histograms of the noise (developed from the volume-rate fluctuations in a nonleaking tank compiled for all conditions under which a test had been conducted), and of the signal-plus-noise (developed from the relationship between leak rate and these volume-rate fluctuations). If the evaluation had included only a few test methods, each manufacturer could have been requested to perform a standard tank test for each ambient condition in the test matrix, and a histogram could have been generated from all of the volume rates measured. However, because both the test matrix and the number of methods to be tested were large, this approach would have been too time-consuming and too costly to implement. In addition, this direct approach would not have provided any useful information, either to assess the limits of the technology in general, or to improve the performance of a given method. Instead, a unique approach, which also provides this information, was developed to perform the evaluation; this latter approach takes advantage of the common methodology of the majority of the volumetric test methods. This approach was first formulated in [9] and is summarized in [10]. A detailed description of the evaluation protocol is given in [11].

A three-step procedure was used to conduct the evaluations. The first step was to develop and experimentally confirm models of the important sources of noise that control the performance of each test method. If the total noise field is accurately modeled, the sum of the volume contributions from each noise source will be equal to the product-level changes in a nonleaking tank. As part of the modeling effort, a large database, reflecting the different product temperature conditions which could be experienced during field testing, was obtained to simulate a test performed after a delivery of approximately 15,000 L (4,000 gal) of product at one temperature to a 30,000-L storage tank half-filled with product at another temperature.

The second step was to develop and validate, for each leak detection method, a model that mathematically described it. The test-method model includes the precision and accuracy of the instruments, the test protocol, the data collection, analysis and compensation algorithms, and the detection criterion. The model, in turn, was validated in two steps. First, each manufacturer was required to review the model for accuracy, make corrections to the model as necessary, and finally to concur that it accurately represented the method submitted for evaluation; and second, the manufacturer was required to participate in the Field Verification Tests, a three-day program of tank-test and calibration experiments at the UST Test Apparatus. The manufacturer used his own testing crews and test equipment for the three days of testing. Methods that were not operational at the time of the tests, or that were different from those with which their respective manufacturers had concurred, were not evaluated.

Finally, a performance estimate for each method was made using the test-method model approved by the manufacturer, the product-level measurements estimated from the noise models, and the temperature database. The performance of all test methods but one was evaluated against the same database of temperature conditions encompassing over 500 h of data. A special database of over 180 h was developed to evaluate the one method that continuously circulated the product in the tank during the test. Operational effects and deviations from the prescribed protocols during the Field Verification Tests were also examined and discussed.

1.5.4 Presentation of Results

The performance results are presented and discussed in four categories: underfilled-tank tests, overfilled-tank tests conducted at a nearly constant product level, overfilled-tank tests conducted at a variable product level, and tests for which no performance estimate was or could be made. The performance estimate was made for a 2.43-m (8-ft)-diameter, 30,000-L (8,000-gal) tank containing unleaded gasoline and assumes that the test procedure was followed precisely as specified by the manufacturer.

The performance of each method was obtained by combining several different calculations. First, a performance estimate was made for a single tank without any trapped vapor; it included the instrumentation noise, a wide range of temperature conditions, and one set of tank deformation characteristics. The performance of each method is presented in terms of the P_D and P_{FA} for leak rates between 190 ml/h (0.05 gal/h) and 5,000 ml/h (1.3 gal/h).

Second, the effects of structural deformation and trapped vapor were examined. For a wide range of petroleum storage facilities, neither the range of tank and backfill properties affecting the structural deformation of storage tanks nor the distribution of the volume of trapped vapor is known. For this reason, the effects of structural deformation and trapped vapor are discussed separately if they have a direct influence on the performance of a given method. An arbitrary selection of these conditions could have resulted, unfairly, in anomalously poor performance for many methods.

Third, the impact of the following variables was quantified: (1) operational effects such as topping off the tank before a test, which can impair effective temperature compensation and significantly increase structural deformation of the tank, and (2) protocol deviations such as waiting periods that are longer or shorter than specified for starting or ending a test, which can significantly change the deformation effects. Methods whose performance would be dominated by trapped vapor, deformation, and operational effects are identified in the report so that the performance, which is based primarily on the ability to compensate for product-temperature changes, can be properly interpreted. These effects are very important, since they are a prime cause of false alarms and missed detections.

1.6 Underground Storage Tank Test Apparatus

The evaluations were performed by the RREL at the EPA's UST Test Apparatus located in Edison, New Jersey. The Test Apparatus is environmentally safe, and was designed and built to evaluate the performance of in-tank leak detection systems; construction was completed in August 1986. The Test Apparatus consists of two 2.43-m (8-ft)-diameter, 30,000-L (8,000-gal) underground storage tanks installed in a pea-gravel backfill material; one is a steel tank coated with plastic, and the other is a fiberglass tank (see Section 7). With this combined apparatus, different product temperatures, product levels, and leak rates can be generated and accurately measured. Thus, a wide range of tank testing conditions can be simulated.

1.7 Industry Participation

The only methods evaluated were those in-tank test methods that were capable of quantifying the flow rate produced by a leak in the tank. The EPA openly solicited all manufacturers of commercially available volumetric test methods to participate in the program. This was accomplished by public announcement in the Commerce Business Daily in July 1986 and with assistance from the American Petroleum Institute (API), the Petroleum Equipment

Institute (PEI), and the Leak Detection Technology Association (LDTA). Admission to this program was not closed until 1 April 1987, one month after the start of the Field Verification Tests.

Forty-three manufacturers and vendors of test methods originally indicated their desire to participate in this voluntary program. Twenty-five manufacturers completed the requirements necessary for evaluation. In fifteen of the methods evaluated, tests are conducted in an overfilled tank. In three of these methods, a constant head is maintained during testing. Of the remaining ten methods in which tests are conducted in an underfilled tank, the majority were automatic tank gauging systems (ATGS) for which a special protocol had been developed for this program. As a consequence, the performance of the ATGS evaluated as precision tests in this program may be different from the performance achieved when the same systems are operated as ATGS. A list of the twenty-five test methods and manufacturers that participated throughout the entire program is presented in Table 1.1.

Eighteen chose not to participate in the evaluation program. The reader should not assume that nonparticipation in the program is equivalent to poor performance. Manufacturers were not required to give reasons for not completing the program. About half of the 18 manufacturers who chose not to participate had been active at the beginning of the program, but dropped out because they were unable to complete the development and/or testing of their systems prior to the start of the Field Verification Tests. Several of the manufacturers in question missed their scheduled test times at the UST Test Apparatus because of development problems. Additional opportunities were provided, on a time-available basis, to accommodate the manufacturers' development efforts and still meet the EPA's deadline for completion.

Participation in the program involved a number of steps. First, manufacturers were required to execute a letter stating their desire to participate in the evaluation and their agreement to abide by its rules. Each company was required to designate a single contact for the exchange of technical and administrative information.

Second, each manufacturer was requested to answer a questionnaire that described specific aspects of the test method. This technical information was needed to describe the test method quantitatively; it included a claim of the precision and accuracy of the instrumentation, the configuration of the equipment deployed during a test, the specific procedure for conducting a test, the detailed data collection and data analysis procedures, and the criteria for determining whether a test was validly conducted and for declaring whether a tank is leaking.

Table 1.1 (concluded). Participants Completing the EPA Volumetric Test Method Evaluation Program

Test Method Name	Test Method Manufacturer	
MCG-1100	L & J Engineering, Inc. Mr. L. Jannotta	 (312) 396-2600
Mooney Leak Detection System	The Mooney Equipment Co., Inc.	 (504) 282-6959
OTEC Leak Sensor	OTEC, Inc. Mr. J.W. Hamblen	 (715) 735-9520
PACE Leak Tester	PACE (Petroleum Association for Conservation of the Canadian Environment) Mr. P. Casson	 (416) 298-1144
Petro Tite	Heath Consultants, Inc. Mr. G. Lomax	 (617) 344-1400
Portable Small Leak Detector (PSLD)	TankTech, Inc. Mr. J.A. Carlin	 (303) 757-7876
S.M.A.R.T.	Michael & Associates of Columbia, Inc. Mr. M. Diimmler	 (803) 786-4192
Tank Auditor	Leak Detection Systems, Inc. Mr. W.E. Baird	 (617) 740-1717
Tank Monitoring Device (TMD-1)	Pandel Instruments, Inc. Mr. P. Lagergren	 (214) 660-1106
Tank Sentry II	Core Laboratories, Inc. Mr. M. Sullivan	 (512) 289-2673
TLS-250 Tank Level Sensing System	Veeder-Root Co. Mr. D. Fleischer	 (203) 527-7201

After technical interaction with the manufacturer's representative, a report describing each method as a mathematical model was generated; this model is a logical sequence of mathematical steps that can be (and were) implemented on a computer. The report is referred to as the "mathematical modeling report" or simply the "model report." A written concurrence with the test-method description, as presented in the mathematical modeling report, was required of each manufacturer. Some mathematical modeling reports contained information designated as proprietary, trade-secret, or company-confidential by the manufacturer. So as to prevent the unauthorized release of information, these reports are not available for public distribution by the EPA. Those nonproprietary aspects of the test methods necessary to interpret and understand the results of the evaluation are summarized in the appendix in Volume I and also in Volume II.

Each manufacturer was then invited to participate in the Field Verification Tests at the UST Test Apparatus in Edison, New Jersey. The Field Verification Tests consisted of two parts. First, a series of product temperature conditions was established; under each condition, a leak was simulated by withdrawing product from the Test Apparatus tank at a constant rate. Each manufacturer was asked to test the Test Apparatus tank for leaks by following his standard test protocol, using his own test crew and equipment. Second, the manufacturer's measurement system was calibrated to derive an estimate of its precision and accuracy. These tests and calibrations were used to validate the test-method model.

An evaluation report was prepared for every manufacturer who participated in the Field Verification Tests at the UST Test Apparatus. Each evaluation report is included as an appendix in Volume II of this report.

Finally, the manufacturers were asked to provide a written technical review of their respective appendices and to discuss these with the EPA and its contractor before publication of the final report. The manufacturer had three opportunities to review his evaluation while the final report was being prepared. Valid technical comments were incorporated in the final report.

The evaluation was conducted at no cost to the participants; however, travel and other expenses incurred by the participants during the program were not reimbursed by the EPA.

1.8 How to Use This Report

The body of this report summarizes the results of the evaluation. It contains a description of the approach used for the evaluations, a description of the performance model used to present the results, a summary of the performance currently being achieved by commercial systems, a quantitative description of the important sources of testing errors, and specific recommendations on how to minimize these errors and improve performance. Sections 2 and 3 summarize the main conclusions and recommendations of this research program. Section 4 gives an overview of volumetric tank testing, and provides basic information necessary to understand the other sections of the report. The performance of a test method is described in Section 5. Section 6 describes the simulation used to estimate the performance of the methods evaluated in this program. (Section 6.4 is highly technical and describes the ambient-noise-source models that were used in the simulation and that control the performance of a volumetric method.) Section 7 describes the UST Test Apparatus located in Edison, New Jersey, the data quality objectives, and

2 Conclusions

An important EPA-sponsored research program has been completed that has evaluated and made estimates of the performance of commercially available volumetric leak detection methods as they existed in the period March through July 1987. For each method evaluated, recommendations were made, as required, to improve performance. This two-year project has determined and resolved key technological and engineering issues associated with this type of leak detection. The following objectives were accomplished: (1) evaluation of the performance of 25 currently available volumetric systems for detection of leaks in underground gasoline storage tanks; (2) development of technical information important in the development of EPA's underground storage tank regulations; (3) development of specific recommendations that will allow manufacturers to improve the current practice of each method; and (4) development of basic information to assist the test users in selecting a method that meets EPA's new regulatory requirements for underground storage tanks. A summary of the key conclusions of this research project are provided below.

After minor modifications, most methods should meet EPA performance requirements. By and large, the leak detection systems evaluated were limited by protocol and current practice rather than by hardware. In general, such limitations can be overcome by rather modest modifications to testing practices; major equipment redesign is not necessarily required. As part of this study, an estimate was made of the potential performance that could be achieved by the various precision test methods evaluated. The results show that with modifications, 12 of the 19 methods (over 60%) that completed the evaluations should be able to achieve a performance between 0.19 L/h (0.05 gal/h) and 0.57 L/h (0.15 gal/h), and all 25 methods (100%) evaluated should be able to achieve a performance of approximately 0.76 L/h (0.20 gal/h). Some manufacturers are already using the results of this evaluation to improve practices and equipment to achieve the above performance levels, and are in the process of quantifying the performance actually achieved by the modified systems.

Presentation of evaluation results in terms of PD and PFA gives a quantitative estimate of performance. Twenty-five commercially available volumetric leak detection systems were evaluated. An estimate of the performance of each method was made in terms of the probability of detection and probability of false alarm against a 0.38-L/h (0.10-gal/h) leak rate using the detection threshold employed by each method at the time of the evaluation. Another set of performance estimates was made for each method in terms of the smallest leak rate that could be detected and still maintain probabilities of detection and false alarm of 0.95 and 0.05, and 0.99 and 0.01. This performance estimate does not employ the manufacturer's detection threshold;

instead a threshold was selected which yields a probability of false alarm of 0.05 and 0.01, respectively. The leak rate measurable by these systems ranged from 0.26 to 6.97 L/h (0.07 to 1.84 gal/h), with a probability of detection of 0.95 and probability of false alarm of 0.05. Five of the methods achieved a performance that was better than 0.57 L/h (0.15 gal/h), and a total of eight methods had a performance that was better than 0.95 L/h (0.25 gal/h). The leak rate measurable by these systems ranged from 0.47 to 12.95 L/h (0.12 to 3.42 gal/h) when the probability of detection increased to 0.99 and the probability of false alarm decreased to 0.01. Only one of the methods achieved a performance better than 0.57 L/h, but five methods achieved a performance between 0.57 L/h and 0.95 L/h. While these results are less than what is generally claimed by the manufacturers, the phenomena that degrade performance have been identified, and in most instances, the problems can be easily fixed. Six systems could not be evaluated under the conditions of this evaluation either because the manufacturer was unable to successfully conduct a tank test during a scheduled three-day testing period, because the measurement systems did not perform as described by the manufacturer, or (in one instance) because the Test Apparatus had not been properly configured for the tests. These six appeared to be either new systems or systems whose basic principles of operation were not yet fully understood by the manufacturer.

Tank testing is complex, but a high level of performance can be achieved if several key principles are followed. To avoid serious degradation of performance, several key factors must be accounted for when using any of the volumetric test methods. Those systems that did well in the evaluation had adequate spatial sampling of the vertical temperature profiles of the product in the tank; they incorporated adequate waiting periods after product delivery and/or topping the tank (in tests that overfilled tanks) to allow the spatial inhomogeneities in the product temperature field and the tank deformation to become negligible; they maintained a nearly constant hydrostatic pressure head during the test; they used an experimental estimate of the height-to-volume conversion factor; and they used sound data analysis algorithms and detection criteria. Performance of a test method suffered significantly whenever one of these aspects of testing was ignored or poorly implemented. In general, any method will perform poorly and provide results that are difficult to interpret if it: (1) fails to maintain a nearly constant hydrostatic head during the test; (2) does not accurately estimate the height-to-volume conversion factor; (3) tops the tank and begins to test almost immediately, or (4) waits an insufficient period of time after product delivery before beginning the test. Most manufacturers recognized the need to wait after a product delivery, but they did not appear to fully appreciate the magnitude of the degradation that occurs when the waiting period after topping (in methods that overfill the tank) is not long enough.

Current performance is significantly less than what is claimed by most manufacturers. Of the 25 commercially-available volumetric leak detection systems evaluated, most presently perform at a level that is considerably poorer than the common industry practice of 0.19 L/h (0.05 gal/h). This discrepancy between vendor claims and actual performance appears to be due to two reasons. First, in almost all instances, the measurements made by EPA under this project appeared to be the first systematic evaluation of each test method. Second, the performance estimates were formed in terms of a probability of detection and a probability of false alarm, a presentation that most manufacturers have not previously used to quantitatively describe performance.

Removal of vapor pockets is important to the performance of overfilled-tank test methods. Operationally, achieving a high level of performance with methods that overfill the tank requires the removal of trapped vapor before conducting a test; this is a necessary skill that, during this evaluation, was best demonstrated by the most experienced and best-trained test crews. Test methods designed for use in partially filled tanks are not subject to the effects of trapped vapor but can be affected by evaporation from the product surface and evaporation and condensation from the tank walls. Analysis of the evaporation and condensation data is incomplete. Based on a qualitative inspection of the test results, it is observed that when temperature conditions in the vapor space are relatively stable, the impact of evaporation and condensation on test performance is relatively small.

Constant-level testing is important with overfilled-tank test methods. A serious testing flaw was discovered in all methods which overfill the tank into a fill tube or standpipe and measure product-level changes. The error associated with this flaw was theoretically described and experimentally verified in this program. The flaw is easily eliminated by conducting the test at a nearly constant hydrostatic head. This can be accomplished by releveling the product in the fill tube and measuring volume directly, or by significantly increasing the cross-sectional area of the fill tube. The essence of the flaw is that the volume changes measured in the fill tube, after the waiting period designed for the observed deformation changes to subside, are reduced to an unknown fraction of the true volume changes. The flaw is a result of the fact that the tank structurally deforms continuously with any product-level changes in the fill tube. The contributions from all sources of volume change, including operator-induced and ambient product-level changes, are coupled and interact dynamically in a complex way to deform the tank. The volume changes due to leaks are similarly affected. The magnitude of the error depends on the cross-sectional area of the product surface, the elasticity properties of the tank-backfill-soil system, and the volume of trapped vapor.

Reliable tank testing takes time. The total time required for the methods evaluated at the UST Test Apparatus to complete a reliable tank test, from delivery of product to removal of the equipment from the testing site, is generally 12 to 24 h. The total duration of the test is controlled by the waiting periods after product delivery or topping the tank. The waiting periods can be shortened by incorporating data analysis algorithms into the test protocol. In this way the duration of the waiting periods can be estimated individually for each test.

5 Performance of a Test Method

Detection of leaks in underground storage tank systems is an example of the classical statistical problem of finding a signal in a background of noise. In storage tank testing, the signal is the product-level or product-volume changes produced by a leak, and the noise is the sum of the product-level changes produced by the measurement system itself, by the environment, and by the operational practice. In a properly designed system, the noise introduced by the measurement system and the operational practices should be small compared to the environmental or ambient noise. The measurement system noise is easily controlled and should be designed to be smaller by at least a factor of 5 than the minimum signal to be detected. For some methods, the operational practice may significantly affect the magnitude of the ambient noise field. The impact of the operational practice can be minimized by proper test design.

The solution to the leak detection problem is straightforward and is accepted by the scientific and engineering communities. The same method used to evaluate the performance of a radar or sonar system, for example, can be (and is here) used to evaluate the performance of a leak detection system for an underground storage tank. Numerous descriptions of the statistical models used to analyze the data can be found in the scientific literature [e.g., 16-18]. Application of these models to underground storage tank leak detection systems was first described in [19, 20].

The performance of a test method is presented in terms of its probability of false alarm, or P_{FA} (the probability that a test will result in the declaration of a leak when the tank is tight), and its probability of detection, or P_D (the probability that a test will result in the declaration of a leak when the tank is indeed leaking), for a prescribed leak rate, LR.

The dominant sources of environmental or ambient noise are:

- *product temperature* (changes in product volume produced by temperature changes in the product)
- *vapor pockets* (changes in the volume of trapped vapor produced by temperature changes in that vapor due in turn to atmospheric and hydrostatic pressure changes, and by evaporation and condensation within the trapped vapor)
- *evaporation and condensation* (changes in product volume produced by evaporation from the product surface and condensation from the tank walls, and manifested as losses or gains of product)
- *structural deformation* (changes in the volume of the tank produced by changes in hydrostatic pressure on the tank prior to and/or during testing, e.g., product-level changes)

- *surface waves* (periodic product-level fluctuations that are unrelated to volume changes)
- *internal waves* (periodic subsurface temperature and/or product-level fluctuations that are unrelated to volume changes)

The first four sources of noise have temporal characteristics similar to those of the signal (i.e., linear changes). However, they may also have temporal fluctuations on scales different from those of the signal. Unless the tests are short, the temporal fluctuations of the surface and internal waves generally can be removed by appropriately sampling and filtering the data.

The ability to detect a signal is limited by that portion of the noise energy with the same characteristics as the signal (i.e., that portion which could be confused with the signal). For tank leaks, the signal in its simplest form is assumed to be a linear change of product level or product volume with time. The essential noise, therefore, is that which also leads to a linear change of volume with time. The portion of the noise that does not exhibit a linear change with time can be removed by averaging the data appropriately. A linear least-squares fit of volume as a function of time is one such method. The measurement made during a test may be either noise or the signal-plus-noise; unfortunately, it is not possible to separate the signal from the noise in a volume measurement alone, although measurements of other quantities may provide a separation.

Detection is usually accomplished by selecting a threshold level at the output of the measurement system. When the output exceeds the threshold, a signal is presumed to be present. The four possible outcomes of a leak detection test are presented in Table 5.1, where the test declaration is given on the vertical axis and the actual state of the tank is given on the horizontal

Table 5.1. Possible Outcomes of a Leak Detection Test

Measured Conditions	Actual Conditions	
	Leak	No Leak
Leak	Correct Declaration *(Leak)*	Incorrect Declaration *(False Alarm)*
No Leak	Incorrect Declaration *(Missed Detection)*	Correct Declaration *(Tight)*

axis. The two correct declarations are that the tank is accurately declared to be leaking or nonleaking. The two incorrect declarations are that a tight tank is declared to be leaking (i.e., a false alarm) and that a leaking tank is declared to be tight (i.e., a missed detection). For illustration, a measurement system's output for many tank tests is shown in Figure 5.1. The output fluctuates because of the random nature of the noise. If the signal (i.e., the leak) is much larger than the threshold, as it is for Tank C, it is not difficult to decide that the signal is present. But consider the measurements for Tanks A and B, which are leaking at the same rate. The noise fluctuation at A is large enough that the combination of signal-plus-noise exceeds the threshold. At B, the noise fluctuation is negative, and the resultant signal-plus-noise does not exceed the threshold. Thus, the presence of noise can sometimes enhance the detection of weak signals, but it may also cause the loss of a signal that would otherwise be detected, i.e., a missed detection.

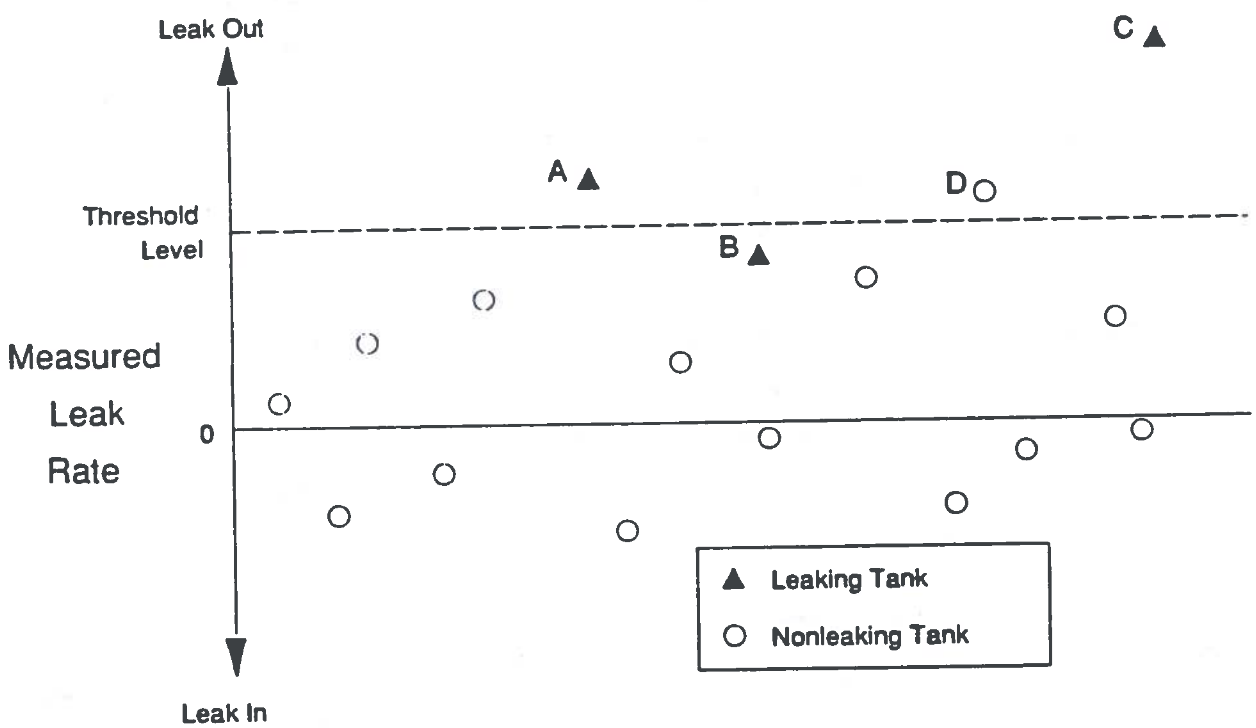

Figure 5.1. Typical measurement output for a sequence of tank tests. A and B are tanks leaking at the threshold rate. A is declared leaking and B is declared nonleaking. Tank C is leaking at a rate well above the threshold level, so there is no ambiguity in declaring it leaking. The open dots represent nonleaking tanks; one of them (D) has a noise fluctuation exceeding the threshold, producing a false alarm.

5.1 Signal

The signal is the rate of change of product level or product volume produced by a leak. The flow rate produced by a leak is assumed to be a constant (i.e., to be a linear change in volume with time) during the tests. For tests conducted at a constant hydrostatic pressure, the signal will be equal to the leak rate. Tests in partially filled tanks, or tests in overfilled tanks in which the product level is kept at a constant level by adding or removing a measured volume, are examples of constant-head tests. However, as is shown in Section 6.4.4, it is *not* true that the signal is equal to the leak rate if the product level is allowed to fluctuate during a test. Tests conducted in a tank overfilled into the fill tube or an above-grade standpipe, in which the product level changes, are examples of tests conducted under variable hydrostatic pressure. For these tests, the signal will be only a fraction, k, of the actual product level or product volume expected to be produced by a given leak rate. For constant-head tests the measured leak rate, LR, is equal to the actual leak rate, LR_{actual}. For variable-head tests, $LR = k\ LR_{actual}$. The volume changes caused by noise will be similarly affected, such that $VR = k\ VR_{actual}$, where VR_{actual} is a volume rate due to any noise source.

The specification of the weakest detectable signal is sometimes difficult because the criterion for deciding whether or not the signal is present (i.e., the threshold) may be hard to define. For example, weak signals, such as at B, would not be lost if the threshold were lower. However, too low a threshold increases the likelihood that a noise fluctuation alone will rise above the threshold and be mistaken for a real signal, such as the noise fluctuation at D, a false alarm. Conversely, too high a threshold means that signals might be missed. The selection of the proper threshold level is a compromise that depends on the relative importance of avoiding missed detections as opposed to the importance of avoiding false alarms.

5.2 Noise Histogram

The performance of a detection system can only be determined once the fluctuation level (product-level or product-volume changes) at the output of the measurement system is known with and without the signal present. For any test method, the statistical fluctuation of the noise is observed in the histogram of the volume-rate results created by plotting the measured volume rates from a large number of tests conducted (1) over a wide range of conditions, (2) with many systems on one or more nonleaking tanks, and (3) by many different operators. The histogram indicates the probability that a particular volume rate will result from a test on a nonleaking tank. The performance analysis requires that the test sample consist of random, independent events. If there are no systematic errors in the measurement, the mean will not be statistically different from zero, and the *standard deviation* will reflect the uncertainty of the test method. It is usually assumed that the data are stationary (i.e., that the histogram of the noise does not change with

An example of the signal-plus-noise histogram for a -1.2-L/h leak with k = 0.6 (variable-head test), assuming the entire contribution to the noise is from thermally induced product-volume changes, is presented, before and after thermal compensation, in Figures 5.7 and 5.8. If the noise has a nonzero mean, the mean of the signal-plus-noise histograms will be different before and after temperature compensation.

For comparison, the histogram of the signal-plus-noise with k = 1.0 (constant-headtest) after temperature compensation would be identical to the leak rate (i.e., TCVR = LR and $S_{TCVR} = 0$). Before temperature compensation, TCVR = LR and $S_{TCVR} = S_{TVR}$.

5.4 Performance Model

The performance of a volumetric test method is determined from the histograms of the signal-plus-noise and the noise. For tests conducted under a constant hydrostatic pressure (e.g., partially-filled tank tests, or overfilled-tank tests which relevel), performance is estimated from the model shown in Figure 5.9. This model assumes that the data are stationary and spatially homogeneous, that the noise histogram has a zero mean, and that the signal is constant, equal to the leak rate, independent and additive with the noise. This model applies to all volumetric tests, providing that the systematic errors are small.

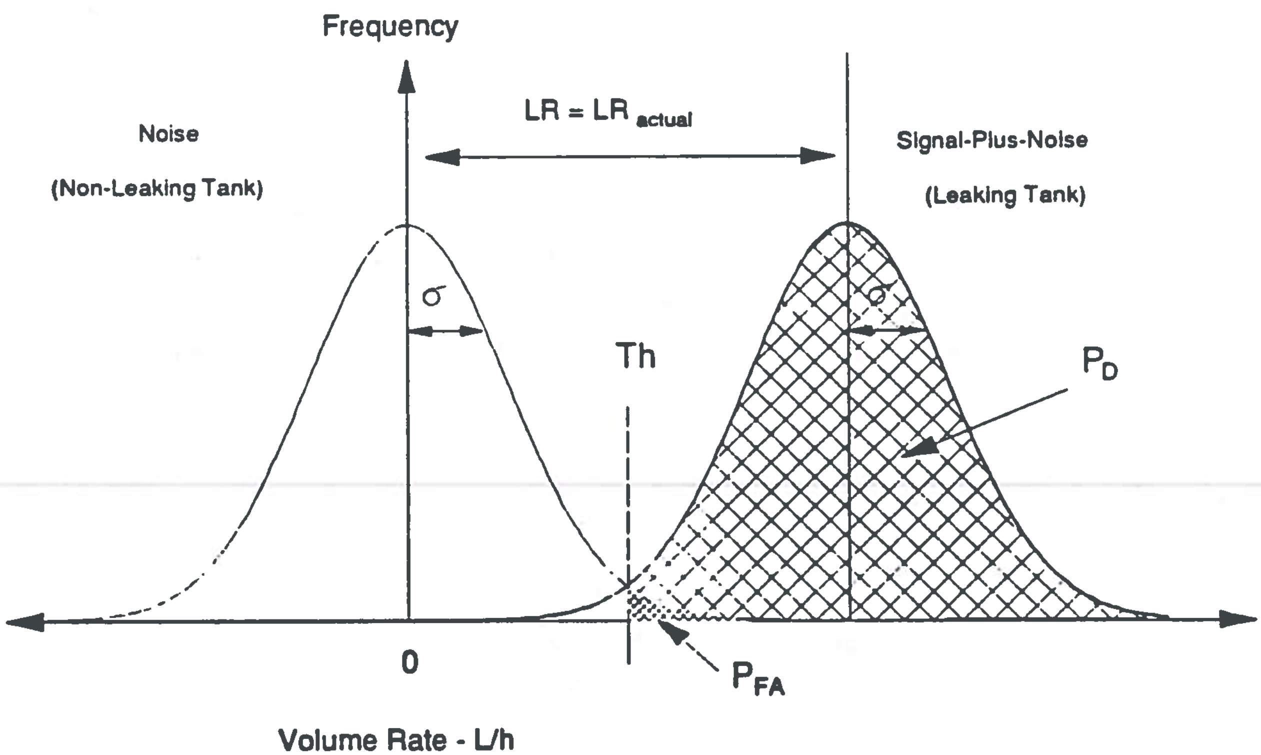

Figure 5.9. Statistical model to estimate the accuracy of a constant-head leak detection system.

Figure 5.9 shows the P_D, P_{FA}, Th, and the leak rate, LR, for the constant-head test ($k = 1$). Once Th has been selected, the P_{FA} is determined. The P_D is defined as the fractional time the signal-plus-noise fluctuation will exceed the threshold, and is represented by the hatched area. Clearly, if the threshold does not change, the P_D will be higher for larger leak rates. For tests conducted in an overfilled tank in which the product level fluctuates during the test, performance is estimated from the model shown in Figure 5.10. In this case, the leak rate determined by the signal-plus-noise histogram is not equal to the actual leak rate and the temperature-compensated noise histogram has a larger spread than it does for a constant-head test. As discussed in Sections 5.2.2 and 5.3.2, the noise and signal-plus-noise histograms, after temperature compensation, are impacted by the structural deformation of the tank. Since the noise histogram derived after temperature compensation has a larger standard deviation for variable-head tests ($k < 1$) than for constant-head tests ($k = 1$), the P_D will decrease and the P_{FA} will increase in comparison.

It is important to understand that the P_D, P_{FA}, Th, and LR are all interrelated; changing one parameter affects the value of one or more of the other parameters. If any two parameters are known, the others are fixed by the model. The choice of parameters affects the conclusions to be drawn from leak detection tests (i.e., the reliability of the test result). For a given leak, LR, choosing a high threshold, Th, gives an extremely small P_{FA} but results in a reduced P_D (i.e., the number of false declarations will be small, but the number of missed leaking tanks will be large). A low value for Th yields extremely large values for both the P_D, and P_{FA} (i.e., the number of leaking tanks detected will be large, but the number of false declarations will also be large). The benefits and costs associated with reducing the number of missed detections and false alarms can be balanced by judicious selection of the threshold.

The standard deviation of the noise and the signal-plus-noise is a measure of the spread of the data and is directly proportional to performance (e.g., Figure 5.9). The smaller the standard deviation, the better the performance. The performance can be directly calculated from the standard deviation if (1) the noise is stationary, spatially homogeneous, and normally distributed with a zero mean, and (2) the signal is constant, equal to the leak rate, independent, and additive with the noise. For such conditions, the leak rate that can be detected with a $P_D = 0.99$ and a $P_{FA} = 0.01$ is 4.67 times the standard deviation. The threshold, established by the selection of a $P_{FA} = 0.01$, is 2.33 times the standard deviation. In this particular instance, the threshold is one half the leak rate because the P_{FA} plus the P_D is equal to 1. (However, this is not true in general.) Thus, a standard deviation of 0.163 L/h (0.043 gal/h) will result in the detection of a 0.76-L/h

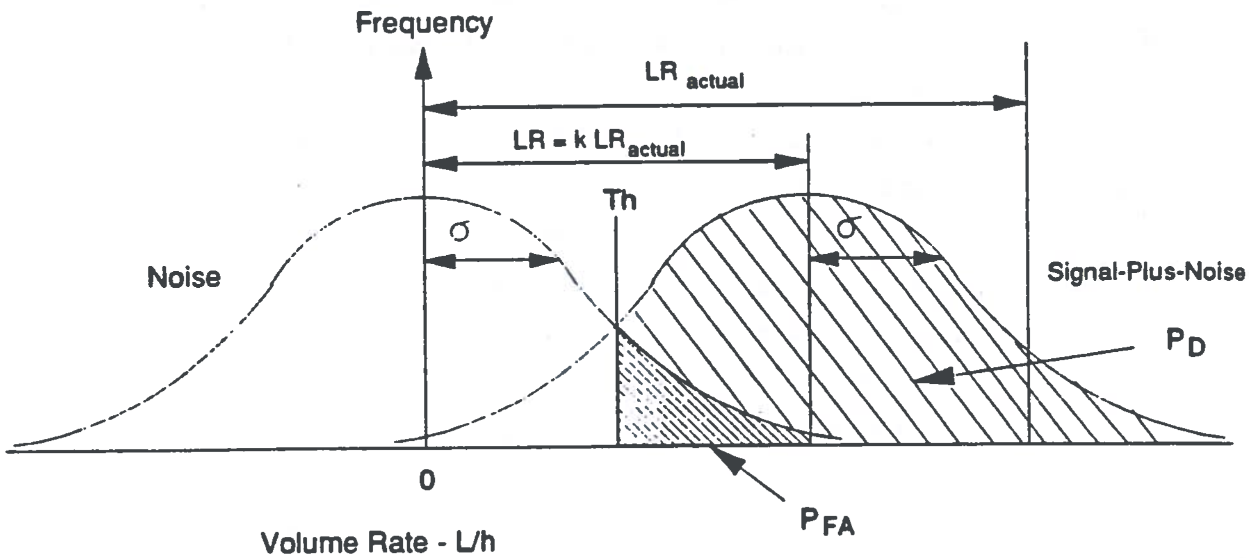

Figure 5.10. Statistical model to estimate the performance of a variable-head test. The same conditions apply for this model as for the constant-head model in Figure 5.9.

(0.20-gal/h) leak rate with a $P_D = 0.99$ and a $P_{FA} = 0.01$ for a threshold of $\pm$ 0.38 L/h (0.10 gal/h). The P_D is greater than 0.99 for leak rates of more than 0.76 L/h and smaller than 0.99 for leak rates less than 0.76 L/h.

In most of the methods evaluated here, the threshold has been set so as to be equal either to (1) the smallest leak rate detectable by the system or (2) the leak rate specified by regulatory policy or industrial practice. When the threshold is equal to the leak rate (common practice in the industry), the probability that a leak will be detected is only 50%. Typically, the methods evaluated here claim a high performance against leak rates of 0.19 L/h (0.05 gal/h), and yet they use a 0.19-L/h threshold to declare a leak. The threshold would have to be set to a value less than the minimum detectable leak rate in order for the probability of detection to be better than 50%.

Measurements of the ambient noise associated with underground storage tanks show fluctuations much larger than the smallest leaks to be detected (i.e., less than 0.76 L/h (0.20 gal/h)). In order to achieve satisfactory detection performance, the ambient noise fluctuation must be substantially reduced. The two approaches to noise reduction are (1) incoherent averaging, and (2) coherent cancellation or compensation. The goal of both approaches is to reduce the mean and standard deviation of the noise to zero.

Incoherent averaging reduces noise only if successive measurements contain substantially different noise fluctuations. The need to make many measurements spaced many hours apart makes incoherent averaging impractical as an approach to noise reduction.

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SPECIFICATION FOR PROCUREMENT OF WATER-LEVEL SENSING INSTRUMENTATION, SPECIFICATION NUMBER HIF-I-1

Open-File Report 82-89

UNITED STATES
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SPECIFICATION FOR PROCUREMENT OF WATER-LEVEL SENSING INSTRUMENTATION, SPECIFICATION NUMBER HIF-I-1

by D.H. Rapp

Open-File Report 82-89

NSTL Station, Mississippi

January 1982

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For more information write to:

Chief, Hydrologic Instrumentation Facility
U. S. Geological Survey, WRD
Building 2101
NSTL Station, MS 39529

CONTENTS

TABLES

REVISIONS

HIF-I-1
AMENDMENT-1
April 20, 1983

U.S. GEOLOGICAL SURVEY, WATER RESOURCES DIVISION

SPECIFICATION INSTRUMENTATION, WATER-LEVEL SENSING

This amendment, which forms a part of HIF-I-1, dated January 1982, is the specification used to establish a Qualified Products List (QPL) for water-level sensing instrumentation.

Page 5

Paragraph 1.2.2

DELETE: Sensor type and distance. Sensors are classified by type as follows:

ADD: Sensor: Sensors are classified as follows:

ADD: 1.2.2.3 Target area. The area of unobstructed water surface required by the sensor. The area is a function of sensor height above or below the water surface.

ADD: 1.2.2.4 Dead band. The distance above or below the sensor that the system does not operate satisfactorily.

Page 8

Paragraph 2.2

ADD: American National Standards (ANSI), Graphic Symbols for Electrical and Electronics Diagrams, ANSI Y32.2, 1975 and IEEE Std. 315, 1975.

Reference Designations for Electrical and Electronics parts and equipment, ANSI Y32.16, 1975 and IEEE Std. 200, 1975 (Copies may be obtained from The Institute of Electrical and Electronics Engineers, 345 East 47th Street, New York, N.Y. 10017).

Page 9

Paragraph 3.1

ADD: Line 6, "±" 0.01 foot ...

ADD: Line 7, "±" 0.001 for group A ...

ADD: 3.1.5 Synergetics GOES Hydrologic Data Collection Platform, Model 3400A-001/3451A.

ADD: 3.1.6 Any system furnished by a stage-sensing system manufacturer that will produce a printed copy in digital format on paper or paper tape.

Page 10

Paragraph 3.5

ADD: All operational manuals shall be written in English.

ADD: 7. (Symbols shall comply with ANSI Y32.2 and reference designations shall comply with ANSI Y32.16).

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Paragraph 3.6

DELETE: From the first sentence "and the Analog to Digital Recorders (ADR's)".

Paragraph 3.6.1.1

DELETE: From -40°C (-40°F) to 60°C (140°F)

ADD: Air temperature range must meet one of the following:

From -40°C (-40°F) to 65°C (149°F)
From -25°C (-13°F) to 65°C (149°F)
From 0°C (32°F) to 65°C (149°F)

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Paragraph 4.2.2

DELETE: Sample size for qualification. The sample size for qualification shall be two production models for each classification submitted for qualification.

ADD: Sample size for qualification. The sample size for qualification shall be one production model for each classification submitted for qualification.

Specification for Procurement
of Water-Level Sensing Instrumentation
Specification Number HIF-I-1

INTRODUCTION

The performance of the U.S. Geological Survey's mission requires the installation of water-level sensing instrumentation at many diverse river, canal, lake, storm-sewer, and observation-well sites. Currently, stilling wells with float and counter weight, or gas purge Mercury manometer systems are used to sense water level (stage). A number of hydrologic instrumentation manufacturers have developed alternative methods to sense stage. Stage can be detected by pressure-transducer systems and by sonic, or ultrasonic transducer and receiver systems. Some of these recent developments, especially the noncontact sensing systems, could reduce installation costs at suitable sites and may have lower maintenance costs.

Both the new systems and those currently in use by the Survey will be tested at the Hydrologic Instrumentation Facility to see if they meet Survey requirements for the collection of stage data. This report sets forth only the minimum Survey requirements for stage-sensing systems for the purpose of conducting qualification tests. Each Survey office will have to determine complete requirements for each field location, but the following requirements will cover the majority of sites. All stage-sensing systems will be tested before procurement by the Hydrologic Instrumentation Facility. The results of these tests will be published in a separate report for use by Survey personnel. Systems that pass the qualification tests will be placed on the Survey's Qualified Products List (QPL).

The Code of Federal Regulations (Title 41) allows the procurement office to require prospective bidders to have their product tested and qualified for the QPL before bids are submitted in response to a solicitation for bids. After a QPL is established, only bidders for stage-sensing instrumentation whose products have met the requirements in this report will be invited to bid.

The Regulations require this specification report in advance of the qualification tests. The following six sections are in the format used by the General Services Administration and the Department of Defense.

Section 1 defines the stage instrumentation that this specification report covers. Also, Section 1 classifies the various system characteristics in outline form as an aid to Survey personnel purchasing these systems. References used in Sections 3-6 are listed in Section 2. These references are nationally recognized standard test procedures used by industry and government. Stage-sensing system requirements are listed in Section 3. These are the minimum requirements that must be met by each system before it will be approved for procurement by the Survey. Section 4 covers quality-assurance (QA) provisions, including the qualification tests. The manufacturer is responsible for QA inspections and tests. The qualification tests will be conducted by Survey personnel at the Hydrologic Instrumentation Facility or by an independent test laboratory under contract with the Survey.

Section 5 lists the standard packing instructions for delivery, in case this specification report is used as a part of a procurement contract document. The last section of the specification is Section 6, which describes ordering information for purchasers of qualified products, and qualification information for suppliers and manufacturers.

This specification report serves to communicate to the manufacturers of hydrologic instruments and to Survey procurement personnel the Survey's minimum requirements for stage-sensing systems.

U.S. GEOLOGICAL SURVEY, WATER RESOURCES DIVISION

SPECIFICATION INSTRUMENTATION, WATER-LEVEL SENSING

1. SCOPE AND CLASSIFICATION

1.1 Scope. This specification covers instrumentation for sensing the elevation of the water surface in open channels, rivers, lakes, reservoirs, storm-sewer pipes, and observation wells at U.S. Geological Survey gaging sites. Water-surface levels, hereafter will be called stage. A stage-sensing instrument system as defined by this specification shall be a complete system from the sensor to the required output. The system shall include the stage sensor, all electronic, mechanical, and/or hydraulic subsystems, all interface systems, all hardware items, cables, hoses, chain drives, sprockets, timers, controllers, software and instrument cases to meet all the requirements listed in Section 3. The signal output of this sensing system (mechanical or electrical) shall meet the signal input requirements of analog to digital recorders (ADR), digital input recorders, and graphic recorders listed in section 3. Many of the gaging sites where these instruments are installed are at remote locations and will be visited only once every 6 to 12 weeks with 75 days as the minimum requirement between visits. The systems must be capable of operating in an instrument shelter that is not heated in the winter nor air conditioned in the summer.

1.2 Classification. Stage-sensing instrumentation under this specification shall be classified by all the following characteristics:

1. Contact or noncontact system
2. Sensor, type and distance
3. Error
4. Maximum range in stage
5. Suspended sediment concentration
6. Water surface
7. Power requirement
8. Instrument package size and weight
9. System data output signal

1.2.1 Contact or noncontact systems. All systems that have stilling well pipes or sensors in or on the water surface are classified as contact systems. All systems that have sensors and all hardware mounted above the maximum measured water surface are classified as noncontact systems.

1.2.2 Sensor type and distance. Sensors are classified by type as follows:

1.2.2.1 Type.

Float and counterweight

Gas purge, mercury manometer

Gas purge, mechanical manometer (that is, balance-beam type)

Pressure transducer

Sonic or ultrasonic transducer and receiver

Electromagnetic spectrum sensors (that is, lasers, electro-optical,RF)

Electronic sensor cable (that is, resistance cable)

Other

1.2.2.2 Distance. The distance that a sensor can be located away from the rest of the stage-sensing system is classified by either the maximum allowable length of sensor cable or maximum length of air line when no cables are required, as follows:

10 Feet
25 Feet
50 Feet
100 Feet
500 Feet
1000 Feet
+ 1000 Feet

1.2.3 Error. Allowable output error is defined in Section 3. Overall stage-sensing system error, in feet, is classified by one of the following error-range groups for full range (full scale) in stage and for all environmental conditions (Section 3): A, 0.001 to 0.005; B, 0.006 to 0.01; C, 0.02 to 0.10; D, 0.11 to 0.25; E, 0.26 to 0.49; and F, 0.50 to 1.00.

1.2.4 Range in stage. The maximum ranges (full scale) in stage, in feet, are as follows: 0 to 10, 0 to 20, 0 to 35, 0 to 50, 0 to 100, 0 to 200, and + 200.

1.2.5 Suspended-sediment concentration. The stage-sensing system will be classified by the range in suspended-sediment of the water. The system shall be capable of sensing stage within the allowable output error requirements. The range normally found is from 0 to 100,000 milligrams per liter particle concentration with a density of 2.65 specific gravity of quartz particles, and a particle size diameter of d50 = 0.10 mm (1/2 mm maximum).

1.2.6 Water surface. The water surface will be from level and smooth surface (laminar flow) to 8.0 foot standing waves (supercritical and turbulent flow). Surface velocity will be from 0 to 40 feet per second. The surface, at times, may be covered with an oil film, foam, floating debris, or ice cover.

1.2.7 Power requirements. Power required to operate the sensing system, including interface, if required, is classified as battery alone, a-c power, or a-c power with battery backup. See Section 3 for details of maximum acceptable power requirements.

1.2.8 Instrument package size and weight. The space requirements to house the instrument system including interface hardware, nitrogen gas tanks, pressure system, power supply, and batteries are classified as follows:

A. Smaller than 18 inches long, by 12 inches wide by 18 inches high, and weighs less than 25 pounds.

B. Larger than size A, but smaller than 36 inches long by 18 inches wide by 36 inches high, and weighs less than 50 pounds.

C. Larger than size B, but smaller than 4.0 feet long by 3.0 feet wide by 8.0 feet high, and weighs less than 75 pounds.

D. Larger than size C, and/or weighs more than 75 pounds.

The weight excludes the weight of a full nitrogen gas tank for all four classes.

1.2.9 System data output. Signal output is classified either as analog or digital signal. The analog output can be either a mechanical shaft input, or a voltage.

2. APPLICABLE DOCUMENTS

2.1 The following documents, of the issues in effect on date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein.

Federal Standards:

Fed. STD. NO. 123 - Marking for Domestic Shipment (Civil Agencies).

Fed. STD. No. 151 - Federal Test Methods.

(Copies of Federal Specifications and Standards required by contractors in connection with specific procurement functions should be obtained from the procuring office or as directed by the contracting officer).

Military Standards:

MIL-STD-901C, Shock Test, HI (High Impact), Shipboard machinery.

MIL-STD-167B, Mechanical Vibration of Shipboard Equipment.

MIL-STD-202F, Test Methods for Electronic and Electrical Component Parts.

MIL-I-46058C, Type UR, Conformal Coating Requirements.

(Copies of Military Specifications and Standards required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 Other publications. The following documents form a part of this specification to the extent specified herein. Unless a specific issue is identified, the issue in effect on date of invitation for bids or request for proposal shall apply.

National Electrical Code, National Fire Protection Association, 1981 Edition. (Copies may be obtained from the National Fire Protection Association, Inc., 470 Atlantic Avenue, Boston, MA 02210.)

National Weather Service, Transient Susceptibility Standard, May 1978.

National Environmental Testing Criteria and Recommended Test Methodologies for Proposed Standard for National Weather Service Equipment, September, 1980.
(Copies may be obtained from the National Weather Service, Test and Evaluation Division, National Oceanic and Atmospheric Administration, Rt. 1, Box 105, Sterling, VA 22170.)

3. REQUIREMENTS

3.1 System output requirements. The stage-sensing system shall include interface hardware that will input the correct signal to one or more of the recorders,[1/] listed below, unless otherwise specified in the contract or purchase order. The input signal to the recorder shall be in the proper format so that the stage data shall be in units of feet. System output resolution shall be 0.01 foot over full scale range for all error-range groups except group A. Resolution shall be 0.001 for group A systems. The stage-sensing system shall display the output value in digital format on demand of the servicing personnel.

3.1.1 Fischer and Porter shaft-input, analog to digital, paper-punch tape recorder, Model 1542.

3.1.2 Leupold and Stevens shaft-input analog to digital, paper-punch tape recorder, Model 7001.

3.1.3 Leupold and Stevens digital input/output, paper-punch tape recorder, Model 7041.

3.1.4 Leupold and Stevens shaft-input, graphic recorder, Model A 71 or Model A 35.

3.2 Interface requirements. The interface shall include all required cables and connectors, pulleys, chains, belts, power supplies, reference voltage batteries, and any other items required to connect the stage-sensing system to one or more of the recorders listed under Section 3.1. All electrical cables shall have polarized connectors or clearly marked terminal identification.

1/ Use of trade names and trademarks in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

3.3 Materials. All parts of the system shall be fabricated from materials which will resist corrosion under humidity and resist deterioration by solar radiation (section 3.6). All circuit boards and electronic components shall be protected by Type UR Conformal Coating from internal moisture and condensation per MIL-I-46058C.

3.4 Housing and connectors. The system shall be housed in a drip-proof, dust-proof, shock-resistant, and waterproof case or cases.

All cover plates, lids, and removeable plugs shall be either hinged or tethered so they can not be dropped accidently. Lock washers or lock nuts shall be required on screws and bolts to prevent loosening by vibration. All external electrical connectors shall be watertight and shall not loosen by vibration.

3.5 Operational manual. Operational manuals for the complete system (including the interface) shall be provided. These manuals are for use by U.S. Geological Survey field personnel and shall contain the following procedures and items:

1. General description
2. Installation instructions
3. Calibration procedures
4. Operation instructions
5. Maintenance instructions
6. Trouble shooting and repair guide
7. Schematic and wiring diagrams
8. Complete parts list
9. Pictorial exploded assembly drawing with all parts identified
10. Manufacturer's design specifications
11. Factory service information

3.6 Environmental conditions. The instrument package excluding the sensors and the Analog to Digital Recorders (ADR's) shall be housed in an U.S. Geological Survey instrument shelter that is not heated in the winter nor air conditioned in the summer. The system including the sensor shall operate throughout the range of environmental conditions as follows:

3.6.1 Temperature. Air and water temperatures as follows:

3.6.1.1 Air temperature. From -40°C (-40°F) to 60°C (140°F).

3.6.1.2 Water temperature. From -5°C (20.6°F) to 50°C (122°F).

3.6.2 Relative humidity. From 0 to 100 percent, condensing.

3.6.3 Pressure. From 890 millibar (26.3 in) to 1063 millibar (31.4 in).

3.6.4 Elevation. From -280 feet (Death Valley, Calif.) to 12,000 feet above National Geodetic Vertical Datum of 1929.

3.6.5 Biological fouling. Fouling (plant and animal) and corrosion must meet the requirements specified in test method 811.1 of Fed-STD-151 for corrosion.

3.6.6 Electromagnetic and electrical disturbances. Lightning and other sources of disturbances on powerline, signal line, and electrostatic discharge transients as specified in tests in Section 4.

3.6.7 Airborne sand and dust. 5.0 mg/ft^3 concentration, 74 to 1000 micometers, dust and sand particle size, 3 to 24 mi/h windspeed, and temperature from 23°C (74°F) to 63°C (145°F).

3.6.8 Silt and sand deposits. There can be as much as 0.25-foot deposit of wet silt and sand on top of any sensors placed under the water surface.

3.6.9 Water chemistry. The water pH ranges from 3.5 to 10.5 units. The water conductivity from 5 to 20,000 micromhos per centimeter at 25°C.

3.6.10 Precipitation. Rainfall from 0.1 to 6.0 in/h which can be freezing in winter climates and snowfall from 0.1 to 4.0 in/h.

3.6.11 Solar Radiation. 90 to 115 w/ft^2 insolation with 4.7 to 6.4 w/ft^2 ultraviolet radiation.

3.6.12 Shock, vibration, and noise. The system must be capable of passing MIL-STD-901C and MIL-STD-167B tests. Also the system's output shall not be altered by noise from highway or railroad traffic. The system will be housed in a shelter attached to a highway or railroad bridge. The non-contact type sensor will be attached directly to the bridge.

3.6.13 Plugged orifice condition. In a gas purge system, an automatic pressure relief and reset device is required to protect the system from damage if the orifice becomes restricted or plugged. Mercury systems shall have an overflow reservoir to prevent loss of mercury.

3.7 Storage and transit conditions. The system must be capable of surviving long periods (as much as 24 months) in storage and transport modes and be capable of functioning within specifications when put into the operating mode. The system shall not be damaged when subjected to the following environmental conditions while in storage and/or transport.

3.7.1 Ambient air temperature. From -60°C (-76°F) to 71°C (160°F).

3.7.2 Humidity. From 0 to 100 percent, condensing.

3.7.3 Pressure. From 750 millibar (26.3 in.) to 1063 millibar (31.4 in).

3.7.4 Shock and vibration. Per MIL-STD-901C and MIL-STD-167B.

3.8 Initial calibration. If calibration is required, the stage-sensing system and interface shall be designed to be initially calibrated during installation at the gaging station, by no more than two Survey hydrologic technicians using only a portable 3 1/2 digital volt ohm meter (DVOM) and hand tools. No other electronic test instruments or special power supplies shall be required.

3.9 Recalibration. Intervals between required recalibrations shall not be shorter than 180 days and shall require only one Survey technican with only a portable 3 1/2 DVOM and hand tools.

3.10 Allowable error. Error in stage output is defined as the difference between the true water-surface height above a given datum and that measured simultaneously by the stage-sensing system. The error in the independent measurements (for example, the hook-gage readings) of stage shall be within ± 0.005 feet for error groups B to F and ± 0.001 for group A. Errors caused by non-linear response or drift with time over the period of testing that change the error classification to a lower error range group shall be grounds for classification at the lowest error range group determined by various qualification tests. Maximum range in stage (full scale) and the maximum allowable error is as follows in table I for daily discharge stations and table II for special-case stations. A stage-sensing system shall be unacceptable for qualification if more than 2.50 percent of all check measurements of stage exceed the maximum allowable error listed in table II. In a period of 60 days of controlled laboratory tests at least 100 check measurements of stage will be made. These measurements will be distributed throughout the range of temperature and other Section 4 tests.

TABLE I. Systems Accuracy for Daily Discharge Stations

Range in stage (feet)	Maximum allowable error 1/ (feet)
0-10	± 0.005
0-20	± 0.010
0-35	± 0.018
0-50	± 0.025
0-100	± 0.050
0-200	± 0.100
+ 200	± 0.100

1/ Full-scale error is 0.050 percent for all ranges of less than 200 feet.

TABLE II. Systems Accuracy for Special Case Stations

Range in stage (feet)	Maximum allowable error 2/ (feet)
0-10	± 0.050
0-20	± 0.100
0-35	± 0.180
0-50	± 0.250
0-100	± 0.500
0-200	± 1.000
+ 200	± 1.000

2/ Full-scale error is 0.50 percent for all ranges of less than 200 feet.

3.11 Frequency and duration of data output. The system's stage output shall be current within 5 seconds of the instantaneous value at the time that the ADR punches. The user shall be able to select the frequency of the ADR punch. The frequencies shall be 1, 2, 5, 6, 15, 30, or 60 minutes. If the system is designed to shut down between outputs to conserve power, the duration of each output period shall be a minimum of 25 $\pm$ 1.0 seconds to allow recording by the ADR. If necessary the system shall turn on in advance of the ADR recording interval to insure a stable output and be synchronized with the ADR timer.

3.12 Power system requirements. The following requirements apply to all types of power systems. All power connections shall have polarized connectors and terminal polarity clearly marked. Where terminal strip connectors are used, accidentally reversed connections shall not cause any damage to the system. All fuses and/or circuit breakers shall be mounted on the outside of the instrument case at an accessible location next to the control switches or display panel. They must be sealed so that moisture and water cannot enter the instrument case. The electrical system shall meet all grounding requirements, wiring methods, and materials that are approved for swimming and fountain pools by the National Electrical Code (NEC) of the National Fire Protection Association. When a power supply interruption occurs, the system shall automatically restart within one second after the power is restored.

3.12.1 Voltage-reference batteries. If voltage-reference batteries are required, minimum required voltage output must exceed 180 days of continuous service under the full range of environmental conditions. The battery must be a commerical product available from at least two different U.S. manufacturers.

3.12.2 Dry-cell batteries. If the system, including the interface, has dry-cell batteries, the batteries must provide power for satisfactory operation for at least 180 days of continuous service under the full range of environmental conditions. These batteries shall be standard 6-and/or 12-volt batteries with screw or plug-in terminals, and be a commercial product available from at least two different U.S. manufacturers.

3.12.3 Rechargeable batteries. If the system is equipped with rechargeable batteries, they must provide power for satisfactory operation of at least 75 days of continuous service under the full range of environmental conditions and these batteries shall be easily removed for recharging on a standard a-c charger for that type of battery. These batteries must be a commercial product available from at least two different U.S. manufacturers.

3.12.4 A-c power supply. If the system uses an a-c power supply it shall operate at a maximum of 10 amperes, at 120 volts ac, single phase 60 Hz.

3.12.5 A-c power-supply with rechargeable battery back-up. The a-c power supply shall have the same requirements as 3.12.4. The back-up rechargeable batteries shall be capable of running the system for 14 continous days without a-c power and must be available from at least two different U.S. manufacturers.

3.13 Installation. The system shall be designed so that two but no more than three Survey hydrologic technicans can carry it to the shelter and install the complete system using only hand electric-powered tools and hand tools in an existing appropriate sized gaging-station shelter.

3.14 Maintainability. The system shall be capable of unattended operation of periods of at least 75 continuous days. The system shall be designed so that routine maintenance and service procedures can be performed by one Survey technician on inspection visits. The frequency of required major maintenance procedures shall be no less than 365 days and require no more than two Survey technicians to perform the work.

3.15 Interchangeability. Major system components, interfaces, sensors, and all system modules shall be interchangeable, with like parts and must be available for purchasing from the stage-sensing system manufacturer and/or distributor.

3.16 Safety. The sensors signal output or any part of the system shall not create any safety hazard to the personnel or to the aquatic life. The sensors signal output systems shall create no undesirable signal or condition that is actually or potentially unhealthy to human, animal, or plant life. Maximum allowable electro-magnetic emission shall be the Federal limits for Class A computing device, Federal Communication Commission Rules, Part 15, Subpart J. No toxic or harmful materials are to be released to the environment.

3.17 Workmanship. The system shall be manufactured and finished in such a manner as to meet all the requirements specified herein and shall be free from characteristics or defects which affect the appearance, or which might affect the serviceability or render the system unsuitable for the intended use.

3.18 Qualification. Stage-sensing instrumentation purchased under this specification shall be a product that has been tested in accordance with the qualification test described in section 4 of this specification and has been listed on or approved for listing on the applicable Federal Qualified Products List.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for quality assurance inspection. Unless otherwise specified in the contract or purchase order, the contractor is responsible for the performance of all quality assurance (QA) inspection requirements as specified herein. Except as otherwise specified in the contract or order, the contractor may use his own or any other facilities suitable for the performance of the QA inspection requirements specified herein, unless disapproved by the Government. The Government reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure that supplies and services conform to prescribed requirements.

4.2 Qualification tests. Qualification tests shall consist of all performance tests specified in 4.3.

4.2.1 Place of qualification test. Qualification tests shall be conducted at a Government or a commercial laboratory designated by the Test and Evaluation Section, Hydrologic Instrumentation Facility, Water Resources Division, U.S. Geological Survey.

4.2.2 Sample size for qualification. The sample size for qualification shall be two production models for each classification submitted for qualification No prototype models will be accepted for qualification.

4.2.3 Test conditions. Test conditions to be used are described in detail in the two National Weather Service reports (Section 2).

4.3 Performance tests. The following tests will be performed.

4.3.1 Installation. The instrumentation system will be installed per manufacturer installation manuals by Survey technicians or by a government selected contractor. Unless otherwise specified, the test item shall be installed in the test facility in a manner that will simulate service usage, making connections and attaching ADR and other instrumentation as necessary. Plugs, covers, and inspection plates not used in operation, but used in servicing shall remain in place. When mechanical or electrical connections are not used, the connections normally protected in service shall be adequately covered.

4.3.2 Test data. Test data shall include complete identification of all test equipment and accessories. The data shall include the actual test sequence used and the ambient test conditions recorded periodically during the test period. The test record shall contain a signature and data block for certification of the test data by the test engineer or techician.

4.3.3 Tests. Ambient temperature and relative humidity will be controlled to simulate outdoor conditions throughout the range of requirements listed in Section 3. The tests will subject the system to a total of 60 days of repeated winter weather cycles, summer weather cycles, and periods of constant temperature and relative humidity within Section 3 stated limits of the test conditions. The water surface will be varied throughout the specified range of stage and also held constant for periods of time.

4.3.4 Electrical disturbances. A-c power line transient susceptibility, will be tested in accordance with National Weather Service (NWS) Transient Susceptibility Standard, May, 1978: Test Level 1 with acceptance criteria 3.3(b) stated in the NWS Standard. Signal line transient susceptibility will be tested in accordance with NWS Transient Susceptibility Standard, May, 1978: Cross talk and lightning test with acceptance criteria 3.3(b) stated in the NWS Standard.

4.3.5 Period of time. The system will be tested over a period of 90 days, or longer if necessitated by longer than normal set-up time and/or time needed for repair of laboratory test equipment. The actual time of all the cyclic and static tests will not exceed sixty days for properly operating stage-sensing system submitted for qualification.

4.4 Qualification failure criteria. The system shall have failed the test when any of the following occur:

(1) Monitored functional parameters deviate beyond acceptable specification limits established in Section 3.

(2) Catastrophic or structural failure. The U.S. Geological Survey will not be responsible for damages to units which fail during tests.

(3) Mechanical binding or loose parts including screws, clamps, bolts, and nuts, that clearly result in component failure or a hazard to personnel safety.

(4) Malfunction.

(5) Degradation of performance beyond maximum allowable error specification requirements (Tables I & II).

5. PREPARATION FOR DELIVERY

5.1 Packaging. Packaging shall be level A or Commercial as specified (see 6.1).

5.3 Marking. Unless otherwise specified (see 6.1), marking shall be in accordance with 5.3.1, 5.3.2, and 5.3.3.

5.3.1 Unit packages. Each unit package shall be plainly marked to indicate the name of the article, model number, serial number, dates of manufacture, contract number, and the quantity contained therein.

5.3.2 Intermediate packages. The intermediate packages shall be marked with the following, arranged in this order shown:

A. Item name.

B. Model number.

C. Quantity therein.

5.3.3 Shipping container. Each shipping container shall be marked in an upper right-hand corner on one side panel and one end panel with the following, arranged in the order shown:

A. Item name.

B. Item model number.

C. Quantity therein.

D. Contractor's name and address (and manufacturer's name and address, if different).

E. Contract and purchase or delivery order number.

F. Gross weight and cubic displacement (to the nearest 0.1 of a cubic foot). In addition, shipping containers shall be marked with appropriate exterior caution markings.

5.4 Unitization. When shipment to Government depots are full carload or truckload, the shipping containers shall be unitized to facilitate handling in accordance with normal commercial practice. The unitized load shall not exceed 2,500 pounds, in weight, 63 inches in height, 56 inches in length, and 45 inches in width.

6. NOTES

6.1 Ordering data. Purchasers should select the preferred options permitted herein, and include the following information in procurement documents:

A. Title, number, and date of this specification.

B. Title, number, and date of any other applicable detailed specification.

C. Complete classification listing all characteristics (see Section 1.2.).

D. List any optional equipment covered by qualification.

E. Responsibility for inspection if other than specified (see 4.1).

F. First article quantity, if required.

G. Marking required if other than specified (see 5.3).

H. Specified packaging level (see 5.1).

6.2 Qualification information. With respect to products requiring qualification, awards will be made only for such products as have, prior to the time set for opening of bids, been tested and approved for inclusion in the applicable Qualified Products List whether or not such products have actually been so listed by that date. The attention of suppliers is called to this requirement, and manufacturers are urged to arrange to have the products that they propose to offer to the U.S. Geological Survey, tested for qualification in order that they may be eligible to be awarded contracts or orders for the products covered by this specification. The agency responsible for the Qualified Products List is the U.S. Geological Survey, Water Resources Division, Hydrologic Instrumentation Facility, Test and Evaluation Section, Bldg. 2101, NSTL Station, MS 39529, and information pertaining to qualification of stage-sensing instrumentation may be obtained from the agency.

REFERENCES

1979, Code of Federal Regulation, Title 41, Public Contracts and Property Management, Chapter 1 p. 104-105

1978, Transient Susceptibility Standard, National Weather Service.

1980, National Environmental Testing Criteria and Recommended Test Methodologies for Proposed Standards for National Weather Service Equipment, National Weather Service.

RULES FOR
CLASSIFICATION OF

STEEL SHIPS

MACHINERY AND SYSTEMS
MAIN CLASS

PART 4 CHAPTER 5

INSTRUMENTATION AND AUTOMATION

JANUARY 1985

SECTIONS

PAGE

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SECTION 1
GENERAL REQUIREMENTS

Contents.

A. Classification.

A 100 Application.

101 The requirements in this Chapter are in general to be complied with for all machinery plants where instrumentation is required according to other Chapters of the Rules. In addition, the requirements apply to the following when installed:

- remote control systems for propulsion machinery, controllable pitch propeller, and steering gear.
- safety systems for propulsion plants and electric power generating plants.
- instrumentation equipment of boiler plants.
- instrumentation in other functions as defined in Pt. 1 Ch. 1 Sec. 2.

Note:
The requirements in this Chapter are considered to meet the regulations of the International Convention for the Safety of Life at Sea — 1974 (SOLAS).
Attention should, however, be given to any relevant statutory requirements of the National Authority of the country in which the ship is to be registered.

102 Subject to approval are the systems specified in Section 2, including instrumentation and automation components of the systems, see Section 3. The approval may be either case-by-case approval for each ship, or preferably type approval as specified in Certification Note No. 2.4.

B. Definitions.

B 100 Terms.

101 *Normal conditions* exist when external characteristics such as sea water temperature, quality of fuel oil, loads etc. are within design limits and the entire plant is functioning as intended.

102 *The automatic control systems* comprise all equipment installed to keep variables such as temperatures, pressures, liquid levels, etc. within given limits under normal conditions.

103 *The monitoring systems* comprise alarm and safety systems installed to monitor engine plants and react to abnormal conditions.

104 *The alarm systems* comprise the total systems for warning of abnormal conditions (including sensors, central units and panels, and devices for calling the attention of the personnel).

Alarm is a combined optical and acoustic signal, where the acoustic part calls the attention of personnel, and the optical part serves to identify the fault.

105 *The safety systems* serve to limit the consequences of failures by intervening automatically in the process when abnormal conditions arise, e.g. by starting standby pumps, stopping auxiliary engines, etc.

106 *The indicating and recording systems* give information on the plant's current and preceding state of operation.

107 *The remote control systems* comprise all equipment necessary to operate units from a position where the operator cannot directly observe the effect of his actions. Equipment necessary for remote operation of locally situated manual operating devices is regarded as part of the remote control systems.

108 *The sequence control* provides control of machinery so that necessary operations are automatically carried out in correct sequence and at the correct time.

109 *Manual operation* is an operation where the decisions on initiation and execution are made by the personnel onboard.

110 *Direct manual operation* is as stated in 109, except that the operation can be executed without power aids, i.e. electrical, hydraulic, or mechanical power.

C. Documentation.

C 100 Plans and particulars.

101 The following plans and particulars covering the information stipulated below, are to be submitted in triplicate for approval before installation is commenced. Symbols used are to be explained or reference to a standard code is to be given.
For type approved systems, statement of manufacturer and type, or submission of documentation as stated in the type approval certificate, is adequate.

- *Instrument list* stating manufacturer, type, etc., necessary to identify components, and information on their working ranges and set points.
  Cross references to system drawings (e.g. piping diagram) are to show where each component is located and used in the installation. Data sheets for components may be required.
- *Arrangement and layout.* Plans or diagrams showing the location of sensors, controllers, and actuators in the automatic control and monitoring systems. Arrangement drawings of manoeuvring stand and panels for instruments and controls, outlining the functions of all operating devices, indicating lamps, etc., as well as internal mechanical arrangement.
- *Automatic control systems.* Drawings showing the interconnections between the different units of the system, and description of the working principle.
  Specification of control ranges, showing the ability to cover actual loads and load changes during normal conditions.
- *Systems for remote control, sequence control, and monitoring.* Plans and specifications showing the working principle of these systems. For electromechanical (relay) systems, key diagrams.
  For electronic systems, drawings showing operating principle (data sheets for integrated circuits etc. may be required to the extent necessary for the understanding of the installation).
  For pneumatic systems piping diagram is required.
  Functional block diagram is to be submitted for all systems.

Specifications of normal values and maximum permissible deviations of the monitored parameters may be required.
Power supply. Plans showing power supply to electrical systems, cable type, cable cross sectional area; nameplate data for transformers, rectifiers, batteries, etc. and fuse sizes.
Arrangement of air supply to pneumatic systems, stating dew point, manufacturer and type of compressor, reduction valves, dust filter and moisture filter.
For hydraulic systems, see Ch. 1 Sec. 5.
— *Test programme* for testing of the plant on board, see D.

D. Testing of Plant on Board.

D 100 Test programme.

101 The testing is to be carried out in accordance with a detailed programme, which is to be submitted for approval well in advance of the commencement of the testing. The test programme is to specify in detail how the respective functions are to be tested and what is to be observed during the test.
The tests specified in 200 through 500 are to be included in the test programme.

102 A copy of the approved test programme is to b[e] kept onboard. It is to be completed with final setpoint etc. and endorsed by the Surveyor.

D 200 Monitoring systems.

201 Failure conditions are to be simulated as realisti[c]ally as possible, preferably by letting the monitored parameters pass the alarm and safety limits.
Alarm and safety limits are to be checked.

D 300 Automatic control systems.

301 It is to be verified that the automatic control systems function satisfactorily during normal load changes.

D 400 Remote control systems.

401 Testing of remote control systems is to be carrie[d] out in accordance with test programmes specified in Pt. [6] Ch. 3 to the extent these are applicable.

D 500 Boiler plants.

501 Testing of boiler plants is to be carried out in accordance with test programmes specified in Pt. 6 Ch. 3 t[o] the extent these are applicable.

SECTION 2
SYSTEM DESIGN

Contents.

A. General.

100 Design principles.

101 Redundant systems, e.g. manual operating facilities, are to be installed to the extent necessary for maintaining the manoeuvrability and safe operation of the ship. Switch-over to redundant systems is to be simple, also in event of failure in the control and monitoring systems.

102 Whenever possible, the systems are to be built so that the effects of a single failure can not disperse from one system to others (e.g. by use of selective fusing of electrical distribution systems).

103 Functions which can replace each other (redundant functions), are to be designed so that a failure of one function does not inhibit the operation of the others (e.g. automatic start systems for two or more auxiliary engines).

104 The most probable failures, e.g. loss of power, are to result in the least critical of any possible new conditions (fail to safety).

B. Automatic Control Systems.

100 General.

101 Automatic control systems are to keep process variables within the limits specified for the machinery (the process) during normal working conditions.

102 Physical changes in the process due to wear, fouling of pipes, filters and heat exchangers, changes in the characteristics of control valves, etc. are to be taken into account.

103 The automatic control is to be stable over the entire control range. The margin of stability is to be sufficient to ensure that reasonable variations in the parameters of the controlled process will not cause instability.

C. Alarm Systems.

C 100 Functions and design.

101 Alarm may be required for abnormal conditions which can not be expected to be detected in due time by routine inspection, and when the consequence of a failure is critical.

102 The alarm system is to be independent of the automatic control system so that failure in one of the systems will not inhibit operation of the other system. However, alarm and automatic control functions may be combined in a computer system provided adequate self checking.

103 All alarms are to include acoustic signals. For localization of faults, visual signals are to be applied.

Guidance:
In view of standardizing, visual alarm signals should preferably be red or orange.

104 Alarm signals are to be readily distinguishable from signals from other alarm systems, signals indicating normal conditions, telephone signals and noise.

105 Acoustic signalling devices are to have an acknowledging device for silencing. After acknowledgement, the acoustic signalling device is to operate for any new failure.

106 Acoustic signals are to be audible in all parts of the machinery space.

Guidance:
Several suitably placed low volume acoustic alarm units should preferably be used rather than a single unit for the whole area. A combination of acoustic signals and rotating light signals may be of advantage.

107 Execution of performance tests of the alarm system are to be possible during operation.

108 Permanent switch-off of alarm units is not to be possible. In particular cases, however, partial disconnection may be accepted provided optical warning signal is given.

109 The more frequent failures within the alarm system, such as broken connections to measuring elements, are to release alarm (normally closed circuit).

110 Interlocking of alarms is to be arranged so that broken connection in external wiring does not prevent alarms.

D. Safety Systems.

D 100 Functions and design.

101 A safety system can be required when dangerous conditions can not be expected to be counteracted by manual intervention, e.g. if the process is distant from personnel on duty.

102 The safety system is to be independent of the automatic control system. However, safety and automatic control functions may be combined in one computer system provided adequate self checking.

103 When the safety system stops a unit, the unit is not to start again automatically.

104 When a safety system is made inoperative by a manual override, this is to be clearly indicated.

105 The number of automatically repeated starting attempts is to be limited.

106 When the safety system has been activated, it is to be possible by means of central or local indicators to trace the cause of the safety action.

E. Indicating and Recording Systems.

E 100 General.

101 Indicating instrumentation sufficient to allow safe operation of the machinery is to be installed at all control stands in the engine room. Alarms are not considered as substitutes for indicating instruments for this purpose.

Guidance:
It is advised that indicating and recording instruments are centralized and arranged to facilitate watch-keeping, e.g. by standardizing the scales, applying mimic diagrams, etc.

F. Remote Control Systems.

F 100 General.

101 At the remote control station, the operator is to receive continuous information on the effects of his orders.

102 The manoeuvring procedure is to consist of simple operations.

103 When machinery can be remotely controlled from more than one position, a system of preference is to be applied in order to prevent simultaneous operation from different positions.
Switchover from bridge control to engine room control or vice versa is only to be possible from the engine room.

F 200 Bridge control of diesel propulsion machinery.

201 Orders from the bridge are to be indicated in the control room.

202 There are to be means for stopping of the propulsion machinery from the bridge independent of the normal remote control system.

203 For reversible engines, both speed and direction of rotation are to be indicated on the bridge. For controllable pitch propeller plants, propeller pitch and speed of rotation are to be indicated on the bridge.

204 In addition to the system for remote control from the bridge, there is to be a standby system for control from the engine room. This system is as far as possible to be independent of the bridge system. Switchover to the standby control system is to be possible by simple operations at the control station of the standby system. Switchover is to be independent of the condition of the remote control system.

205 A communication system is to be provided between the bridge and the engine room manoeuvring place.

206 Remote start of the propulsion machinery is to be inhibited when the turning gear is engaged.

207 If the safety system includes automatic fuel shutoff or load reduction of the engine, cancelling of this action is to be possible by means of an emergency device on the bridge. The emergency device is to be so designed that unintentional operation is prevented. It is to be impossible to leave the device in operated position without this being clearly indicated.
Cancelling of load reduction can be omitted if the manoeuvrability is maintained.
Automatic shutoff by overspeed or by loss of lubricating oil pressure can be accepted without cancelling possibility being provided.

208 Overload is to be indicated if automatic load lim tation is not provided.

209 The design of the remote control system shall b such that in case of a failure in external circuitry or p wer supply an alarm will be given.
Where practical the preset speed and direction of thru shall be maintained until local control is in operation.

210 Operations following an arbitrary setting of th manoeuvring device, are to take place in a sequence an with time intervals normally acceptable to the machiner The programmed systems are to prevent erroneous ma noeuvres, e.g. fuel supply is to be shutoff when there no agreement between:

— desired and actual direction of rotation of the engine
— desired direction of rotation and camshaft position.

211 The number of possible automatic restart attemp is to be limited in order to ensure that sufficient quanti of starting air will be left for 6 manual starts. The air cor sumption of each starting attempt is to be limited.
Alarm is to be released on the bridge and in the engir room at starting failure.

212 For ships less than 2000 tons gross, some of th normally programmed operations may instead be carrie out manually.
It is to be prevented that the starting air receivers ar emptied by faulty operations.

F 300 Bridge control of steam turbine propulsion plants.

301 Operations following an arbitrary setting of th manoeuvring device, are to take place in a sequence an with time intervals normally acceptable to the boile and turbines.
The sequence control system is to be so designed that e roneous operations are prevented.

Guidance:
As to manoeuvring devices on the bridge, setting of speed an direction of rotation should be effected by means of a sing control lever.

302 Propulsion machinery manoeuvrable from th bridge, is also to be manoeuvrable from the monitorin centre in the engine room. The machinery is further to b directly and manually manoeuvrable from the engi room, regardless of the position or condition of the re mote control system. When direct manual manoeuvrin can be conveniently carried out from the monitoring cen tre, no other local manoeuvring possibility is required.

303 Requirements in 201, 202, 205, 206 and 209 apply.

F 400 Bridge control of gas turbine propulsion plants.

401 Operations following an arbitrary setting of th manoeuvring device, are to take place in sequence wit time intervals normally acceptable to the turbine, and th programme is to prevent erroneous manoeuvres.

402 Restart and restoring of normal conditions afte turbine trip are to be easily carried out after trip condi tion has been eliminated.

Guidance:
As to manoeuvring devices on the bridge, setting of r.p.m. an direction of rotation should be affected by means of a singl control lever.

403 Propulsion machinery manoeuvrable from th bridge, is also to be manoeuvrable from the monitorin centre. The machinery is further to be directly manoeuvr able from the engine room, regardless of the position an state of the remote control system. When direct manua manoeuvring can be conveniently carried out from th monitoring centre, no other local manoeuvring possibili ty is required.

404 Requirements in 201, 202, 205, 206 and 209 apply.

G. Sequence Control Systems.

100 General.

101 Sequence control systems are to ensure correct operations in the correct sequence and at correct intervals. If erroneous sequence of operation can cause damage, pure time-dependent operations are not to be applied.
Requirements for sequence control of boilers having automatic ignition of burners, see Pt. 4 Ch. 3.

H. Indication and Transfer of Responsibility.

I 100 General.

101 The system are to allow no possibility for misunderstanding as to which station is in charge of watch-keeping and control.
At all main monitoring and control stations there is to be a continuous indication of which station is in charge.
When responsibility is transferred from one main station to another, the system is to give appropriate warning.
Acknowledgement of transfer is only to be possible from the station which takes charge of the watch-keeping or control.
Local control stations are not considered as main stations.

I. Computer Based Systems.

I 100 General.

101 If a failure in a computer based system may affect the safety of the ship, the Society will specify requirements concerning:

— Documentation.
— System design principles.
— Testing.
— Spare parts.

For further details, see Classification Note No. 14, Instrumentation and Automation, Computer Based Systems.

SECTION 3
COMPONENT DESIGN AND INSTALLATION

Contents.

A. General.

A 100 Environmental strains.

101 The equipment is to be suitable for marine use, and is normally to be designed to operate under environmental conditions as described in B.

102 Data sheets, sufficiently detailed to ensure proper application of the instrumentation equipment, are to be available.

103 Performance and environmental testing may be required to ascertain the suitability of the components.

A 200 Materials.

201 Explosive materials and materials which may develop toxic gases, are not to be used. Covers, termination boards, printed circuits cards, constructive elements and other parts which may contribute to spreading fire, are to be of flame-retardant material.

Guidance:
Materials with a high resistance to corrosion and ageing should be used. Metallic contact between different materials should not cause electrolytic corrosion in a marine atmosphere.
As base material for printed circuit cards, glass-reinforced epoxy resin or equivalent should be used. Printed circuit cards should be preserved by a moisture protecting coating.

A 300 Component design and installation.

301 The component design and installation is to be so that operation, adjustment, repair and replacement are facilitated. As far as practicable, screw connections are to be secured.

302 Mechanical resonances with amplification greater than 10 are not to occur.

303 The temperature inside control stands, cabinets, etc. is not to exceed the ambient temperature by more than 5°C, unless all equipment within the enclosure is designed for temperature class B (see B 400).

304 Electric cables and components are to be effectively separated from all equipment, which, in case of leakage, could cause damage to the electrical equipment. In desks, consoles and switchboards, which contain electrical equipment, pipes and equipment conveying oil, water or other fluids or steam under pressure are to be built into a separate section with drainage.

305 Means are to be provided for preventing moisture (condensate) to accumulate inside the equipment, also when the plant is shut down.

306 Differential pressure elements (dp-cells) are to be able to sustain a pressure differential at least equal to the highest process pressure.

307 Thermometer wells are to be used when measuring temperature in fluids, steam or gases under pressure.

308 The installation of temperature sensors is to permit easy dismantling for functional testing.

309 Clamps used to secure capillary tubes are to be made of a material which is softer than the tubing.

310 Analogue temperature measuring circuits are to be provided with means for compensating changes in wire resistance.

311 Three-way cocks or other suitable arrangement for functional testing are to be mounted in the connections between pressure transducers and process.

312 Maintenance, repair and performance test of systems and components are as far as practicable to be possible without affecting the operation of other systems or components.

A 400 Maintenance, checking.

Guidance:
The installation should as far as possible be built up from easily replaceable units and designed for easy troubleshooting, checking and maintenance. When a spare unit is mounted, only minor adjustments/calibrations of the unit should be necessary.
Faulty replacements should not be possible.

A 500 Marking.

501 All units, terminal strips, cable ends and test points are to be clearly and permanently marked. Transducers, controls and actuators are to be marked with their system function, so that they can be easily and clearly identified on plans and in instrument lists.

Guidance:
The marking of system function should preferably not be placed on the unit itself, but adjacent to it.

A 600 Standardizing.

Guidance:
Systems, components and signals should be standardized as far as practicable.

B. Environmental Conditions.

B 100 General.

101 The environmental parameters given in 200 to 1200, including any of their combinations, represent «average adverse» conditions, which will cover the majority of applications on board ships. Where environ-

mental strains will exceed those specified, special arrangements and special components will have to be considered.

102 Table B1 states the parameter class for the different environmental zones on board.

Table B1 Parameter class for the different environmental zones on board.

Parameter	Class	Location
Temperature	*A*	Machinery spaces, control rooms, accommodation, bridge
	B	Inside cubicles, desks, etc. with temperature rise of 5°C or more
	C	Pump rooms, holds, rooms with no heating
	D	Open deck, masts
Humidity	*A*	Locations, where special precautions are taken to avoid condensation
	B	All locations except as mentioned under A
Vibration	*A*	On bulkheads, beams, deck, bridge
	B	On machinery such as internal combustion engines. Compressors, pump including piping on such machinery
	C	Masts

Components and systems designed in compliance with IEC environmental specifications for ships, Publication No. 92—504 (1974), may be accepted after consideration.

B 200 Electric power supply

201 Successive power breaks with full power between breaks.

202 Nominal voltage +10%, −15% (stationary). Voltage transients (up to 2 sec. duration) ±20% of nominal.

203 For battery power sources: Nominal voltage ±17% (stationary).
Voltage transients (up to 2 sec. duration) ±20% of nominal.

204 For A.C. systems: Nominal frequency ±5% (stationary).
Frequency transients (up to 2 sec. duration) ±15% of nominal.

B 300 Pneumatic and hydraulic power supply.

301 Nominal pressure ±20% (long and short time deviations).

B 400 Temperature.

401 *Class A:*
Ambient temperatures +5°C to +55°C.

402 *Class B:*
Ambient temperatures +5°C to +70°C.

403 *Class C:*
Ambient temperatures −25°C to +55°C.

404 *Class D:*
Ambient temperatures −25°C to +70°C.

B 500 Humidity.

501 *Class A:*
Relative humidity up to 96% at all relevant temperatures.
Temperature and humidity cycling.

502 *Class B:*
Relative humidity up to 100% condensation. Temperature and humidity cycling.

B 600 Salt contamination.

601 Salt-contaminated atmosphere up to 1 mg salt per m³ of air, at all relevant temperatures and humidity conditions.

B 700 Oil contamination.

701 Mist and droplets of fuel and lubricating oils. Oily fingers.

B 800 Acceleration.

801 Acceleration caused by the ship's movement in waves. Peak accelerations ±1,0 g for ships with length less than 90 metres, and ±0,6 g for ships of greater length. Period 5—10 sec.

B 900 Vibrations.

901 *Class A:*
Frequency range; 5—50Hz.
Vibration velocity amplitude: 20 mm/sec.

902 *Class B:*
Frequency range: 5—80 Hz.
Vibration level: 5—30 Hz: 100 mm/sec.
30—80 Hz: 1,9 g.

903 *Class C:*
Frequency range: 3—30 Hz.
Vibration velocity amplitude: 100 mm/sec.

B 1000 Inclination.

1001 Inclination up to 40° from vertical.

B 1100 Cable insulation.

1101 Inferior cable insulation resistance down to 200 k Ω.

B 1200 Miscellaneous.

1201 In particular applications other environmental parameters may influence the equipment, e.g.:

— fire
— explosive atmosphere
— temperature shock
— wind, rain dust
— radiation
— acoustic noice
— mechanical shock/bump forces equivalent to 20 g of 10 ms duration
— splash and drops of liquid
— corrosive atmospheres of various composition, e.g. ammonia on an ammonia carrier
— electromagnetic noise.

C. Electrical and Electronic Equipment.

C 100 General.

101 Fused isolating transformers are to be fitted between the main power supply and the different unit/systems.

102 The switching on and off of the power supply is not to cause excessive voltage or other strains which may damage internal or external components.

103 Units requiring insulating resistance in cables and wirings higher than 200 kΩ, are normally not to be used. Exceptions can be made for special cable arrangements.

Guidance:
Due consideration should be given to interference signals, electrical noise etc.

C 200 **Mechanical design. Installation.**

Guidance:
Circuits should be designed to prevent damage of the unit or adjacent elements by internal or external failures. No damage should occur when the signal transmission line between measuring elements and other units are short-circuited, grounded or broken. Such failures should lead to a comparatively safe condition (fail to safety).

Guidance:
The equipment should preferably function without forced cooling. Where such cooling is necessary, precautions should be taken to prevent the equipment from being damaged in case of failure of the cooling unit.

201 The components are to be effectively secured to avoid mechanical stressing of wires and soldered joints through vibrations and mechanical shock. Components weighing more than 10 grammes (0,35 oz), are not to be fastened by their connecting wires only.

C 300 **Protective covering.**

301 Covering of the equipment is to satisfy the minimum requirements of the table below. The required degree of protection is specified in IEC 529 (International Electrotechnical Commission, Publication No. 529).

Class	Location	Degree of protection
A	Control rooms, accommodation, bridge	IP 22
B	Engine room	IP 44
C	Open deck, masts below floor plates in engine room	IP 56
D	Submerged application, bilges	IP 68

Protection of the equipment itself as specified above may be dispensed with when the equipment is installed in consoles or desks providing the required protection.

C 400 **Cables and wires.**

401 Cables and wires satisfying the requirements of Pt. 4 Ch. 4 will normally be accepted in instrumentation systems.
Stranded conductors are to be used in external wiring, and in desks and cabinets where movement of the wiring must be expected.

402 The conductor cross sectional area of external cables and wires is not to be less than 0,5 mm^2. This requirement also applies to internal cables and wires where movement of the wiring must be expected.

403 The weight of the wire or cable between a soldered connection and the nearest point of fastening is to be less than 10 grammes.

C 500 **Cable installation.**

501 Cable entries and terminals are to allow the use of approved types of ship cables.

502 Cable entries are to comply with the enclosure requirements specified in 301.

503 Screw type terminals where the screw is applied directly against the conductor are normally not accepted.

504 Cable terminations and connectors are to be secured against loosening by vibration.

505 Equipment with supply voltages higher than 30 volts A.C. or higher than 50 volts D.C., is to have a terminal for earthing the exposed metal parts.

506 Permanent cabling can be terminated in close vicinity of the equipment. A more flexible cable may then be used between the terminal box and the equipment.

507 Terminal boxes in the engine room are to be mounted with cable entry from the sides or bottom. When entering from the side, the cables are to be arranged with a downwards loop which will prevent penetration of liquids through the cable entry.
Cable entry from the top may be approved if satisfactory drip-proofing is arranged, e.g. by use of a cover plate above the terminal box and a downwards loop in the cable.

508 Cable clamps are to be made of metallic material (or plactic-covered metal).
Exceptions can be made where the cables are placed so that they will not drop out of position when the clamps are removed.

509 Cables are to be secured with a spacing between fixing points according to Ch. 4 and are to be installed according to this section.

Guidance:
At the equipment, the cable can be terminated by use of regular terminals, plugs or sockets, or the cable can be moulded into the units.
Where maintenance work requires disconnection of cables, proper wiring diagrams should be provided, preferably attached to the inside of removable coverings, doors, etc.

C 600 **Power supply.**

601 When using low voltage (less than 50 volt) battery supply, the charging equipment, batteries and cables are to keep the voltage at equipment terminals within ± 17% of the nominal voltage during charging and discharging.

602 Systems including a standby battery connected for continuous charging are not to be disturbed in any way by disconnection of the battery.

603 Battery installations are to be in accordance with Ch. 4.

604 Regulated rectifiers are to be designed for the variations in voltage and frequency stated in B.

605 Different system voltages are to be supplied through different cables.

606 Terminal lists are to be clearly marked. Various system voltages are to be distinguished.

D. Pneumatic and Hydraulic Equipment.

D 100 **Pipe materials.**

101 Signal pipes are to be of metallic materials. In pneumatic systems, pipes of plastic materials may be accepted as specified in 203.

D 200 **Pneumatic equipment.**

201 Components requiring extremely clean air are not to be used. Extremely small openings in air passages are to be avoided.

202 Main pipes are to be inclined relative to the horizontal, and drainages are to be arranged.

203 Pipes and other equipment made of plastic materials is accepted if they have satisfactory mechanical strength, low thermoplasticity, high oil resistance, and flame retardency.
For application see Pt.4 Ch.1 Sec. 2 C 700, Plastic pipes.

D 300 **Pneumatic power supply.**

301 Air supply may be taken from the starting air receiver, if the main engine is not used for charging. If a separate power supply is arranged for the instrumentation system, there are to be two separate compressors or one compressor with alternative air supply from the starting air receiver. To compensate for leakages in the system separate compressors are each to have a capacity of at least 1,2 times the calculated consumption. Reduction valves and filters are to be duplicated when serving more than one function (for instance more than one control loop).

302 Air to instrumentation equipment is to be free from oil, moisture and other contaminants. Condensation is not to occur at relevant pressures and temperatures. The dew point is to be below 5°C for air flowing in pipes which are located entirely inside engine room and accommodation. The dew point of air flowing in pipes on open deck is to be below −25°C.

303 For lubricating purposes the air for slide valves, power cylinders and other units with sliding surfaces is to be oil-mist injected. However, this is not required when the sliding surface is self-lubricating or when special materials not requiring lubrication, are used. Special care is to be taken to prevent air from this system from leaking into air systems requiring dry and clean air.

D 400 Hydraulic equipment.

401 System components and arrangement are to satisfy the requirements of Ch. 1.

APPENDIX B

Analysis of cargo tank distortion during load/ballast operations

PROCEDURAL SUMMARY OF FINITE ELEMENT ANALYSIS

A finite element analysis of oil tanker structure was undertaken to determine the magnitude of tank volume change due to changes in loading conditions. The center tank bulkheads of two tankers, a 400,000 dwt VLCC and a 77,000 dwt lightering ship, were modeled a finite element program to determine deflections caused by a common situation in tank loading, which is from a net load of zero on the bulkhead to one where one side only is fully loaded. The initial condition may be both tanks full or empty.

The program used was Engineering Mechanics Research Corporation's NISA II, version 90.0. The longitudinal bulkheads which form the tank boundaries were broken down into panels that were modeled individually. The panels are bounded by horizontal girders and major transverse stiffener frames. A grid of panels is thus formed, one of which is modelled and analyzed at each horizontal row on the assumption of uniformity within each row.

All elements used in the models were of the "thin shell" type (NISA II type 40). The reasons for this are that the aspect ratio of the plate elements (length of the longest side divided by thickness) was far too large to be in the "solid" element's range of reliable accuracy in the computation of deflections and stresses and that the thin shell elements made it easier to model the plate/stiffener combinations.

The scenario is as follows: a tanker, loaded to capacity, unloads its cargo until a center tank remains full while all of the surrounding tanks are empty. The tank oil level, which was originally at 98% capacity, will drop slightly due to the now unimpeded hydrostatic pressure of the oil against the tank walls. The resulting change in the oil level is desired result.

The assumptions used are the following. The loading was assumed to be hydrostatic, with uniform pressure across each horizontal row of plate elements. The cargo oil was assumed to have a specific gravity of 0.9. The edges of the plate were held fixed (0 degrees of freedom) because they are rigidly attached to very large girders in the ship. The vertices of the stiffeners, at the end points, are also held fixed for the same reason. The ends of the flanges are free to move and rotate, as indicated by the shipbuilders drawings.

Web frames and horizontal girders are assumed fixed (no deflection). Deflections in the end bulkheads are ignored since they will contribute relatively small changes in the tanks' volumes. As these assumptions are both conservative, the results for both the changes in tank volume and liquid level will tend likewise.

The results of the program runs were obtained. The contours of deflections were printed in color, and the numerical values of the nodal displacements were obtained and printed. The nodal displacements were numerically integrated to determine the volume changes.

A sample nodal displacement output is given, as well as the color graphics of "Z" deflections for each panel analyzed.

APPENDIX B

****** DISPLACEMENT SOLUTION ******

LOAD CASE ID NO. 1

NODE	UX	UY	UZ	ROTX	ROTY	ROTZ
1	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
2	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
3	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
4	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
5	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
6	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
7	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
8	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
9	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
10	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
11	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
12	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
13	2.92328E-05	1.99538E-05	2.52620E-03	4.65334E-03	-5.47754E-04	0.00000E+00
14	3.69040E-05	2.49509E-06	3.01989E-03	6.09485E-03	-1.18440E-04	0.00000E+00
15	3.59915E-05	-1.16749E-05	3.22679E-03	6.46271E-03	-9.01620E-05	0.00000E+00
16	2.13597E-05	-1.98565E-05	3.36958E-03	6.87112E-03	-4.77322E-05	0.00000E+00
17	-6.63561E-19	-2.25860E-05	3.42318E-03	6.99572E-03	1.30517E-17	0.00000E+00
18	-2.13597E-05	-1.98565E-05	3.36958E-03	6.87112E-03	4.77322E-05	0.00000E+00
19	-3.59915E-05	-1.16749E-05	3.22679E-03	6.46271E-03	9.01620E-05	0.00000E+00
20	-3.69040E-05	2.49509E-06	3.01989E-03	6.09485E-03	1.18440E-04	0.00000E+00
21	-2.92328E-05	1.99538E-05	2.52620E-03	4.65334E-03	5.47754E-04	0.00000E+00
22	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
23	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
24	6.64427E-05	3.39535E-05	4.69899E-03	6.18309E-04	-1.31879E-03	0.00000E+00
25	9.43361E-05	3.51951E-06	6.05783E-03	1.69219E-03	-4.45496E-04	0.00000E+00
26	8.60216E-05	-2.03909E-05	6.70767E-03	2.33295E-03	-3.49421E-04	0.00000E+00
27	4.86582E-05	-3.39385E-05	7.17809E-03	2.88399E-03	-1.98589E-04	0.00000E+00
28	-1.74083E-18	-3.88841E-05	7.34759E-03	3.06238E-03	4.30286E-17	0.00000E+00
29	-4.86582E-05	-3.39385E-05	7.17809E-03	2.88399E-03	1.98589E-04	0.00000E+00
30	-8.60216E-05	-2.03909E-05	6.70767E-03	2.33295E-03	3.49421E-04	0.00000E+00
31	-9.43361E-05	3.51951E-06	6.05783E-03	1.69219E-03	4.45496E-04	0.00000E+00
32	-6.64427E-05	3.39535E-05	4.69899E-03	6.18309E-04	1.31879E-03	0.00000E+00
33	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
34	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
35	1.27216E-04	3.91876E-05	3.40279E-03	-3.72115E-03	-1.59034E-03	0.00000E+00
36	1.82032E-04	3.06573E-06	5.17907E-03	-3.40674E-03	-5.43596E-04	0.00000E+00
37	1.50353E-04	-2.31740E-05	6.33622E-03	-2.77608E-03	-5.36662E-04	0.00000E+00
38	8.48114E-05	-4.09989E-05	7.15080E-03	-2.30735E-03	-3.30776E-04	0.00000E+00
39	-3.68639E-18	-4.69444E-05	7.44166E-03	-2.15642E-03	6.21327E-17	0.00000E+00
40	-8.48114E-05	-4.09989E-05	7.15080E-03	-2.30735E-03	3.30776E-04	0.00000E+00
41	-1.50353E-04	-2.31740E-05	6.33622E-03	-2.77608E-03	5.36662E-04	0.00000E+00
42	-1.82032E-04	3.06573E-06	5.17907E-03	-3.40674E-03	5.43596E-04	0.00000E+00
43	-1.27216E-04	3.91876E-05	3.40279E-03	-3.72115E-03	1.59034E-03	0.00000E+00
44	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
45	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
46	2.63288E-04	2.90342E-05	1.41025E-03	1.64663E-04	-2.72082E-03	-1.07265E-04
47	2.91627E-04	8.94179E-06	3.21669E-03	5.23822E-04	-1.15116E-03	-9.59004E-05
48	2.36934E-04	-1.92864E-05	4.78433E-03	7.19887E-04	-7.70044E-04	-6.93346E-05
49	1.29941E-04	-3.83224E-05	5.84734E-03	8.90270E-04	-4.17477E-04	-4.57310E-05
50	-8.29959E-18	-4.48028E-05	6.22018E-03	9.41055E-04	5.04731E-17	-2.10500E-17
51	-1.29941E-04	-3.83224E-05	5.84734E-03	8.90270E-04	4.17477E-04	4.57310E-05
52	-2.36934E-04	-1.92864E-05	4.78433E-03	7.19887E-04	7.70044E-04	6.93346E-05
53	-2.91627E-04	8.94179E-06	3.21669E-03	5.23822E-04	1.15116E-03	9.59004E-05

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****** DISPLACEMENT SOLUTION - LOAD CASE ID NO. 1 (CONTINUED) ******

NODE	UX	UY	UZ	ROTX	ROTY	ROTZ
54	-2.63288E-04	2.90342E-05	1.41025E-03	1.64663E-04	2.72082E-03	1.07265E-04
55	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
56	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
57	1.62252E-04	1.78574E-05	3.72571E-03	4.22827E-03	-1.99693E-03	0.00000E+00
58	2.40029E-04	1.30984E-05	6.10095E-03	4.98234E-03	-7.78135E-04	0.00000E+00
59	2.07386E-04	-1.45216E-05	7.69072E-03	5.04669E-03	-7.72217E-04	0.00000E+00

60	1.18531E-04	-3.27811E-05	8.82926E-03	5.16352E-03	-4.49298E-04	0.00000E+00
61	-3.14477E-18	-3.92207E-05	9.23309E-03	5.19633E-03	1.95605E-17	0.00000E+00
62	-1.18531E-04	-3.27811E-05	8.82926E-03	5.16352E-03	4.49298E-04	0.00000E+00
63	-2.07386E-04	-1.45216E-05	7.69072E-03	5.04669E-03	7.72217E-04	0.00000E+00
64	-2.40029E-04	1.30984E-05	6.10095E-03	4.98234E-03	7.78135E-04	0.00000E+00
65	-1.62252E-04	1.78574E-05	3.72571E-03	4.22827E-03	1.99693E-03	0.00000E+00
66	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
67	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
68	1.45728E-04	1.86234E-05	5.48148E-03	1.58068E-05	-2.22995E-03	0.00000E+00
69	2.21745E-04	7.82822E-06	8.15632E-03	3.16387E-05	-9.87031E-04	0.00000E+00
70	2.07211E-04	-1.32019E-05	9.77691E-03	6.44721E-05	-9.09535E-04	0.00000E+00
71	1.18089E-04	-2.97866E-05	1.09722E-02	1.01036E-04	-4.97438E-04	0.00000E+00
72	-4.10956E-19	-3.58063E-05	1.13963E-02	1.08344E-04	-2.30298E-17	0.00000E+00
73	-1.18089E-04	-2.97866E-05	1.09722E-02	1.01036E-04	4.97438E-04	0.00000E+00
74	-2.07211E-04	-1.32019E-05	9.77691E-03	6.44721E-05	9.09535E-04	0.00000E+00
75	-2.21745E-04	7.82822E-06	8.15632E-03	3.16387E-05	9.87031E-04	0.00000E+00
76	-1.45728E-04	1.86234E-05	5.48148E-03	1.58068E-05	2.22995E-03	0.00000E+00
77	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
78	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
79	1.75250E-04	1.99065E-05	3.74408E-03	-4.21170E-03	-2.02852E-03	0.00000E+00
80	2.61368E-04	2.32807E-06	6.14339E-03	-4.92706E-03	-7.70467E-04	0.00000E+00
81	2.29755E-04	-1.17448E-05	7.78036E-03	-4.94021E-03	-8.04507E-04	0.00000E+00
82	1.32675E-04	-2.58413E-05	8.95955E-03	-5.00075E-03	-4.57779E-04	0.00000E+00
83	2.38060E-18	-3.10952E-05	9.37771E-03	-5.02248E-03	-4.19627E-17	0.00000E+00
84	-1.32675E-04	-2.58413E-05	8.95955E-03	-5.00075E-03	4.57779E-04	0.00000E+00
85	-2.29755E-04	-1.17448E-05	7.78036E-03	-4.94021E-03	8.04507E-04	0.00000E+00
86	-2.61368E-04	2.32807E-06	6.14339E-03	-4.92706E-03	7.70467E-04	0.00000E+00
87	-1.75250E-04	1.99065E-05	3.74408E-03	-4.21170E-03	2.02852E-03	0.00000E+00
88	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
89	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
90	2.91992E-04	9.98180E-06	1.42956E-03	-2.03563E-04	-2.83882E-03	-5.02821E-05
91	3.38770E-04	5.62503E-06	3.29266E-03	-4.69648E-04	-1.18532E-03	-3.73927E-05
92	2.85361E-04	-6.38192E-06	4.92868E-03	-6.91699E-04	-8.78937E-04	-2.67912E-05
93	1.60199E-04	-1.71646E-05	6.04793E-03	-8.45674E-04	-4.63674E-04	-2.15987E-05
94	8.48624E-18	-2.13140E-05	6.44193E-03	-9.03391E-04	-1.33466E-17	4.93245E-17
95	-1.60199E-04	-1.71646E-05	6.04793E-03	-8.45674E-04	4.63674E-04	2.15987E-05
96	-2.85361E-04	-6.38192E-06	4.92868E-03	-6.91699E-04	8.78937E-04	2.67912E-05
97	-3.38770E-04	5.62503E-06	3.29266E-03	-4.69648E-04	1.18532E-03	3.73927E-05
98	-2.91992E-04	9.98180E-06	1.42956E-03	-2.03563E-04	2.83882E-03	5.02821E-05
99	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
100	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
101	1.79015E-04	7.90152E-07	3.48642E-03	3.98840E-03	-1.90525E-03	0.00000E+00
102	2.67042E-04	9.09509E-06	5.65536E-03	4.51041E-03	-6.27570E-04	0.00000E+00
103	2.35942E-04	-1.30389E-06	7.10405E-03	4.41422E-03	-7.08416E-04	0.00000E+00
104	1.36852E-04	-8.83177E-06	8.15955E-03	4.41368E-03	-3.99582E-04	0.00000E+00
105	2.18390E-18	-1.18326E-05	8.53140E-03	4.40667E-03	2.96654E-19	0.00000E+00
106	-1.36852E-04	-8.83177E-06	8.15955E-03	4.41368E-03	3.99582E-04	0.00000E+00
107	-2.35942E-04	-1.30389E-06	7.10405E-03	4.41422E-03	7.08416E-04	0.00000E+00
108	-2.67042E-04	9.09509E-06	5.65536E-03	4.51041E-03	6.27570E-04	0.00000E+00
109	-1.79015E-04	7.90152E-07	3.48642E-03	3.98840E-03	1.90525E-03	0.00000E+00
110	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00

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****** DISPLACEMENT SOLUTION - LOAD CASE ID NO. 1 (CONTINUED) ******

NODE	UX	UY	UZ	ROTX	ROTY	ROTZ
111	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
112	1.53957E-04	4.06408E-06	5.16914E-03	5.79462E-05	-2.08501E-03	0.00000E+00
113	2.34573E-04	4.20362E-06	7.58150E-03	1.11116E-04	-8.33338E-04	0.00000E+00
114	2.21275E-04	-2.11675E-07	9.01129E-03	1.68016E-04	-8.29571E-04	0.00000E+00
115	1.27562E-04	-5.06809E-06	1.00906E-02	2.06096E-04	-4.44056E-04	0.00000E+00
116	-8.06379E-19	-7.04659E-06	1.04698E-02	2.19925E-04	3.86348E-17	0.00000E+00
117	-1.27562E-04	-5.06809E-06	1.00906E-02	2.06096E-04	4.44056E-04	0.00000E+00
118	-2.21275E-04	-2.11675E-07	9.01129E-03	1.68016E-04	8.29571E-04	0.00000E+00
119	-2.34573E-04	4.20362E-06	7.58150E-03	1.11116E-04	8.33338E-04	0.00000E+00
120	-1.53957E-04	4.06408E-06	5.16914E-03	5.79462E-05	2.08501E-03	0.00000E+00
121	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
122	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
123	1.76401E-04	8.02927E-06	3.54761E-03	-3.98139E-03	-1.91255E-03	0.00000E+00
124	2.62948E-04	-3.83172E-07	5.75985E-03	-4.53029E-03	-6.75947E-04	0.00000E+00

125	2.33059E-04	6.63652E-07	7.25549E-03	-4.43573E-03	-7.50425E-04	0.00000E+00
126	1.35423E-04	-1.67534E-06	8.34616E-03	-4.44010E-03	-4.20355E-04	0.00000E+00
127	-4.05662E-18	-2.70278E-06	8.73078E-03	-4.43496E-03	7.04907E-17	0.00000E+00
128	-1.35423E-04	-1.67534E-06	8.34616E-03	-4.44010E-03	4.20355E-04	0.00000E+00
129	-2.33059E-04	6.63652E-07	7.25549E-03	-4.43573E-03	7.50425E-04	0.00000E+00
130	-2.62948E-04	-3.83172E-07	5.75985E-03	-4.53029E-03	6.75947E-04	0.00000E+00
131	-1.76401E-04	8.02927E-06	3.54761E-03	-3.98139E-03	1.91255E-03	0.00000E+00
132	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
133	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
134	2.84292E-04	1.05718E-06	1.37245E-03	-1.34344E-04	-2.72152E-03	-6.01860E-05
135	3.31035E-04	3.66514E-06	3.15883E-03	-2.81166E-04	-1.11094E-03	-3.81614E-05
136	2.79855E-04	5.17582E-06	4.72791E-03	-4.11263E-04	-8.34506E-04	-2.48461E-05
137	1.57635E-04	5.52310E-06	5.80171E-03	-5.13196E-04	-4.34633E-04	-1.96067E-05
138	-1.06707E-17	5.51203E-06	6.17974E-03	-5.49364E-04	5.72633E-17	-3.44882E-17
139	-1.57635E-04	5.52310E-06	5.80171E-03	-5.13196E-04	4.34633E-04	1.96067E-05
140	-2.79855E-04	5.17582E-06	4.72791E-03	-4.11263E-04	8.34506E-04	2.48461E-05
141	-3.31035E-04	3.66514E-06	3.15883E-03	-2.81166E-04	1.11094E-03	3.81614E-05
142	-2.84292E-04	1.05718E-06	1.37245E-03	-1.34344E-04	2.72152E-03	6.01860E-05
143	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
144	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
145	1.74370E-04	-5.65593E-06	3.39691E-03	3.87798E-03	-1.85842E-03	0.00000E+00
146	2.59368E-04	7.83084E-06	5.52337E-03	4.42326E-03	-6.26680E-04	0.00000E+00
147	2.29503E-04	9.39556E-06	6.94958E-03	4.36045E-03	-7.04647E-04	0.00000E+00
148	1.33333E-04	1.21194E-05	7.98523E-03	4.37784E-03	-3.93041E-04	0.00000E+00
149	-4.52695E-18	1.30290E-05	8.34951E-03	4.37764E-03	3.08120E-17	0.00000E+00
150	-1.33333E-04	1.21194E-05	7.98523E-03	4.37784E-03	3.93041E-04	0.00000E+00
151	-2.29503E-04	9.39556E-06	6.94958E-03	4.36045E-03	7.04647E-04	0.00000E+00
152	-2.59368E-04	7.83084E-06	5.52337E-03	4.42326E-03	6.26680E-04	0.00000E+00
153	-1.74370E-04	-5.65593E-06	3.39691E-03	3.87798E-03	1.85842E-03	0.00000E+00
154	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
155	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
156	1.49373E-04	-1.00217E-06	5.02919E-03	4.99031E-05	-2.03643E-03	0.00000E+00
157	2.26888E-04	3.78678E-06	7.40055E-03	9.47892E-05	-8.28145E-04	0.00000E+00
158	2.13943E-04	9.83500E-06	8.81654E-03	1.43223E-04	-8.19064E-04	0.00000E+00
159	1.23429E-04	1.44055E-05	9.88028E-03	1.76172E-04	-4.35823E-04	0.00000E+00
160	-2.00371E-18	1.60855E-05	1.02530E-02	1.89022E-04	6.96741E-18	0.00000E+00
161	-1.23429E-04	1.44055E-05	9.88028E-03	1.76172E-04	4.35823E-04	0.00000E+00
162	-2.13943E-04	9.83500E-06	8.81654E-03	1.43223E-04	8.19064E-04	0.00000E+00
163	-2.26888E-04	3.78678E-06	7.40055E-03	9.47892E-05	8.28145E-04	0.00000E+00
164	-1.49373E-04	-1.00217E-06	5.02919E-03	4.99031E-05	2.03643E-03	0.00000E+00
165	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
166	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
167	1.70532E-04	3.71007E-06	3.44976E-03	-3.87160E-03	-1.86244E-03	0.00000E+00

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****** DISPLACEMENT SOLUTION - LOAD CASE ID NO. 1 (CONTINUED) ******

NODE	UX	UY	UZ	ROTX	ROTY	ROTZ
168	2.53739E-04	-2.56305E-07	5.61332E-03	-4.43566E-03	-6.68063E-04	0.00000E+00
169	2.24733E-04	1.01513E-05	7.08041E-03	-4.37099E-03	-7.36094E-04	0.00000E+00
170	1.30583E-04	1.65465E-05	8.14751E-03	-4.39132E-03	-4.10863E-04	0.00000E+00
171	-3.55326E-19	1.89593E-05	8.52322E-03	-4.39081E-03	-2.35927E-17	0.00000E+00
172	-1.30583E-04	1.65465E-05	8.14751E-03	-4.39132E-03	4.10863E-04	0.00000E+00
173	-2.24733E-04	1.01513E-05	7.08041E-03	-4.37099E-03	7.36094E-04	0.00000E+00
174	-2.53739E-04	-2.56305E-07	5.61332E-03	-4.43566E-03	6.68063E-04	0.00000E+00
175	-1.70532E-04	3.71007E-06	3.44976E-03	-3.87160E-03	1.86244E-03	0.00000E+00
176	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
177	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
178	2.74421E-04	-2.70465E-06	1.32654E-03	-1.57734E-04	-2.63066E-03	-5.41780E-05
179	3.19255E-04	3.70604E-06	3.05346E-03	-3.39376E-04	-1.07391E-03	-2.95714E-05
180	2.69722E-04	1.40428E-05	4.57017E-03	-4.96166E-04	-8.06731E-04	-1.64193E-05
181	1.51867E-04	2.26430E-05	5.60808E-03	-6.13426E-04	-4.20062E-04	-1.42663E-05
182	2.02760E-18	2.59025E-05	5.97346E-03	-6.53867E-04	1.98226E-17	2.23710E-17
183	-1.51867E-04	2.26430E-05	5.60808E-03	-6.13426E-04	4.20062E-04	1.42663E-05
184	-2.69722E-04	1.40428E-05	4.57017E-03	-4.96166E-04	8.06731E-04	1.64193E-05
185	-3.19255E-04	3.70604E-06	3.05346E-03	-3.39376E-04	1.07391E-03	2.95714E-05
186	-2.74421E-04	-2.70465E-06	1.32654E-03	-1.57734E-04	2.63066E-03	5.41780E-05
187	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
188	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
189	1.67735E-04	-9.38988E-06	3.26255E-03	3.72510E-03	-1.78270E-03	0.00000E+00

190	2.49610E-04	7.44162E-06	5.29295E-03	4.21809E-03	-5.91061E-04	0.00000E+00
191	2.20732E-04	1.77033E-05	6.65006E-03	4.13006E-03	-6.70411E-04	0.00000E+00
192	1.28151E-04	2.84457E-05	7.63802E-03	4.13023E-03	-3.75141E-04	0.00000E+00
193	-6.73399E-19	3.25237E-05	7.98604E-03	4.12526E-03	2.08279E-17	0.00000E+00
194	-1.28151E-04	2.84457E-05	7.63802E-03	4.13023E-03	3.75141E-04	0.00000E+00
195	-2.20732E-04	1.77033E-05	6.65006E-03	4.13006E-03	6.70411E-04	0.00000E+00
196	-2.49610E-04	7.44162E-06	5.29295E-03	4.21809E-03	5.91061E-04	0.00000E+00
197	-1.67735E-04	-9.38988E-06	3.26255E-03	3.72510E-03	1.78270E-03	0.00000E+00
198	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
199	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
200	1.43071E-04	-5.59939E-06	4.82820E-03	4.22842E-05	-1.94727E-03	0.00000E+00
201	2.17679E-04	2.91784E-06	7.08029E-03	7.75601E-05	-7.77335E-04	0.00000E+00
202	2.05151E-04	1.77572E-05	8.41421E-03	1.16157E-04	-7.74204E-04	0.00000E+00
203	1.18185E-04	3.03368E-05	9.42111E-03	1.42908E-04	-4.14120E-04	0.00000E+00
204	-2.66627E-18	3.51392E-05	9.77473E-03	1.54259E-04	6.96735E-17	0.00000E+00
205	-1.18185E-04	3.03368E-05	9.42111E-03	1.42908E-04	4.14120E-04	0.00000E+00
206	-2.05151E-04	1.77572E-05	8.41421E-03	1.16157E-04	7.74204E-04	0.00000E+00
207	-2.17679E-04	2.91784E-06	7.08029E-03	7.75601E-05	7.77335E-04	0.00000E+00
208	-1.43071E-04	-5.59939E-06	4.82820E-03	4.22842E-05	1.94727E-03	0.00000E+00
209	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
210	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
211	1.62853E-04	-2.29348E-06	3.30717E-03	-3.71992E-03	-1.78276E-03	0.00000E+00
212	2.42710E-04	-1.87893E-06	5.36638E-03	-4.22802E-03	-6.24130E-04	0.00000E+00
213	2.14442E-04	1.77584E-05	6.75607E-03	-4.13852E-03	-6.90823E-04	0.00000E+00
214	1.24340E-04	3.22810E-05	7.77004E-03	-4.14238E-03	-3.89292E-04	0.00000E+00
215	-5.62489E-18	3.78044E-05	8.12753E-03	-4.13614E-03	9.89306E-17	0.00000E+00
216	-1.24340E-04	3.22810E-05	7.77004E-03	-4.14238E-03	3.89292E-04	0.00000E+00
217	-2.14442E-04	1.77584E-05	6.75607E-03	-4.13852E-03	6.90823E-04	0.00000E+00
218	-2.42710E-04	-1.87893E-06	5.36638E-03	-4.22802E-03	6.24130E-04	0.00000E+00
219	-1.62853E-04	-2.29348E-06	3.30717E-03	-3.71992E-03	1.78276E-03	0.00000E+00
220	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
221	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
222	2.62654E-04	-1.03291E-05	1.28956E-03	-9.36933E-05	-2.56241E-03	-6.48583E-05
223	3.04133E-04	9.33924E-07	2.96803E-03	-1.65682E-04	-1.06800E-03	-3.23268E-05
224	2.55830E-04	2.12682E-05	4.44101E-03	-2.37952E-04	-7.92436E-04	-1.64205E-05

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****** DISPLACEMENT SOLUTION - LOAD CASE ID NO. 1 (CONTINUED) ******

NODE	UX	UY	UZ	ROTX	ROTY	ROTZ
225	1.43510E-04	3.81425E-05	5.44831E-03	-3.07242E-04	-4.17359E-04	-1.36751E-05
226	-1.22306E-17	4.44793E-05	5.80283E-03	-3.28250E-04	6.74242E-17	-4.86862E-17
227	-1.43510E-04	3.81425E-05	5.44831E-03	-3.07242E-04	4.17359E-04	1.36751E-05
228	-2.55830E-04	2.12682E-05	4.44101E-03	-2.37952E-04	7.92436E-04	1.64205E-05
229	-3.04133E-04	9.33924E-07	2.96803E-03	-1.65682E-04	1.06800E-03	3.23268E-05
230	-2.62654E-04	-1.03291E-05	1.28956E-03	-9.36933E-05	2.56241E-03	6.48583E-05
231	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
232	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
233	1.55404E-04	-1.89903E-05	3.21938E-03	3.68590E-03	-1.76814E-03	0.00000E+00
234	2.31130E-04	3.48200E-06	5.28020E-03	4.30214E-03	-6.33664E-04	0.00000E+00
235	2.02607E-04	2.45209E-05	6.67127E-03	4.32430E-03	-6.72931E-04	0.00000E+00
236	1.16883E-04	4.34706E-05	7.67084E-03	4.38059E-03	-3.82101E-04	0.00000E+00
237	-4.59450E-18	5.04780E-05	8.02472E-03	4.40146E-03	3.16831E-17	0.00000E+00
238	-1.16883E-04	4.34706E-05	7.67084E-03	4.38059E-03	3.82101E-04	0.00000E+00
239	-2.02607E-04	2.45209E-05	6.67127E-03	4.32430E-03	6.72931E-04	0.00000E+00
240	-2.31130E-04	3.48200E-06	5.28020E-03	4.30214E-03	6.33664E-04	0.00000E+00
241	-1.55404E-04	-1.89903E-05	3.21938E-03	3.68590E-03	1.76814E-03	0.00000E+00
242	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
243	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
244	1.26488E-04	-1.75730E-05	4.78903E-03	8.44705E-05	-1.95071E-03	0.00000E+00
245	1.91972E-04	-1.82623E-06	7.13135E-03	1.62689E-04	-8.65187E-04	0.00000E+00
246	1.79192E-04	2.41500E-05	8.55289E-03	2.33492E-04	-7.97869E-04	0.00000E+00
247	1.02054E-04	4.43390E-05	9.60059E-03	2.69835E-04	-4.34990E-04	0.00000E+00
248	-4.88641E-19	5.17042E-05	9.97179E-03	2.89396E-04	-4.24465E-18	0.00000E+00
249	-1.02054E-04	4.43390E-05	9.60059E-03	2.69835E-04	4.34990E-04	0.00000E+00
250	-1.79192E-04	2.41500E-05	8.55289E-03	2.33492E-04	7.97869E-04	0.00000E+00
251	-1.91972E-04	-1.82623E-06	7.13135E-03	1.62689E-04	8.65187E-04	0.00000E+00
252	-1.26488E-04	-1.75730E-05	4.78903E-03	8.44705E-05	1.95071E-03	0.00000E+00
253	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
254	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00

255	1.38054E-04	-1.64016E-05	3.30829E-03	-3.68550E-03	-1.75307E-03	0.00000E+00
256	2.03865E-04	-6.94357E-06	5.42683E-03	-4.36233E-03	-7.25138E-04	0.00000E+00
257	1.76168E-04	2.34072E-05	6.86359E-03	-4.41471E-03	-7.13080E-04	0.00000E+00
258	1.00682E-04	4.41392E-05	7.89435E-03	-4.51639E-03	-4.12278E-04	0.00000E+00
259	3.10059E-18	5.15183E-05	8.25990E-03	-4.54376E-03	-4.23959E-17	0.00000E+00
260	-1.00682E-04	4.41392E-05	7.89435E-03	-4.51639E-03	4.12278E-04	0.00000E+00
261	-1.76168E-04	2.34072E-05	6.86359E-03	-4.41471E-03	7.13080E-04	0.00000E+00
262	-2.03865E-04	-6.94357E-06	5.42683E-03	-4.36233E-03	7.25138E-04	0.00000E+00
263	-1.38054E-04	-1.64016E-05	3.30829E-03	-3.68550E-03	1.75307E-03	0.00000E+00
264	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
265	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
266	2.21736E-04	-2.53295E-05	1.18597E-03	-4.38282E-04	-2.28458E-03	-2.53871E-06
267	2.45166E-04	-4.08360E-06	2.71412E-03	-1.07555E-03	-9.58341E-04	2.21876E-05
268	1.99024E-04	2.54751E-05	4.04209E-03	-1.52737E-03	-6.44257E-04	2.17609E-05
269	1.09099E-04	4.59262E-05	4.94355E-03	-1.88415E-03	-3.47362E-04	7.80889E-06
270	7.54486E-18	5.29942E-05	5.25980E-03	-2.00227E-03	-3.68244E-17	1.52534E-17
271	-1.09099E-04	4.59262E-05	4.94355E-03	-1.88415E-03	3.47362E-04	-7.80889E-06
272	-1.99024E-04	2.54751E-05	4.04209E-03	-1.52737E-03	6.44257E-04	-2.17609E-05
273	-2.45166E-04	-4.08360E-06	2.71412E-03	-1.07555E-03	9.58341E-04	-2.21876E-05
274	-2.21736E-04	-2.53295E-05	1.18597E-03	-4.38282E-04	2.28458E-03	2.53871E-06
275	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
276	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
277	1.06530E-04	-3.33808E-05	2.67723E-03	2.97117E-03	-1.26415E-03	0.00000E+00
278	1.51849E-04	6.95290E-08	4.04316E-03	2.61328E-03	-3.79850E-04	0.00000E+00
279	1.25084E-04	2.63768E-05	4.91005E-03	2.02863E-03	-3.95013E-04	0.00000E+00
280	7.04805E-05	4.46461E-05	5.52012E-03	1.59488E-03	-2.44330E-04	0.00000E+00
281	4.21060E-18	5.08450E-05	5.73737E-03	1.45329E-03	-2.63678E-17	0.00000E+00

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****** DISPLACEMENT SOLUTION - LOAD CASE ID NO. 1 (CONTINUED) ******

NODE	UX	UY	UZ	ROTX	ROTY	ROTZ
282	-7.04805E-05	4.46461E-05	5.52012E-03	1.59488E-03	2.44330E-04	0.00000E+00
283	-1.25084E-04	2.63768E-05	4.91005E-03	2.02863E-03	3.95013E-04	0.00000E+00
284	-1.51849E-04	6.95290E-08	4.04316E-03	2.61328E-03	3.79850E-04	0.00000E+00
285	-1.06530E-04	-3.33808E-05	2.67723E-03	2.97117E-03	1.26415E-03	0.00000E+00
286	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
287	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
288	5.51688E-05	-2.86494E-05	3.73819E-03	-4.47203E-04	-1.02814E-03	0.00000E+00
289	7.77906E-05	-1.12692E-06	4.75503E-03	-1.26984E-03	-3.03463E-04	0.00000E+00
290	7.06890E-05	2.16921E-05	5.20402E-03	-1.74193E-03	-2.44976E-04	0.00000E+00
291	3.98977E-05	3.52044E-05	5.53218E-03	-2.15760E-03	-1.37892E-04	0.00000E+00
292	2.12061E-18	4.01429E-05	5.64989E-03	-2.28983E-03	-2.00645E-17	0.00000E+00
293	-3.98977E-05	3.52044E-05	5.53218E-03	-2.15760E-03	1.37892E-04	0.00000E+00
294	-7.06890E-05	2.16921E-05	5.20402E-03	-1.74193E-03	2.44976E-04	0.00000E+00
295	-7.77906E-05	-1.12692E-06	4.75503E-03	-1.26984E-03	3.03463E-04	0.00000E+00
296	-5.51688E-05	-2.86494E-05	3.73819E-03	-4.47203E-04	1.02814E-03	0.00000E+00
297	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
298	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
299	2.40414E-05	-1.67230E-05	2.02404E-03	-3.71764E-03	-4.25109E-04	0.00000E+00
300	2.98969E-05	-1.13749E-06	2.38976E-03	-4.80124E-03	-7.48738E-05	0.00000E+00
301	2.90580E-05	1.20608E-05	2.52607E-03	-5.02753E-03	-6.05960E-05	0.00000E+00
302	1.72167E-05	1.99514E-05	2.62076E-03	-5.31080E-03	-3.06442E-05	0.00000E+00
303	9.07148E-19	2.26207E-05	2.65645E-03	-5.39289E-03	-1.58582E-18	0.00000E+00
304	-1.72167E-05	1.99514E-05	2.62076E-03	-5.31080E-03	3.06442E-05	0.00000E+00
305	-2.90580E-05	1.20608E-05	2.52607E-03	-5.02753E-03	6.05960E-05	0.00000E+00
306	-2.98969E-05	-1.13749E-06	2.38976E-03	-4.80124E-03	7.48738E-05	0.00000E+00
307	-2.40414E-05	-1.67230E-05	2.02404E-03	-3.71764E-03	4.25109E-04	0.00000E+00
308	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
309	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
310	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
311	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
312	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
313	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
314	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
315	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
316	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
317	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
318	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
319	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+0

VOLUME CHANGES CALCULATION METHODOLOGY

The method used in obtaining the total volume change of the tanks was straightforward. The finite element program produces an output file from each run. This file contains the "displacement solution" for the model, which is a table of displacements of every node point, in each degree of freedom. The "Z" displacement (perpendicular to the plane of the bulkhead plate) is of interest and can be numerically integrated over the area of the plate to obtain the volume change in the panel.

The Z displacements from the output file were entered into a spreadsheet, samples of which follow. Only the nodes which define the plate elements were included in the integration. Since all of the elements in the plate are identically sized, all of the interior node points (those not on the edge of the model) can be thought of as representing an equal area of plate. The displacements of the nodes were added up. The total was then multiplied by the area of one plate element to obtain the volume change over the whole model.

The calculation was repeated for each section of the bulkheads in the analysis. The results of the individual calculations were then combined, appropriately, to account for the complete length and height of the tank. The total volume change was then doubled to account for identical bulkheads on port and starboard sides (see Tables 4-1 and 4-2). Note that this approach is conservative because it ignores the deflections in the transverse bulkheads which form the forward and aft boundaries of the tank and because the horizontal girders and vertical frames were assumed fixed.

The total volume change for each tank was then divided by the surface area of the tank to obtain the change of the oil level.

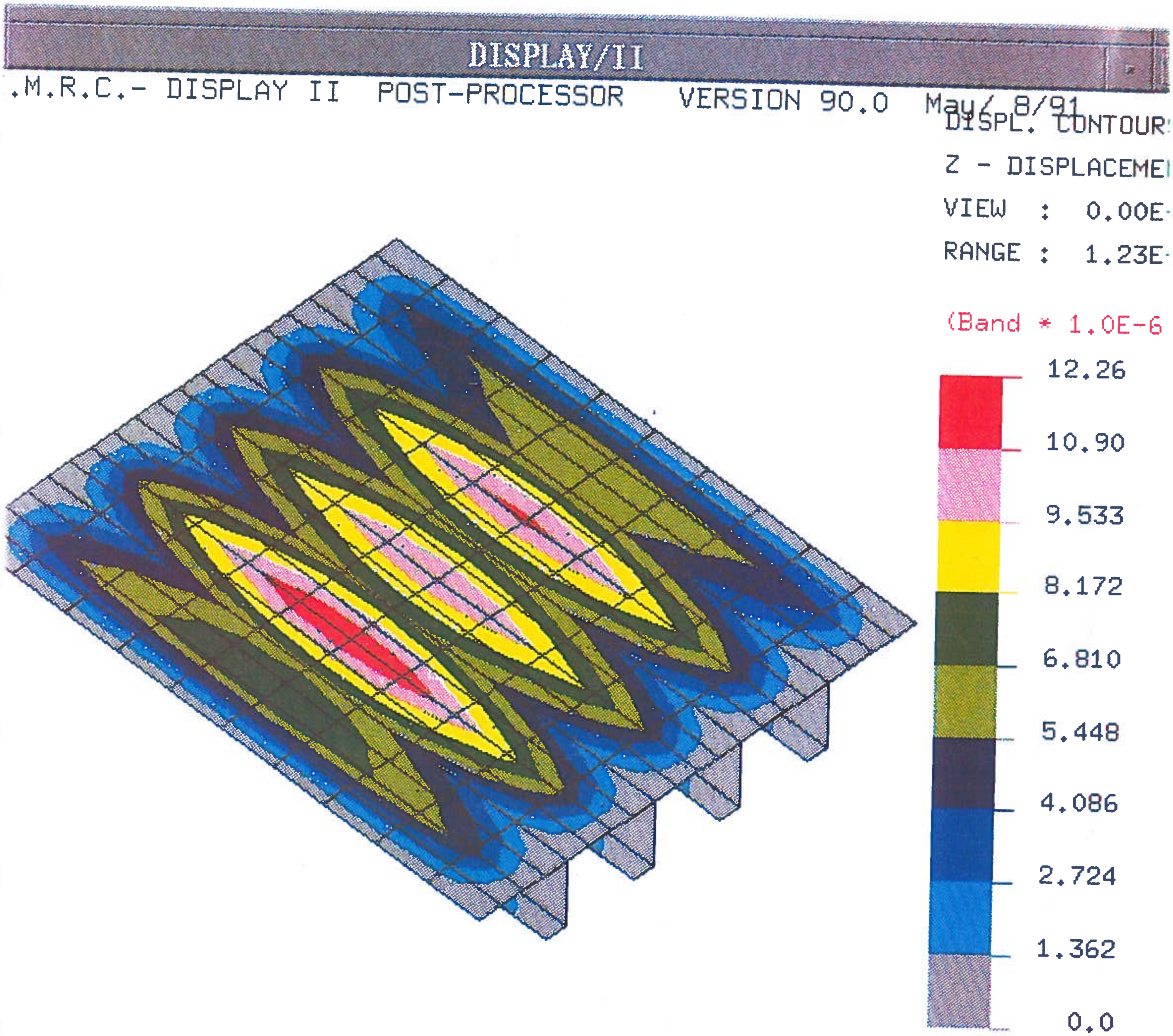

Figure B-1

Deflections due to Oil Cargo load- one side only

400,000 DWT VLCC, panel "B"

Longitudinal bulkhead

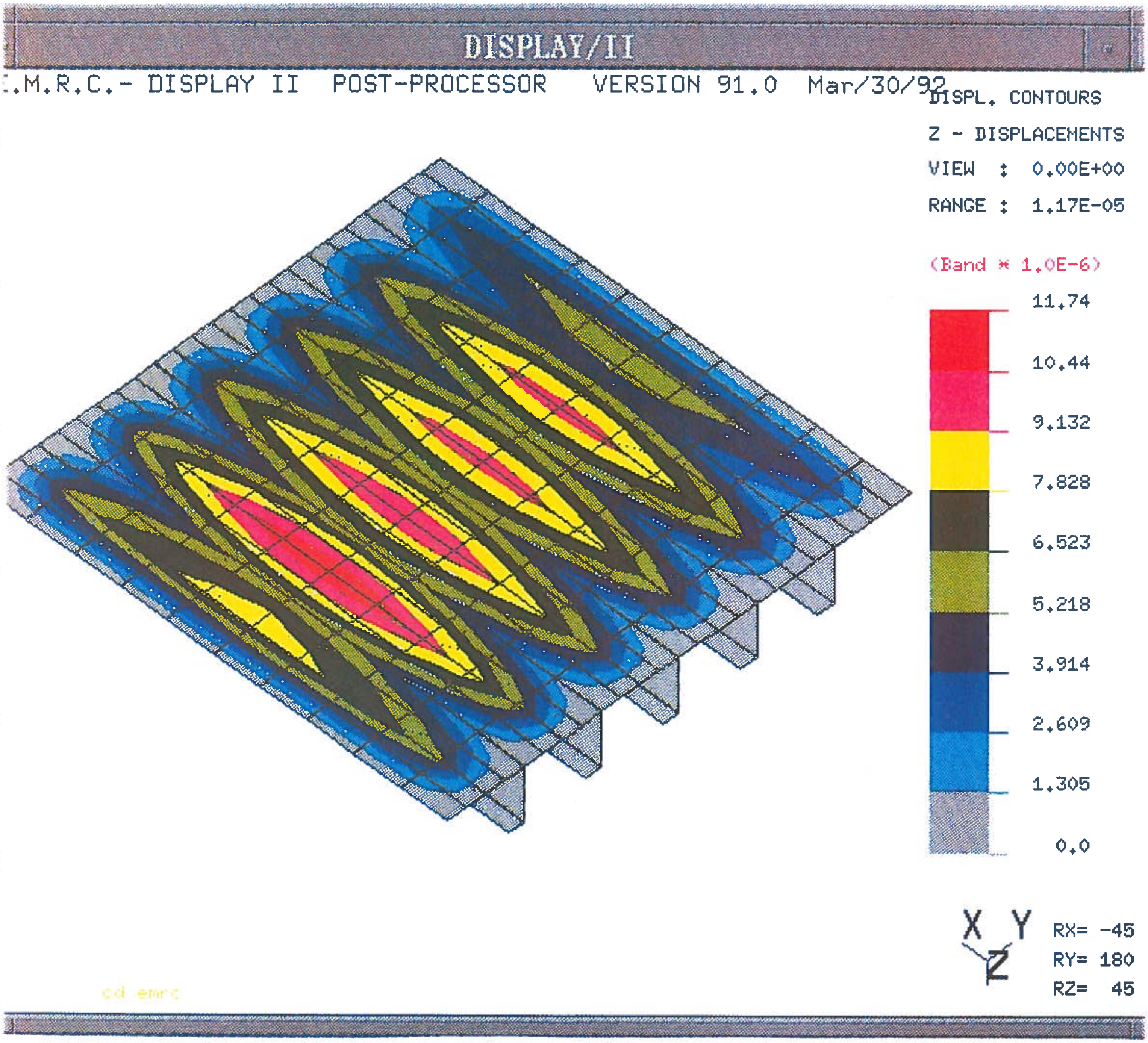

Figure B-2

Deflections due to Oil Cargo load- one side only

400,000 DWT VLCC, panel "C"

Longitudinal bulkhead

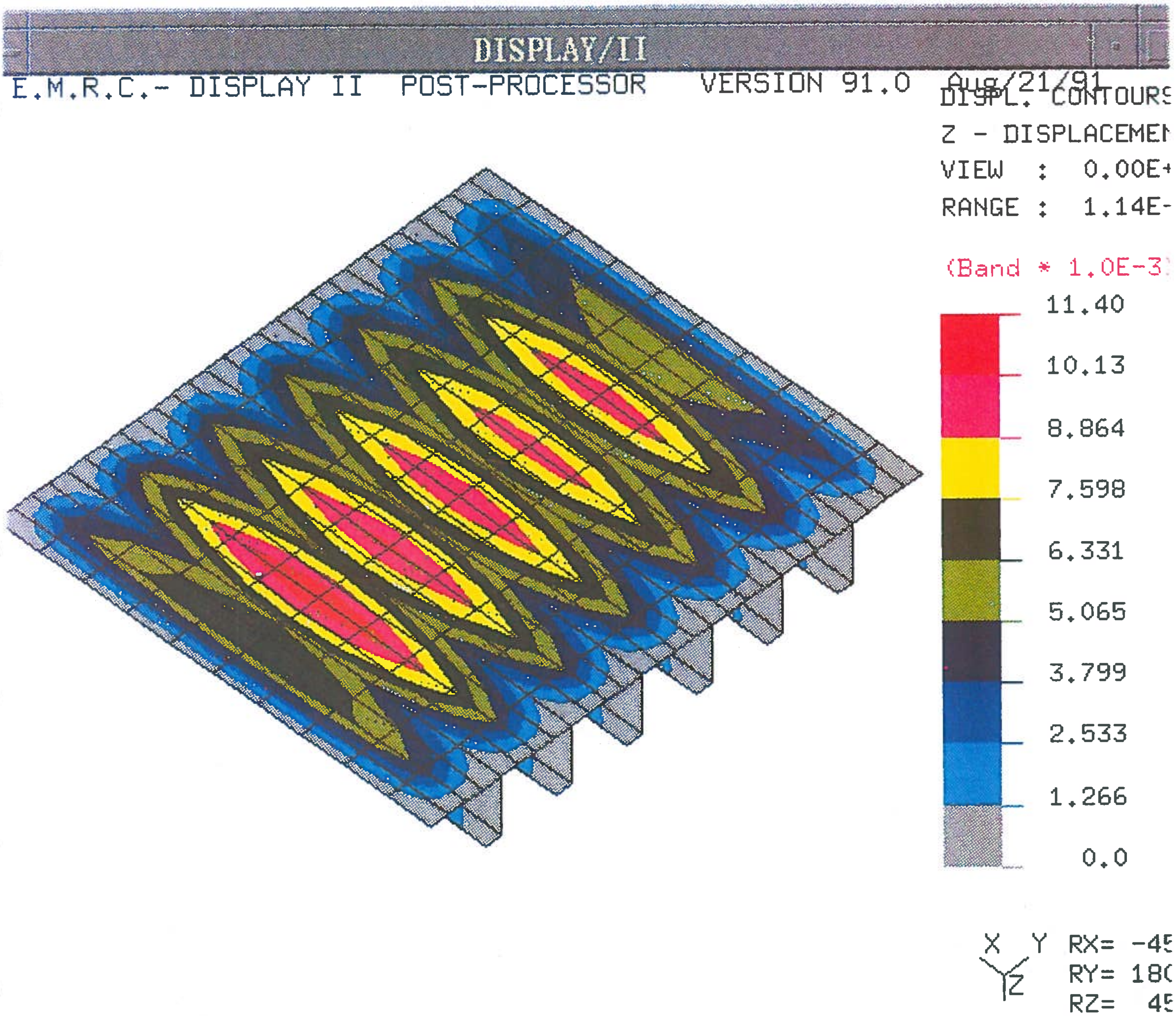

Figure B-3

Deflections due to Oil Cargo load- one side only

400,000 DWT VLCC, panel "D"

Longitudinal bulkhead

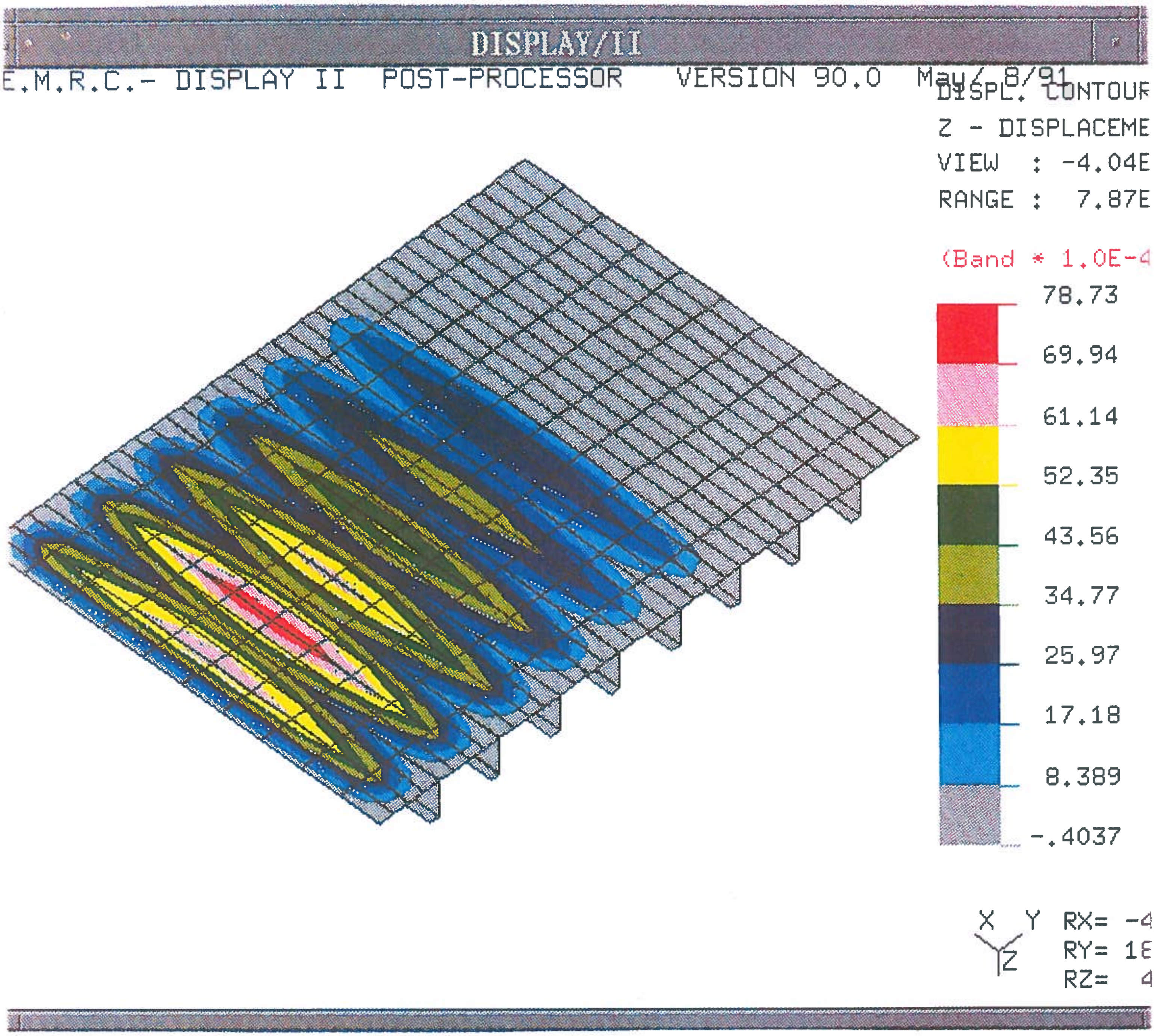

Figure B-4

Deflections due to Oil Cargo load- one side only

400,000 DWT VLCC, panel "E"

Longitudinal bulkhead

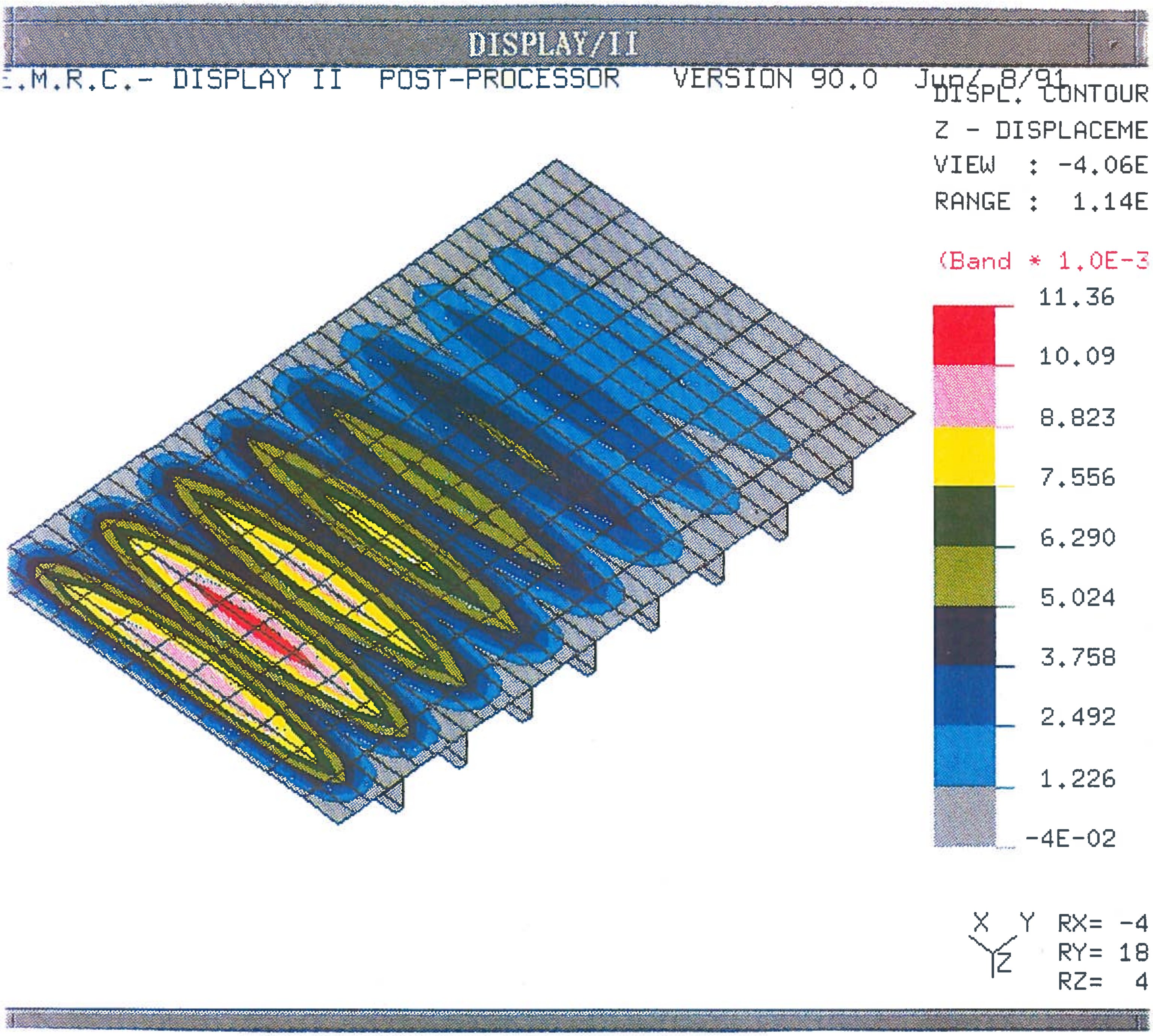

Figure B-5

Deflections due to Oil Cargo load- one side only

77,000 DWT lightering tanker

Longitudinal bulkhead, top panel

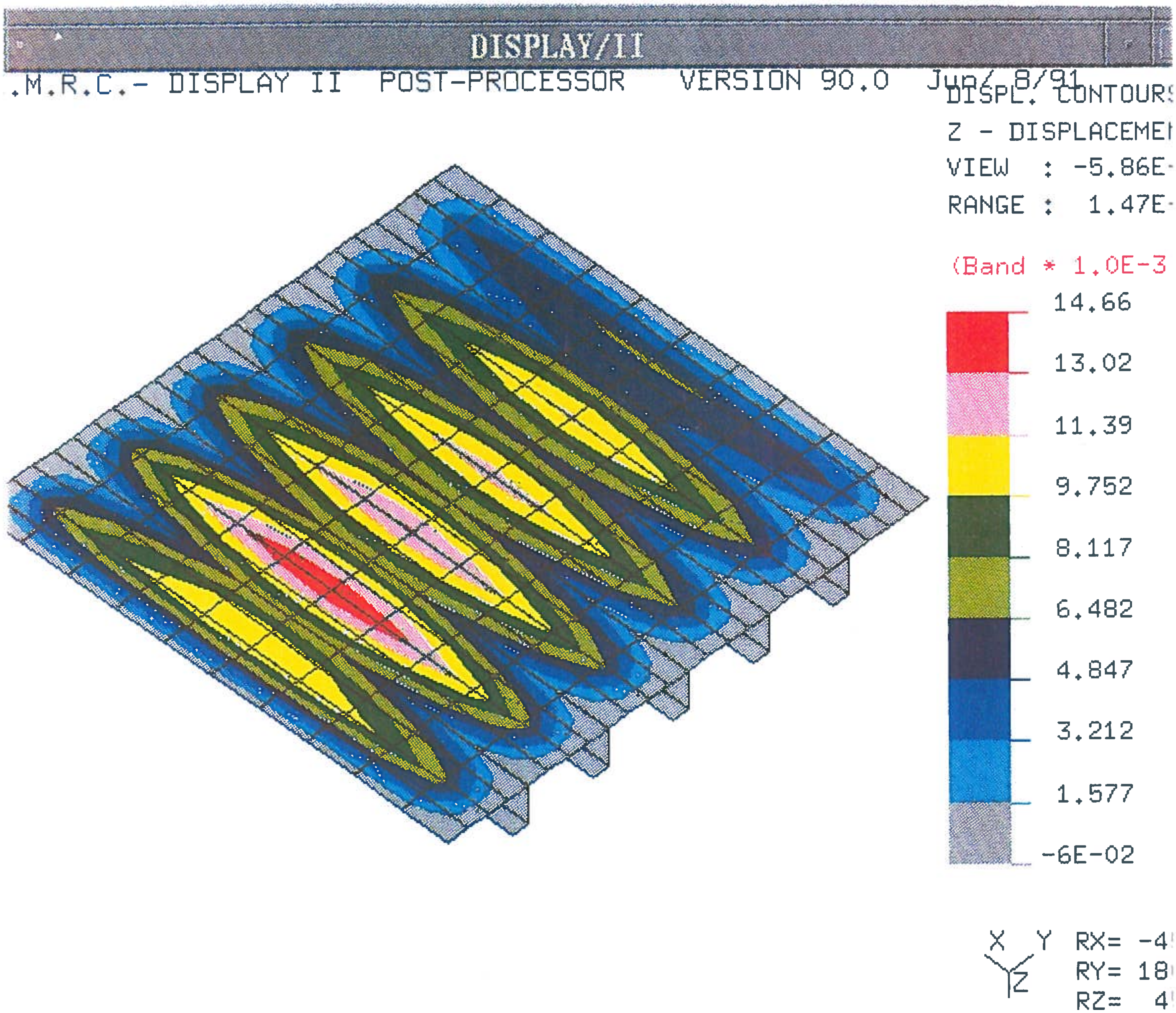

Figure B-6

Deflections due to Oil Cargo load- one side only

77,000 DWT lightering tanker

Longitudinal bulkhead, mid panel

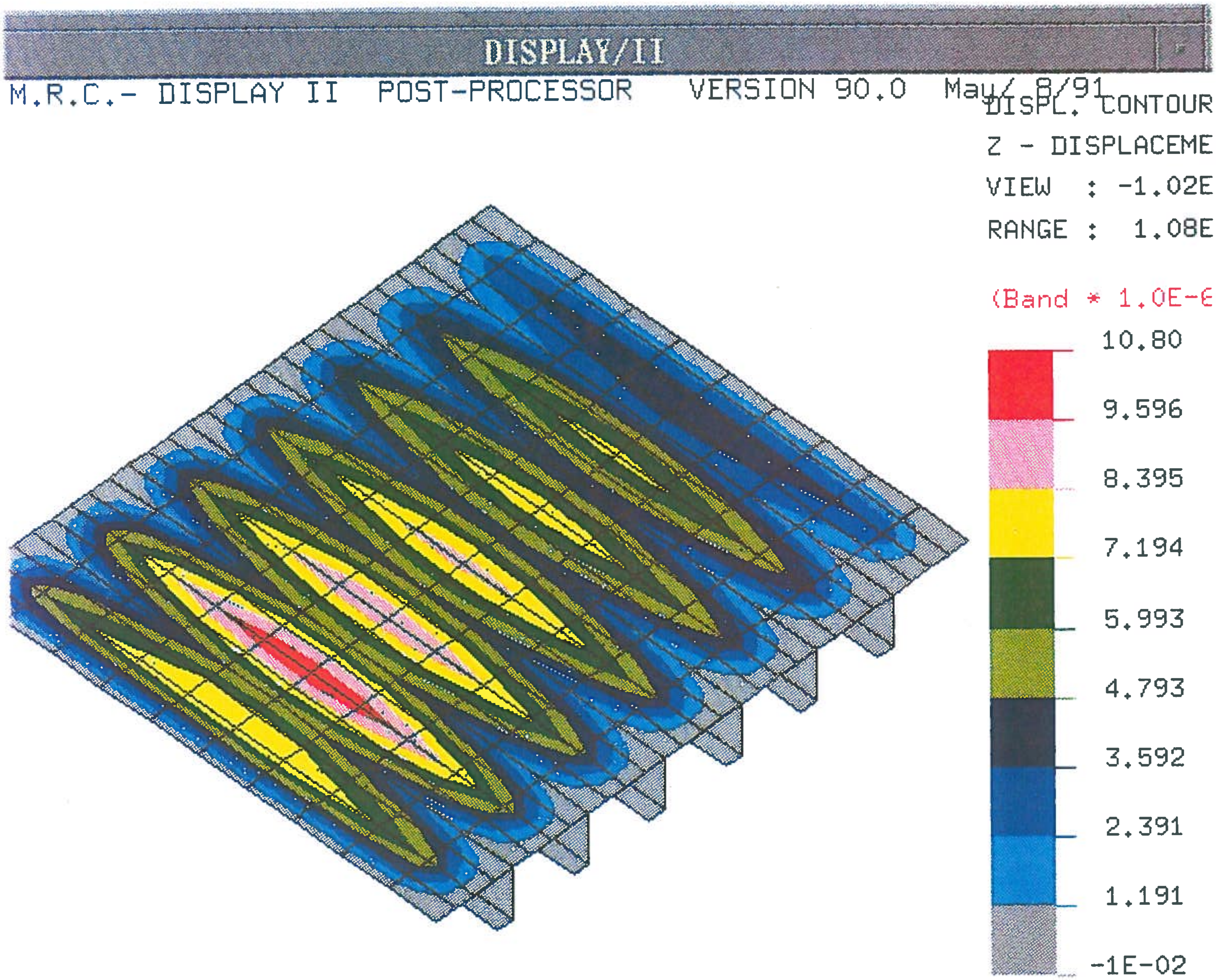

Figure B-7

Deflections due to Oil Cargo load- one side only

77,000 DWT lightering tanker

Longitudinal bulkhead, bottom panel

77,000 dwt lightering tanker, bottom panel TED/MD

Z deflections -- all deflections in thousandths of a foot.
Numbers from "Eight.out" printout.

3.667	4.467	6.323	3.845
4.303	6.995	8.957	6.125
4.592	8.696	10.542	7.724
4.8	9.973	11.78	8.909
4.879	10.426	12.217	9.334
3.667	4.467	6.323	3.845
4.303	6.995	8.957	6.125
4.592	8.696	10.542	7.724
4.8	9.973	11.78	8.909
6.705	6.921	4.153	1.073
8.454	9.782	6.565	2.668
9.342	11.496	8.261	4.132
10.011	12.841	9.533	5.146
10.254	13.315	9.985	5.504
6.705	6.921	4.153	1.073
8.454	9.782	6.565	2.668
9.342	11.496	8.261	4.132
10.011	12.841	9.533	5.146
4.557	4.544	1.241	3.124
6.784	7.176	3.103	4.549
8.316	9.025	4.83	5.437
9.428	10.415	6.034	6.077
9.829	10.909	6.462	6.306
4.557	4.544	1.241	3.124
6.784	7.176	3.103	4.549
8.316	9.025	4.83	5.437
9.428	10.415	6.034	6.077
1.437	1.367	3.869	4.656
3.561	3.418	6.063	5.732
5.508	5.321	7.54	6.168
6.885	6.648	8.649	6.499
7.332	7.12	9.041	6.618
1.437	1.367	3.869	4.656
3.561	3.418	6.063	5.732
5.508	5.321	7.54	6.168
6.885	6.648	8.649	6.499
4.796	4.29	5.988	2.566
7.569	6.733	8.46	2.952
9.428	8.381	9.938	3.081
10.802	9.616	11.098	3.173
11.292	10.053	11.507	3.208
4.796	4.29	5.988	2.566
7.569	6.733	8.46	2.952
9.428	8.381	9.938	3.081
10.802	9.616	11.098	3.173

7.373	6.636	3.926	218.242
10.543	9.402	6.19	

12.471	11.067	7.776
13.951	12.368	8.968
14.48	12.826	9.392
7.373	6.636	3.926
10.543	9.402	6.19
12.471	11.067	7.776
13.951	12.368	8.968
4.822	4.355	1.184
7.682	6.888	2.958
9.701	8.668	4.603
11.203	10.005	5.749
11.74	10.48	6.156
4.822	4.355	1.184
7.682	6.888	2.958
9.701	8.668	4.603
11.203	10.005	5.749
1.437	1.306	3.734
3.595	3.266	5.911
5.596	5.084	7.388
6.992	6.352	8.483
7.488	6.803	8.874
1.437	1.306	3.734
3.595	3.266	5.911
5.596	5.084	7.388
6.992	6.352	8.483

529.916	4.084	5.807
	6.411	8.317
	7.98	9.851
	9.156	11.028
	9.572	11.447
	4.084	5.807
	6.411	8.317
	7.98	9.851
	9.156	11.028
	---------	---------
	613.77	574.681

529.916
613.77
574.681
218.242

1936.609

1.574432 cu. ft.
change in volume

400,000 dwt VLCC, bottom panel TED/MD

Three.out Z-displacements

All displacements in thousandths of a foot.

2.526	3.486	4.828	2.024	
3.02	5.655	7.08	2.39	
3.227	7.104	8.414	2.526	
3.37	8.16	9.421	2.621	
3.423	8.531	9.775	2.656	
2.526	3.486	4.828	2.024	
3.02	5.655	7.08	2.39	
3.227	7.104	8.414	2.526	
3.37	8.16	9.421	2.621	

4.699	5.169	3.307	21.778	
6.058	7.582	5.366		
6.708	9.011	6.756		
7.178	10.091	7.77		
7.348	10.47	8.128		
4.699	5.169	3.307		415.218
6.058	7.582	5.366		500.799
6.708	9.011	6.756		452.134
7.178	10.091	7.77		21.78

3.403	3.548	1.29		1389.931
5.179	5.76	2.968		
6.336	7.255	4.441		1.739098 cu. ft.
7.151	8.346	5.448		change in volume
7.442	8.731	5.803		
3.403	3.548	1.29		
5.179	5.76	2.968		
6.336	7.255	4.441		
7.151	8.346	5.448		
1.41	1.372	3.219		
3.217	3.159	5.28		
4.784	4.728	6.671		
5.847	5.802	7.671		
6.22	6.18	8.025		
1.41	1.372	3.219		
3.217	3.159	5.28		
4.784	4.728	6.671		
5.847	5.802	7.671		
3.726	3.397	4.789		
6.101	5.523	7.131		
7.691	6.95	8.553		
8.829	7.985	9.601		
9.223	8.35	9.972		
3.726	3.397	4.789		
6.101	5.523	7.131		
7.691	6.95	8.553		
8.829	7.985	9.601		
5.481	5.029	3.308		
8.156	7.401	5.427		

9.777	8.816	6.864
10.972	9.88	7.894
11.396	10.253	8.26
5.481	5.029	3.308
8.156	7.401	5.427
9.777	8.816	6.864
10.972	9.88	7.894
3.744	3.45	1.186
6.143	5.613	2.714
7.78	7.08	4.042
8.96	8.148	4.944
9.378	8.523	5.26
3.744	3.45	1.186
6.143	5.613	2.714
7.78	7.08	4.042
8.96	8.148	4.944
1.43	1.326	2.677
3.293	3.053	4.043
4.929	4.57	4.91
6.048	5.608	5.52
6.442	5.973	5.737
1.43	1.326	2.677
3.293	3.053	4.043
4.929	4.57	4.91
6.048	5.608	5.52

415.218	3.263	3.738
	5.293	4.755
	6.65	5.204
	7.638	5.532
	7.986	5.65
	3.263	3.738
	5.293	4.755
	6.65	5.204
	7.638	5.532
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	500.799	452.134

APPENDIX C

Leak outflow data

VESSEL	DEPTH (ft)	DRAFT (ft)	ULLAGE (ft)	BREACH DESCRPT'N	HOLE AREA (ft^2)	OUTFLOW VELOCITY (ft/s)	OUTFLOW Q (gal/min)	TANK SURFACE AREA (m^2)	TRANSLATION OF CARGO SURFACE (mm/min)
400,000 dwt VLCC	95.15	74.15	1.90	6" diameter	0.200	35.1	3185.9	470.4	25.64
(tank at 98% cap.)	95.15	74.15	1.90	3" diameter	0.050	35.1	796.5	470.4	6.41
	95.15	74.15	1.90	1" diameter	0.006	35.1	89.2	470.4	0.72
Tank dimensions=	95.15	74.15	1.90	12" long X1/2"	0.042	35.1	669.0	470.4	5.38
110.2'L x 45.9'W	95.15	74.15	1.90	6" long X 1/2"	0.020	35.1	318.6	470.4	2.56
	95.15	74.15	1.90	12" long X1/8"	0.010	35.1	165.7	470.4	1.33
	95.15	74.15	1.90	6" long X1/16"	0.003	35.1	41.4	470.4	0.33
	95.15	74.15	1.90	3" long X1/16"	0.001	35.1	20.7	470.4	0.17
77,000 dwt lighter-ing tanker	58.36	40.04	1.17	6" diameter	0.200	33.2	3018.9	630.7	18.12
	58.36	40.04	1.17	3" diameter	0.050	33.2	754.7	630.7	4.53
(tank at 98% cap.)	58.36	40.04	1.17	1" diameter	0.006	33.2	84.5	630.7	0.51
	58.36	40.04	1.17	12" long X1/2"	0.042	33.2	634.0	630.7	3.80
Tank dimensions=	58.36	40.04	1.17	6" long X 1/2"	0.020	33.2	301.9	630.7	1.81
75.0'L x 90.4'W	58.36	40.04	1.17	12" long X1/8"	0.010	33.2	157.0	630.7	0.94
	58.36	40.04	1.17	6" long X1/16"	0.003	33.2	39.2	630.7	0.24
	58.36	40.04	1.17	3" long X1/16"	0.001	33.2	19.6	630.7	0.12
25,000 bbl tank-barge	17.25	13.75	1.73	6" diameter	0.200	10.7	969.9	89.2	41.15
	17.25	13.75	1.73	3" diameter	0.050	10.7	242.5	89.2	10.29
(tank at 90% cap.)	17.25	13.75	1.73	1" diameter	0.006	10.7	27.2	89.2	1.15
	17.25	13.75	1.73	12" long X1/2"	0.042	10.7	203.7	89.2	8.64
Tank dimensions=	17.25	13.75	1.73	6" long X 1/2"	0.020	10.7	97.0	89.2	4.12
47.9'L x 20.0'W	17.25	13.75	1.73	12" long X1/8"	0.010	10.7	50.4	89.2	2.14
	17.25	13.75	1.73	6" long X1/16"	0.003	10.7	12.6	89.2	0.53
	17.25	13.75	1.73	3" long X1/16"	0.001	10.7	6.3	89.2	0.27
"450 Series" barge	29.31	20.00	2.50	6" diameter	0.200	20.9	1902.4	192.2	37.46
130,000 bbl	29.31	20.00	2.50	3" diameter	0.050	20.9	475.6	192.2	9.37
(tank at 90% cap.)	29.31	20.00	2.50	1" diameter	0.006	20.9	53.3	192.2	1.05
	29.31	20.00	2.50	12" long X1/2"	0.042	20.9	399.5	192.2	7.87
Tank dimensions=	29.31	20.00	2.50	6" long X 1/2"	0.020	20.9	190.2	192.2	3.75
60.0'L x 34.4'W	29.31	20.00	2.50	12" long X1/8"	0.010	20.9	98.9	192.2	1.95
	29.31	20.00	2.50	6" long X1/16"	0.003	20.9	24.7	192.2	0.49
	29.31	20.00	2.50	3" long X1/16"	0.001	20.9	12.4	192.2	0.24

TABLE C-1

LEAK OUTFLOWS
HULL HOLED AT WATERLINE

VESSEL	DEPTH (ft)	DRAFT (ft)	ULLAGE (ft)	BREACH DESCRPT'N	HOLE AREA (ft^2)	OUTFLOW VELOCITY (ft/s)	OUTFLOW Q (gal/min)	TANK SURFACE AREA (m^2)	TRANSLATION OF CARGO SURFACE (mm/min)
400,000 dwt VLCC	95.15	74.15	1.90	6" diameter	0.200	30.6	2780.9	470.4	22.38
(tank at 98% cap.)	95.15	74.15	1.90	3" diameter	0.050	30.6	695.2	470.4	5.59
	95.15	74.15	1.90	1" diameter	0.006	30.6	77.9	470.4	0.63
Tank dimensions=	95.15	74.15	1.90	12" long X1/2"	0.042	30.6	584.0	470.4	4.70
110.2'L x 45.9'W	95.15	74.15	1.90	6" long X 1/2"	0.020	30.6	278.1	470.4	2.24
	95.15	74.15	1.90	12" long X1/8"	0.010	30.6	144.6	470.4	1.16
	95.15	74.15	1.90	6" long X1/16"	0.003	30.6	36.2	470.4	0.29
	95.15	74.15	1.90	3" long X1/16"	0.001	30.6	18.1	470.4	0.15
77,000 dwt lighter-	58.36	40.04	1.17	6" diameter	0.200	30.8	2794.4	630.7	16.77
ing tanker	58.36	40.04	1.17	3" diameter	0.050	30.8	698.6	630.7	4.19
(tank at 98% cap.)	58.36	40.04	1.17	1" diameter	0.006	30.8	78.2	630.7	0.47
	58.36	40.04	1.17	12" long X1/2"	0.042	30.8	586.8	630.7	3.52
Tank dimensions=	58.36	40.04	1.17	6" long X 1/2"	0.020	30.8	279.4	630.7	1.68
75.0'L x 90.4'W	58.36	40.04	1.17	12" long X1/8"	0.010	30.8	145.3	630.7	0.87
	58.36	40.04	1.17	6" long X1/16"	0.003	30.8	36.3	630.7	0.22
	58.36	40.04	1.17	3" long X1/16"	0.001	30.8	18.2	630.7	0.11
25,000 bbl tank-	17.25	13.75	1.73	6" diameter	0.200	7.7	701.7	89.2	29.78
barge	17.25	13.75	1.73	3" diameter	0.050	7.7	175.4	89.2	7.44
(tank at 90% cap.)	17.25	13.75	1.73	1" diameter	0.006	7.7	19.6	89.2	0.83
	17.25	13.75	1.73	12" long X1/2"	0.042	7.7	147.4	89.2	6.25
Tank dimensions=	17.25	13.75	1.73	6" long X 1/2"	0.020	7.7	70.2	89.2	2.98
47.9'L x 20.0'W	17.25	13.75	1.73	12" long X1/8"	0.010	7.7	36.5	89.2	1.55
	17.25	13.75	1.73	6" long X1/16"	0.003	7.7	9.1	89.2	0.39
	17.25	13.75	1.73	3" long X1/16"	0.001	7.7	4.6	89.2	0.19
"450 Series" barge	29.31	20.00	2.50	6" diameter	0.200	19.0	1722.5	192.2	33.92
130,000 bbl	29.31	20.00	2.50	3" diameter	0.050	19.0	430.6	192.2	8.48
(tank at 90% cap.)	29.31	20.00	2.50	1" diameter	0.006	19.0	48.2	192.2	0.95
	29.31	20.00	2.50	12" long X1/2"	0.042	19.0	361.7	192.2	7.12
Tank dimensions=	29.31	20.00	2.50	6" long X 1/2"	0.020	19.0	172.3	192.2	3.39
60.0'L x 34.4'W	29.31	20.00	2.50	12" long X1/8"	0.010	19.0	89.6	192.2	1.76
	29.31	20.00	2.50	6" long X1/16"	0.003	19.0	22.4	192.2	0.44
	29.31	20.00	2.50	3" long X1/16"	0.001	19.0	11.2	192.2	0.22

TABLE C-2
LEAK OUTFLOWS
HULL HOLED BELOW WATERLINE AT 1/2 THE DRAFT
(TABLE C-2 continued next sheet)

400,000 dwt VLCC	95.15	74.15	47.58	6" diameter	0.200	-44.8	-4066.9	470.4	-32.72
(tank at 50% cap.)	95.15	74.15	47.58	3" diameter	0.050	-44.8	-1016.7	470.4	-8.18
	95.15	74.15	47.58	1" diameter	0.006	-44.8	-113.9	470.4	-0.92
Tank dimensions=	95.15	74.15	47.58	12" long X1/2"	0.042	-44.8	-854.0	470.4	-6.87
110.2'L x 45.9'W	95.15	74.15	47.58	6" long X 1/2"	0.020	-44.8	-406.7	470.4	-3.27
	95.15	74.15	47.58	12" long X1/8"	0.010	-44.8	-211.5	470.4	-1.70
	95.15	74.15	47.58	6" long X1/16"	0.003	-44.8	-52.9	470.4	-0.43
	95.15	74.15	47.58	3" long X1/16"	0.001	-44.8	-26.4	470.4	-0.21
77,000 dwt lighter-ing tanker	58.36	40.04	29.18	6" diameter	0.200	-29.3	-2660.1	630.7	-15.96
	58.36	40.04	29.18	3" diameter	0.050	-29.3	-665.0	630.7	-3.99
(tank at 50% cap.)	58.36	40.04	29.18	1" diameter	0.006	-29.3	-74.5	630.7	-0.45
	58.36	40.04	29.18	12" long X1/2"	0.042	-29.3	-558.6	630.7	-3.35
Tank dimensions=	58.36	40.04	29.18	6" long X 1/2"	0.020	-29.3	-266.0	630.7	-1.60
75.0'L x 90.4'W	58.36	40.04	29.18	12" long X1/8"	0.010	-29.3	-138.3	630.7	-0.83
	58.36	40.04	29.18	6" long X1/16"	0.003	-29.3	-34.6	630.7	-0.21
	58.36	40.04	29.18	3" long X1/16"	0.001	-29.3	-17.3	630.7	-0.10
25,000 bbl tank-barge	17.25	13.75	8.63	6" diameter	0.200	-19.6	-1780.9	89.2	-75.57
	17.25	13.75	8.63	3" diameter	0.050	-19.6	-445.2	89.2	-18.89
(tank at 50% cap.)	17.25	13.75	8.63	1" diameter	0.006	-19.6	-49.9	89.2	-2.12
	17.25	13.75	8.63	12" long X1/2"	0.042	-19.6	-374.0	89.2	-15.87
Tank dimensions=	17.25	13.75	8.63	6" long X 1/2"	0.020	-19.6	-178.1	89.2	-7.56
47.9'L x 20.0'W	17.25	13.75	8.63	12" long X1/8"	0.010	-19.6	-92.6	89.2	-3.93
	17.25	13.75	8.63	6" long X1/16"	0.003	-19.6	-23.2	89.2	-0.98
	17.25	13.75	8.63	3" long X1/16"	0.001	-19.6	-11.6	89.2	-0.49
"450 Series" barge	29.31	20.00	14.66	6" diameter	0.200	-20.6	-1868.8	192.2	-36.80
130,000 bbl	29.31	20.00	14.66	3" diameter	0.050	-20.6	-467.2	192.2	-9.20
(tank at 50% cap.)	29.31	20.00	14.66	1" diameter	0.006	-20.6	-52.3	192.2	-1.03
	29.31	20.00	14.66	12" long X1/2"	0.042	-20.6	-392.4	192.2	-7.73
Tank dimensions=	29.31	20.00	14.66	6" long X 1/2"	0.020	-20.6	-186.9	192.2	-3.68
60.0'L x 34.4'W	29.31	20.00	14.66	12" long X1/8"	0.010	-20.6	-97.2	192.2	-1.91
	29.31	20.00	14.66	6" long X1/16"	0.003	-20.6	-24.3	192.2	-0.48
	29.31	20.00	14.66	3" long X1/16"	0.001	-20.6	-12.1	192.2	-0.24

TABLE C-2 (cont'd.)
LEAK OUTFLOWS
HULL HOLED BELOW WATERLINE AT 1/2 THE DRAFT

VESSEL	TANK LOAD (% CAP.)	DEPTH (ft)	DRAFT (ft)	ULLAGE (ft)	BREACH	HOLE AREA (ft^2)	OUTFLOW VELOCITY (ft/s)	OUTFLOW Q (gal/min)	TANK SURFACE AREA (m^2)	TRANSLATION OF CARGO SURFACE (mm/min)
77,000 dwt lighter-	98	58.36	40.04	1.17	3" long X1/16"	0.001	28.1	16.6	630.7	0.10
ing tanker	90	58.36	40.04	9.51	3" long X1/16"	0.001	15.8	9.4	630.7	0.06
	75	58.36	40.04	23.79	3" long X1/16"	0.001	-25.9	-15.3	630.7	-0.09
T = 1.0T reg	60	58.36	40.04	38.06	3" long X1/16"	0.001	-39.8	-23.5	630.7	-0.14
	50	58.36	40.04	47.58	3" long X1/16"	0.001	-46.9	-27.7	630.7	-0.17
	35	58.36	40.04	61.85	3" long X1/16"	0.001	-55.9	-33.0	630.7	-0.20
	25	58.36	40.04	71.36	3" long X1/16"	0.001	-61.1	-36.1	630.7	-0.22
	0	58.36	40.04	95.15	3" long X1/16"	0.001	-72.6	-42.8	630.7	-0.26
77,000 dwt lighter-	98	58.36	36.04	1.17	3" long X1/16"	0.001	32.8	19.4	630.7	0.12
ing tanker	90	58.36	36.04	9.51	3" long X1/16"	0.001	23.2	13.7	630.7	0.08
	75	58.36	36.04	23.79	3" long X1/16"	0.001	-19.5	-11.5	630.7	-0.07
T = 0.9T reg	60	58.36	36.04	38.06	3" long X1/16"	0.001	-36.0	-21.3	630.7	-0.13
	50	58.36	36.04	47.58	3" long X1/16"	0.001	-43.7	-25.8	630.7	-0.15
	35	58.36	36.04	61.85	3" long X1/16"	0.001	-53.2	-31.4	630.7	-0.19
	25	58.36	36.04	71.36	3" long X1/16"	0.001	-58.7	-34.6	630.7	-0.21
	0	58.36	36.04	95.15	3" long X1/16"	0.001	-70.5	-41.6	630.7	-0.25
77,000 dwt lighter-	98	58.36	32.03	1.17	3" long X1/16"	0.001	37.0	21.8	630.7	0.13
ing tanker	90	58.36	32.03	9.51	3" long X1/16"	0.001	28.8	17.0	630.7	0.10
	75	58.36	32.03	23.79	3" long X1/16"	0.001	-9.5	-5.6	630.7	-0.03
T = 0.8T reg	60	58.36	32.03	38.06	3" long X1/16"	0.001	-31.8	-18.8	630.7	-0.11
	50	58.36	32.03	47.58	3" long X1/16"	0.001	-40.3	-23.8	630.7	-0.14
	35	58.36	32.03	61.85	3" long X1/16"	0.001	-50.4	-29.8	630.7	-0.18
	25	58.36	32.03	71.36	3" long X1/16"	0.001	-56.2	-33.2	630.7	-0.20
	0	58.36	32.03	95.15	3" long X1/16"	0.001	-68.4	-40.4	630.7	-0.24
77,000 dwt lighter-	98	58.36	28.03	1.17	3" long X1/16"	0.001	40.7	24.0	630.7	0.14
ing tanker	90	58.36	28.03	9.51	3" long X1/16"	0.001	33.5	19.8	630.7	0.12
	75	58.36	28.03	23.79	3" long X1/16"	0.001	14.1	8.3	630.7	0.05
T = 0.7T reg	60	58.36	28.03	38.06	3" long X1/16"	0.001	-26.8	-15.8	630.7	-0.10
	50	58.36	28.03	47.58	3" long X1/16"	0.001	-36.5	-21.6	630.7	-0.13
	35	58.36	28.03	61.85	3" long X1/16"	0.001	-47.4	-28.0	630.7	-0.17
	25	58.36	28.03	71.36	3" long X1/16"	0.001	-53.5	-31.6	630.7	-0.19
	0	58.36	28.03	95.15	3" long X1/16"	0.001	-66.3	-39.1	630.7	-0.23

TABLE C-3
77,000 dwt Lightering Tanker, Crack on bottom
Various Drafts & Tank Loadings

VESSEL	TANK LOAD (% CAP.)	DEPTH (ft)	DRAFT (ft)	ULLAGE (ft)	BREACH	HOLE AREA (ft^2)	OUTFLOW VELOCITY (ft/s)	OUTFLOW Q (gal/min)	TANK SURFACE AREA (m^2)	TRANSLATION OF CARGO SURFACE (mm/min)
25,000 bbl tank-	90	17.25	13.75	1.73	3" long X1/16"	0.001	2.4	1.4	89.2	0.06
barge	80	17.25	13.75	3.45	3" long X1/16"	0.001	-10.3	-6.1	89.2	-0.26
	70	17.25	13.75	5.18	3" long X1/16"	0.001	-14.7	-8.7	89.2	-0.37
T = 1.0T reg	60	17.25	13.75	6.90	3" long X1/16"	0.001	-18.1	-10.7	89.2	-0.45
	50	17.25	13.75	8.63	3" long X1/16"	0.001	-20.9	-12.4	89.2	-0.52
	35	17.25	13.75	11.21	3" long X1/16"	0.001	-24.6	-14.5	89.2	-0.62
	25	17.25	13.75	12.94	3" long X1/16"	0.001	-26.8	-15.8	89.2	-0.67
	0	17.25	13.75	17.25	3" long X1/16"	0.001	-31.5	-18.6	89.2	-0.79
25,000 bbl tank-	90	17.25	12.38	1.73	3" long X1/16"	0.001	10.2	6.0	89.2	0.26
barge	80	17.25	12.38	3.45	3" long X1/16"	0.001	-2.5	-1.5	89.2	-0.06
	70	17.25	12.38	5.18	3" long X1/16"	0.001	-10.8	-6.4	89.2	-0.27
T = 0.9T reg	60	17.25	12.38	6.90	3" long X1/16"	0.001	-15.1	-8.9	89.2	-0.38
	50	17.25	12.38	8.63	3" long X1/16"	0.001	-18.4	-10.9	89.2	-0.46
	35	17.25	12.38	11.21	3" long X1/16"	0.001	-22.5	-13.3	89.2	-0.56
	25	17.25	12.38	12.94	3" long X1/16"	0.001	-24.8	-14.7	89.2	-0.62
	0	17.25	12.38	17.25	3" long X1/16"	0.001	-29.9	-17.7	89.2	-0.75
25,000 bbl tank-	90	17.25	11.00	1.73	3" long X1/16"	0.001	14.3	8.4	89.2	0.36
barge	80	17.25	11.00	3.45	3" long X1/16"	0.001	9.7	5.7	89.2	0.24
	70	17.25	11.00	5.18	3" long X1/16"	0.001	-4.2	-2.5	89.2	-0.11
T = 0.8T reg	60	17.25	11.00	6.90	3" long X1/16"	0.001	-11.3	-6.7	89.2	-0.28
	50	17.25	11.00	8.63	3" long X1/16"	0.001	-15.5	-9.1	89.2	-0.39
	35	17.25	11.00	11.21	3" long X1/16"	0.001	-20.2	-11.9	89.2	-0.51
	25	17.25	11.00	12.94	3" long X1/16"	0.001	-22.8	-13.4	89.2	-0.57
	0	17.25	11.00	17.25	3" long X1/16"	0.001	-28.2	-16.7	89.2	-0.71
25,000 bbl tank-	90	17.25	9.63	1.73	3" long X1/16"	0.001	17.4	10.3	89.2	0.44
barge	80	17.25	9.63	3.45	3" long X1/16"	0.001	13.9	8.2	89.2	0.35
	70	17.25	9.63	5.18	3" long X1/16"	0.001	9.0	5.3	89.2	0.23
T = 0.7T reg	60	17.25	9.63	6.90	3" long X1/16"	0.001	-5.5	-3.2	89.2	-0.14
	50	17.25	9.63	8.63	3" long X1/16"	0.001	-11.9	-7.0	89.2	-0.30
	35	17.25	9.63	11.21	3" long X1/16"	0.001	-17.5	-10.4	89.2	-0.44
	25	17.25	9.63	12.94	3" long X1/16"	0.001	-20.5	-12.1	89.2	-0.51
	0	17.25	9.63	17.25	3" long X1/16"	0.001	-26.4	-15.6	89.2	-0.66

TABLE C-4
25,000 bbl tank barge, Crack on bottom
Various Drafts & Tank Loadings

VESSEL	TANK LOAD (% CAP.)	DEPTH (ft)	DRAFT (ft)	ULLAGE (ft)	BREACH	HOLE AREA (ft^2)	OUTFLOW VELOCITY (ft/s)	OUTFLOW Q (gal/min)	TANK SURFACE AREA (m^2)	TRANSLATION OF CARGO SURFACE (mm/min)
"450 Series" barge	90	29.31	20.00	2.93	3" long X1/16"	0.001	15.9	9.4	192.2	0.18
130,000 bbl	80	29.31	20.00	5.86	3" long X1/16"	0.001	8.0	4.7	192.2	0.09
	70	29.31	20.00	8.79	3" long X1/16"	0.001	-11.2	-6.6	192.2	-0.13
T = 1.0Treg	60	29.31	20.00	11.72	3" long X1/16"	0.001	-17.7	-10.5	192.2	-0.21
	50	29.31	20.00	14.66	3" long X1/16"	0.001	-22.4	-13.2	192.2	-0.26
	35	29.31	20.00	19.05	3" long X1/16"	0.001	-28.0	-16.5	192.2	-0.33
	25	29.31	20.00	21.98	3" long X1/16"	0.001	-31.2	-18.4	192.2	-0.36
	0	29.31	20.00	29.31	3" long X1/16"	0.001	-38.0	-22.5	192.2	-0.44
"450 Series" barge	90	29.31	18.00	2.93	3" long X1/16"	0.001	19.9	11.8	192.2	0.23
130,000 bbl	80	29.31	18.00	5.86	3" long X1/16"	0.001	14.4	8.5	192.2	0.17
	70	29.31	18.00	8.79	3" long X1/16"	0.001	4.5	2.6	192.2	0.05
T = 0.9Treg	60	29.31	18.00	11.72	3" long X1/16"	0.001	-13.0	-7.7	192.2	-0.15
	50	29.31	18.00	14.66	3" long X1/16"	0.001	-18.9	-11.2	192.2	-0.22
	35	29.31	18.00	19.05	3" long X1/16"	0.001	-25.3	-14.9	192.2	-0.29
	25	29.31	18.00	21.98	3" long X1/16"	0.001	-28.8	-17.0	192.2	-0.33
	0	29.31	18.00	29.31	3" long X1/16"	0.001	-36.1	-21.3	192.2	-0.42
"450 Series" barge	90	29.31	16.00	2.93	3" long X1/16"	0.001	23.3	13.7	192.2	0.27
130,000 bbl	80	29.31	16.00	5.86	3" long X1/16"	0.001	18.8	11.1	192.2	0.22
	70	29.31	16.00	8.79	3" long X1/16"	0.001	12.8	7.6	192.2	0.15
T = 0.8Treg	60	29.31	16.00	11.72	3" long X1/16"	0.001	-4.9	-2.9	192.2	-0.06
	50	29.31	16.00	14.66	3" long X1/16"	0.001	-14.6	-8.6	192.2	-0.17
	35	29.31	16.00	19.05	3" long X1/16"	0.001	-22.3	-13.2	192.2	-0.26
	25	29.31	16.00	21.98	3" long X1/16"	0.001	-26.2	-15.5	192.2	-0.30
	0	29.31	16.00	29.31	3" long X1/16"	0.001	-34.0	-20.1	192.2	-0.40
"450 Series" barge	90	29.31	14.00	2.93	3" long X1/16"	0.001	26.2	15.5	192.2	0.30
130,000 bbl	80	29.31	14.00	5.86	3" long X1/16"	0.001	22.3	13.2	192.2	0.26
	70	29.31	14.00	8.79	3" long X1/16"	0.001	17.6	10.4	192.2	0.20
T = 0.7Treg	60	29.31	14.00	11.72	3" long X1/16"	0.001	11.0	6.5	192.2	0.13
	50	29.31	14.00	14.66	3" long X1/16"	0.001	-8.3	-4.9	192.2	-0.10
	35	29.31	14.00	19.05	3" long X1/16"	0.001	-18.7	-11.1	192.2	-0.22
	25	29.31	14.00	21.98	3" long X1/16"	0.001	-23.2	-13.7	192.2	-0.27
	0	29.31	14.00	29.31	3" long X1/16"	0.001	-31.8	-18.8	192.2	-0.37

TABLE C-5
130,000 bbl tank barge, Crack on bottom
Various Drafts & Tank Loadings